IRENA
International Renewable Energy Agency

INNOVATION OUTLOOK

OCEAN ENERGY TECHNOLOGIES

A contribution to the
Small Island Developing
States Lighthouses
Initiative 2.0

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About IRENA

The International Renewable Energy Agency (IRENA) serves as the principal platform for international co-operation, a centre of excellence, a repository of policy, technology, resource and financial knowledge, and a driver of action on the ground to advance the transformation of the global energy system. An intergovernmental organisation established in 2011, IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy, in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity.

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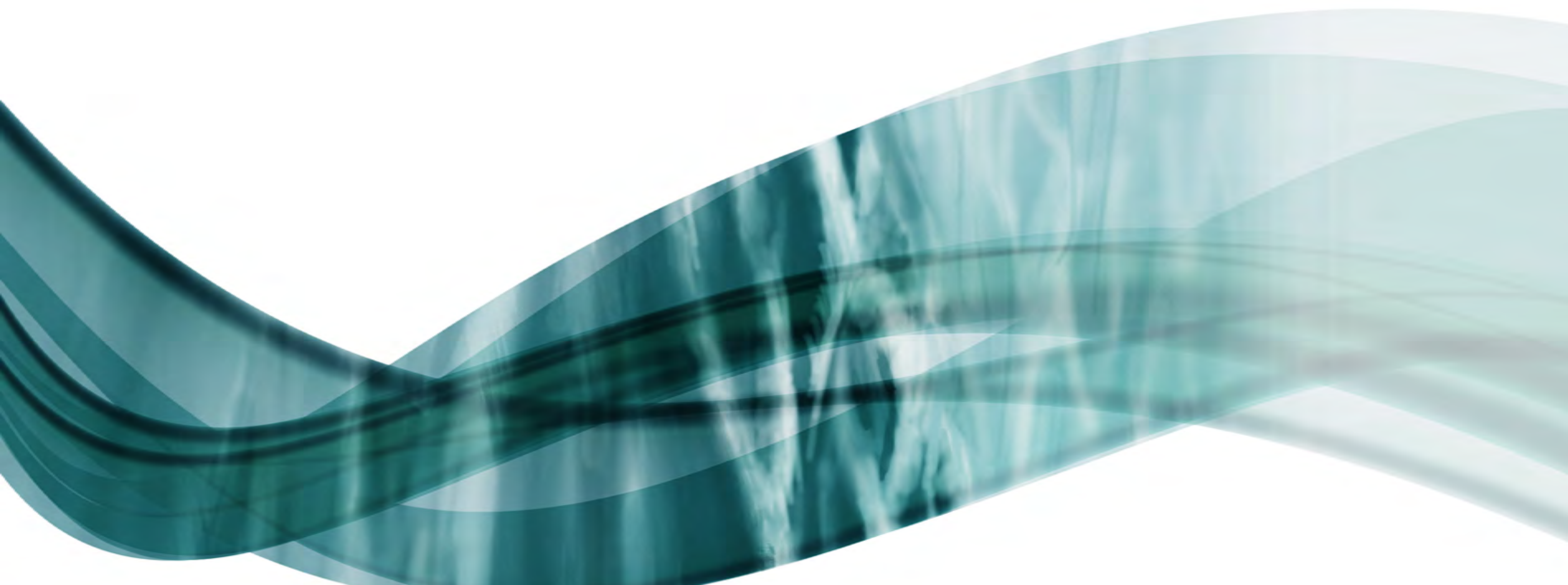

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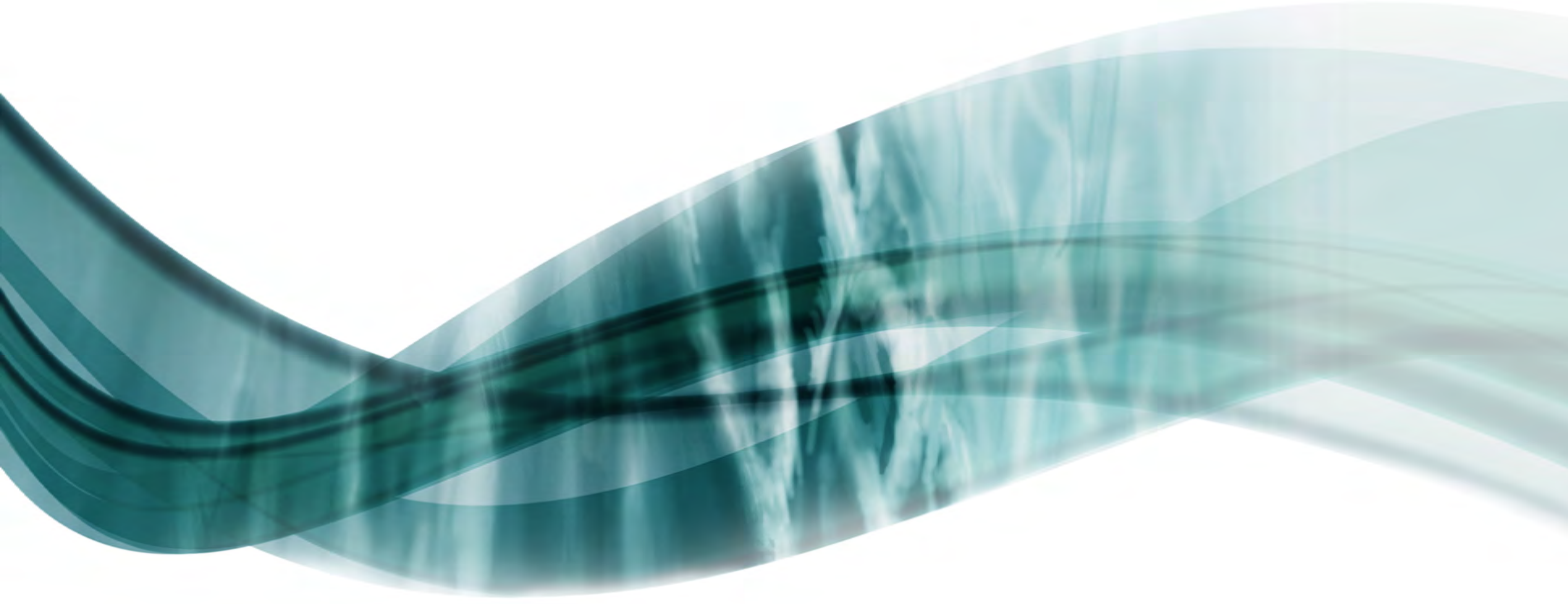


ABBREVIATIONS

°C	Degrees Celsius
AUV	Autonomous underwater vehicle
CfD	Contract for Difference
CO2	Carbon dioxide
EC	European Commission
EIT	European Institute of Innovation and Technology
EMEC	European Marine Energy Centre
EU	European Union
EUR	Euro
GET FIT	Global Energy Transfer Feed-in Tariff
GIEC	Guangzhou Institute of Energy Conversion
GW	Gigawatt
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IECRE	IEC System for Certification to Standards Relating to Equipment for Use in Renewable Energy Applications
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
IPPA	Innovative power purchase agreement
IRENA	International Renewable Energy Agency
KRISO	Korea Institute of Ships and Ocean Engineering
kW	Kilowatt
kWh	Kilowatt-hour
LCOE	Levelised cost of electricity
MEECE	Marine Energy Engineering Centre of Excellence
MSP	Marine spatial planning
MW	Megawatt
NDC	Nationally Determined Contribution
NREL	National Renewable Energy Laboratory
O&M	Operations and maintenance
OB	Oscillating body
OD	Overtopping device
OPT	Ocean Power Technology
ORE	Offshore Renewable Energy Catapult
OTEC	Ocean thermal energy conversion
OWC	Oscillating water column
OWSC	Oscillating water surge converter
PPA	Power purchase agreement
PRO	Pressure retarded osmosis
PV	Photovoltaic
R&D	Research and development
RBS	Risk Breakdown Structure
REC	Renewable energy certificate
RED	Reversed electro dialyses
REIF	Renewable Energy Investment Fund
RPO	Renewable purchase obligation
SDG	Sustainable Development Goal
SIDS	Small island developing state

SME	Small and Medium Enterprise
SNMREC	South National Marine Renewable Energy Centre
SPM	Submerged pressure differential
SWAC	Seawater air conditioning
SWRO	Seawater reverse osmosis
TAP	Technology Assessment Process
TC	Technical Committee
TRL	Technology Readiness Level
TS	Technical specifications
TWh	Terawatt-hour
UK	United Kingdom
US	United States
USD	United States dollar
VRE	Variable renewable electricity/energy
WEC	Wave energy converter

SUMMARY FOR POLICY-MAKERS

Key messages: Technology and market

- **Tidal stream and wave energy are picking up speed and projects are developing dynamically.** A total capacity of 12.91 megawatts (MW) of tidal stream[1] and wave energy is now operational, *i.e.* 2.31 MW wave and 10.6 MW tidal (see Figure S1). A significant number of devices of both technologies are being scaled up quickly, and units of 1 MW and higher are being successfully deployed. Tidal stream is more advanced and is getting closer to reaching commercialisation with several tidal arrays[2] in the pipeline. Wave energy is also advancing quickly but is less mature compared to the other technologies, as it is mostly in the prototype and demonstration phase.

- **Tidal barrage (or tidal range) technology still dominates deployed capacity.** More than 98% of the total combined capacity that is currently operational, or 521.5 MW, is tidal barrage technology (see Figure S2). This comprises mainly three large projects – a 254 MW plant in the Republic of Korea (which came online in 2011), a 240 MW plant in France (1966) and a 20 MW station in Canada (1984) – and the remaining 7.5 MW is split between two plants in China (4.1 MW) and the Russian Federation (3.4 MW). Despite the dominance of this technology, no tidal barrage power plants of relevant scale have been developed in almost 10 years, and there is relatively low resource potential to be explored. However, a pipeline of more than 2.5 gigawatts (GW) in planned projects worldwide indicates that the market still sees opportunities.

Figure S1: Ocean energy deployment excluding tidal barrage (MW)

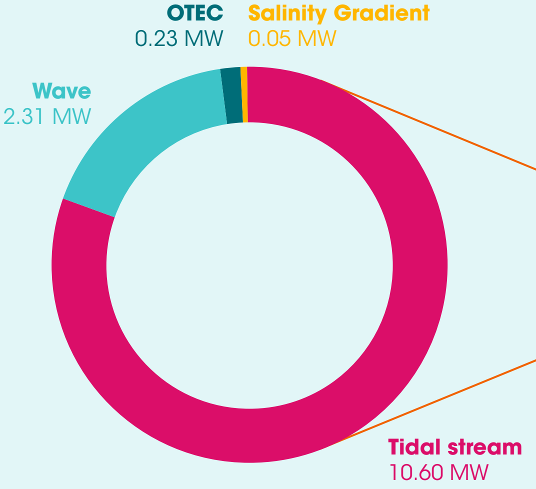
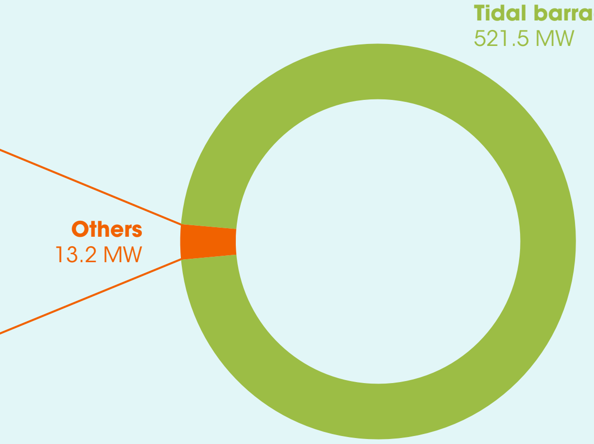


Figure S2: Total ocean energy deployment (MW)



Source: *IRENA ocean energy database*

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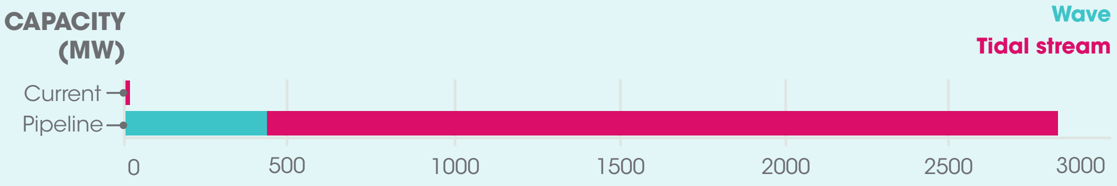
[1] A distinction is made between tidal barrage (or tidal range) and tidal stream (or tidal current) technologies. Tidal barrage makes use of the tidal range – i.e., the actual height difference between high and low tide – and harnesses the potential energy. Tidal stream makes use of the tidal currents. Throughout this report "tidal" refers to both technologies, unless otherwise specified.

[2] An array of tidal turbines at a single site is considered a power plant.

Figure S3: Active and projected tidal stream and wave capacity beyond 2020



Note: *While their capacity is too small to appear on this chart, additional projects are planned for the other ocean energy technologies beyond 2020. For example, a 2 MW ocean thermal energy conversion plant and a 1 MW salinity gradient energy plant are planned in the Netherlands (Johnson, 2019).*

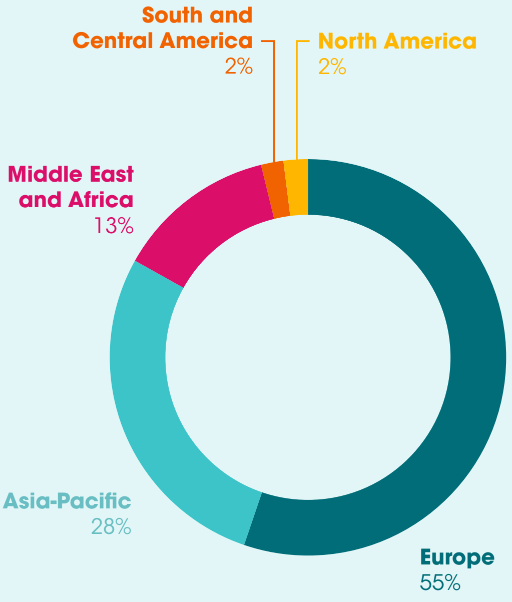
Source: *IRENA ocean energy database*

- **The coming years may witness an increased uptake of ocean energy.** In the longer run, more capacity additions are expected, as wave and tidal stream projects with combined capacities of 2.83 GW were in the pipeline[3] as of 2020 (see Figure S3). The International Renewable Energy Agency (IRENA) estimates that around 10 GW could be commercially deployed by 2030.

- **Ocean thermal energy conversion (OTEC), salinity gradient and ocean current technologies have opportunities to start picking up at the end of the decade.** Although projects at small scales are starting to be deployed and are increasing in size, the technologies are all still mainly in the research and development stages. A number of barriers still need to be overcome, and work on these technologies is therefore conducted mainly in research institutes and universities.

- **Interest in ocean energy is global, with Europe as the frontrunner.** Although 31 countries on 6 continents have deployed or are planning to deploy ocean energy technologies, three-quarters of the currently installed capacity and more than half of the pipeline capacity is projected to be deployed in Europe[4] (see Figure S4 and S5).

Figure S4: Active and projected ocean energy capacity



Source: *IRENA ocean energy database*

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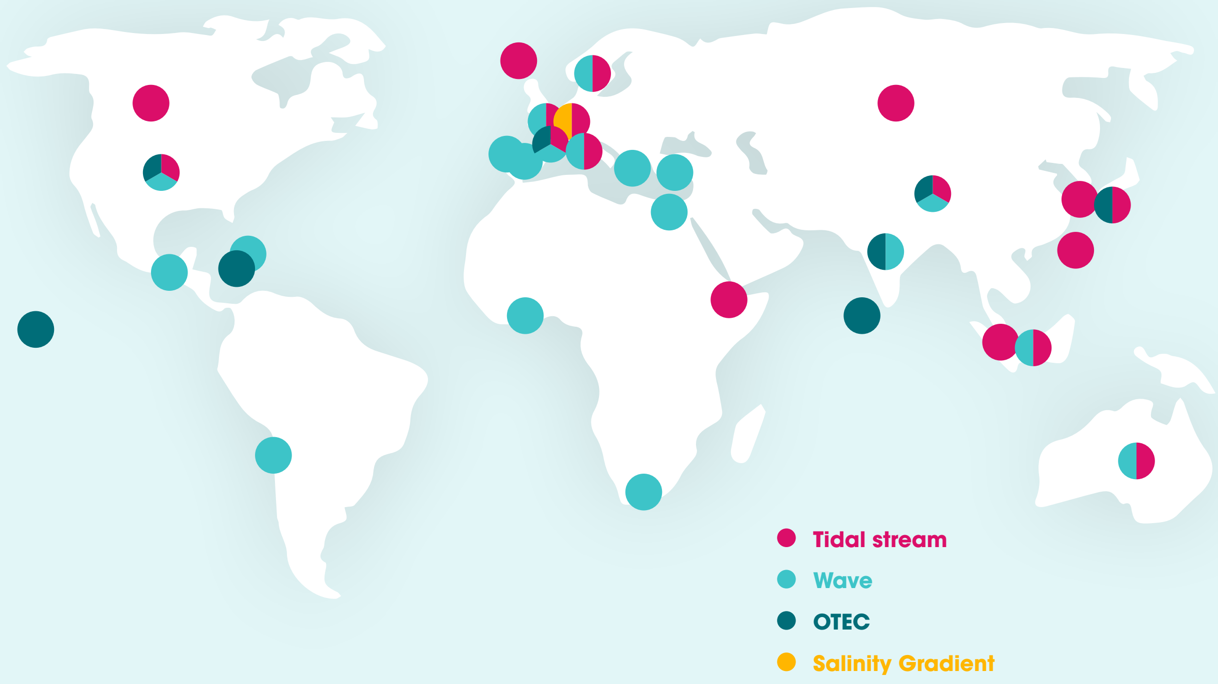
[3] Set of planned projects, which are in various levels of development.

[4] Not including tidal barrage (tidal range) technologies.

Figure S5: Global distribution of ocean energy activity (active and projected power plants)



Boundaries and names shown on this map do not imply any endorsement or acceptance by IRENA

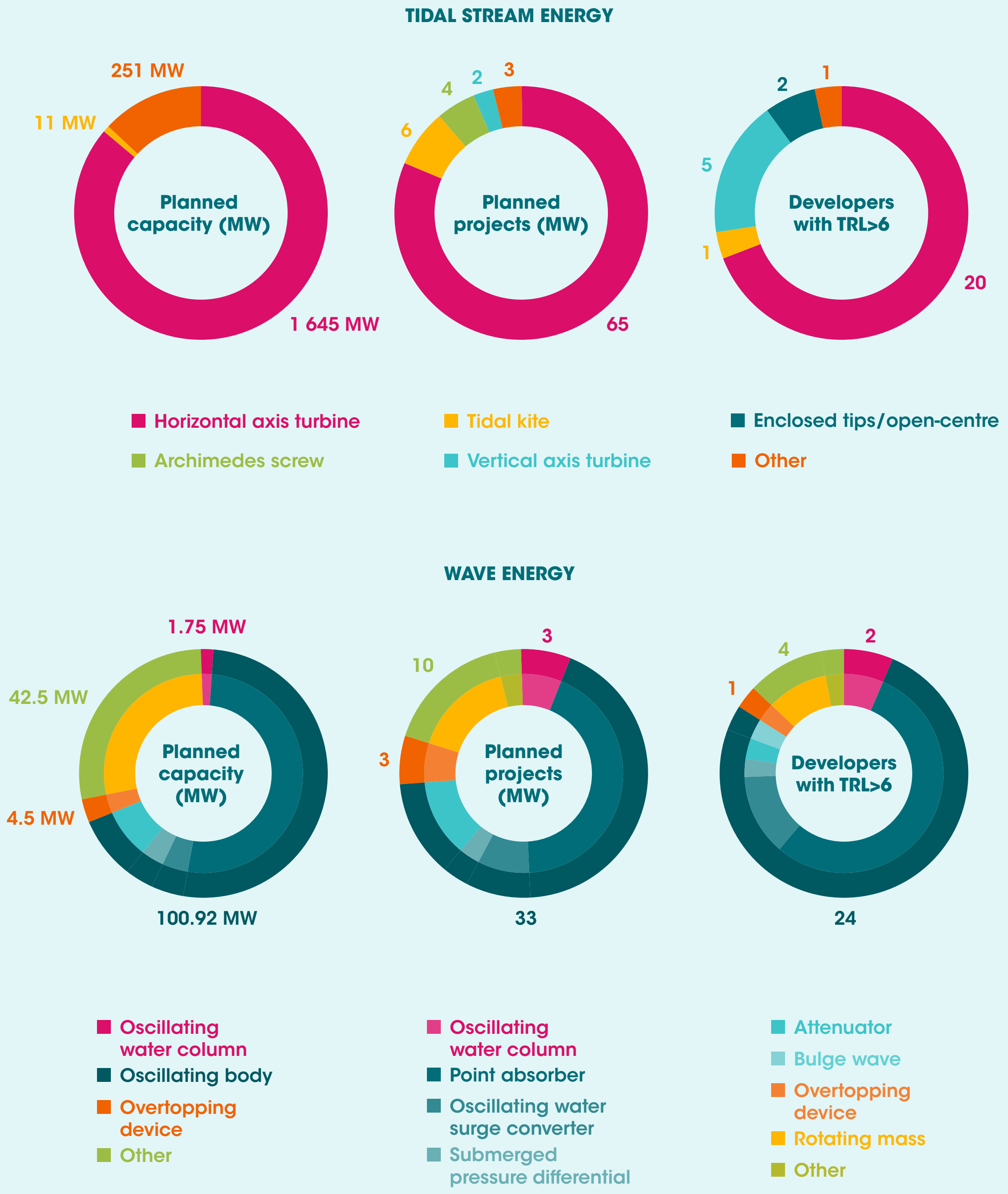
Source: *IRENA ocean energy database*

- **Tidal stream energy is seeing a convergence in technology, but the race is not yet won.** Horizontal-axis turbines have shown to be the most popular technologies for tidal stream energy and are the technologies proposed in all planned major tidal array projects (see Figure S6). The long-awaited convergence (from a developer point of view) towards one particular technology, however, is being disrupted by innovative technologies such as tidal kites that can operate at lower current speeds. Whether the horizontal-axis turbine emerges as the main source for tidal stream energy remains to be seen.

- **Wave energy has not yet seen a convergence in technology and is following two parallel paths.** Almost 10 different types of wave energy technologies are being pursued simultaneously, in part because wave energy is not yet as mature as tidal stream energy. Two parallel development paths can be witnessed, one aimed at scaling up devices and potentially deploying arrays, and the other aimed at deploying much smaller, purpose-built devices to target a more specific operation, such as providing power to offshore platforms or pumping water to shore for desalination.

- **The levelised cost of electricity (LCOE) for ocean energy may be lower than originally anticipated.** Due to the relatively early life-cycle stage of all ocean energy technologies, their LCOEs are difficult to predict and uncertain. The current LCOE for tidal is estimated at between USD 0.20/kWh and USD 0.45/kWh and for wave between USD 0.30/kWh and USD 0.55/kWh (see Figure S7). Recent estimations by developers with active projects show that costs may be lower. For tidal energy, an LCOE of USD 0.11/kWh is expected to be reached between 2022 and the early 2030s, while the costs for wave would lag five years behind, reaching

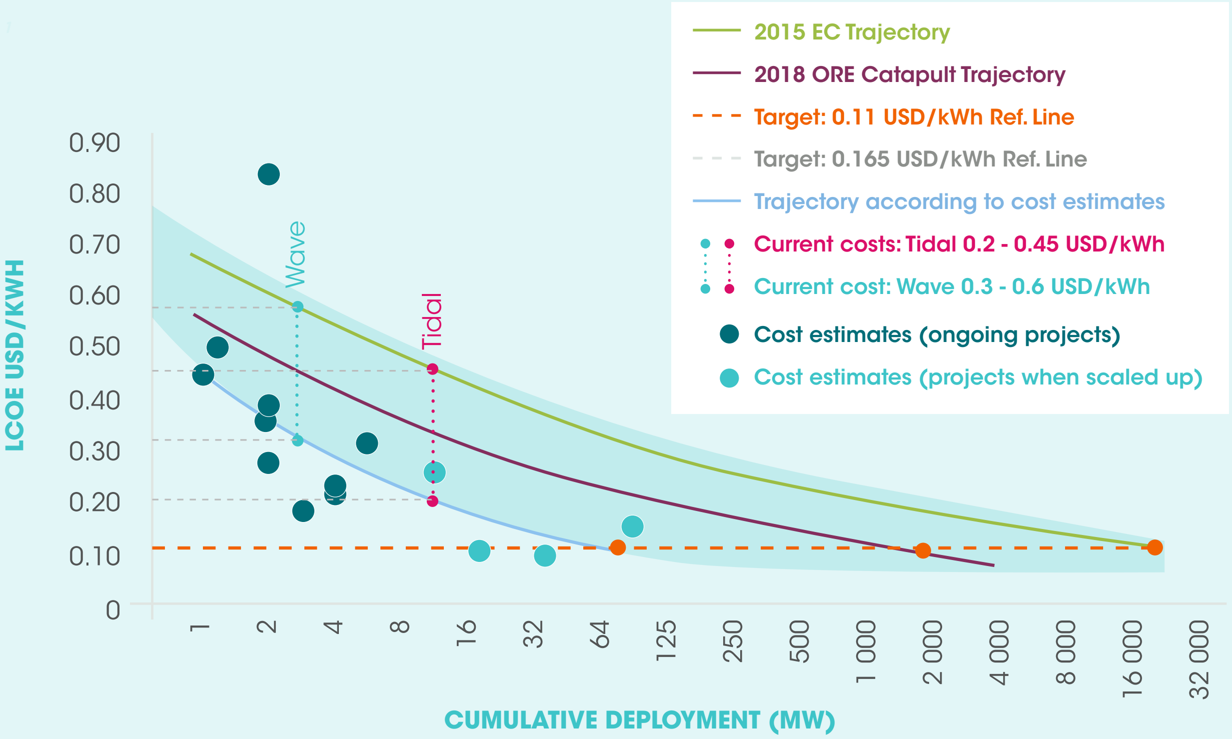
Figure S6: Projected capacity and number of project developers by technology



Note: *The Technology Readiness Level (TRL) is a scale from 1 to 9 where 1-3 represents the research phase, 4-5 the development phase, 6 the demonstration phase and 7-9 the deployment phase (with 7 representing prototype demonstration and 9 a fully deployed, proven and operational technology).*

Source: *IRENA ocean energy database*

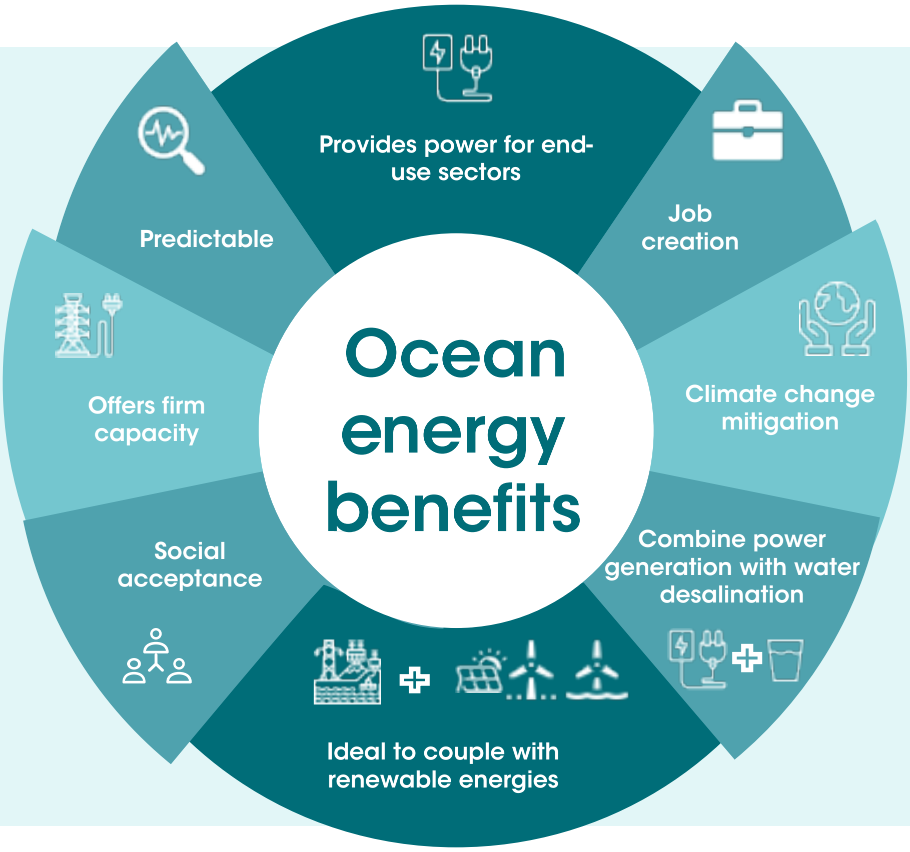
Figure S7: Target cost reduction curve and LCOE estimates



Note: *EC = European Commission; ORE = ORE Catapult*

Source: *Adapted from Magagna, 2019a; ORE Catapult, 2018*

Figure S8: Key benefits of ocean energy technologies



USD 0.22/kWh by 2025 and USD 0.165/kWh by 2030 (European Commission, 2016a; Magagna, 2019a; ORE Catapult, 2018). In small island developing states (SIDS), where ocean energy would compete with diesel imports, these technologies could reach grid parity first.

- **Ocean energy can bring key technological and socio-economic benefits, in addition to helping mitigate climate change, especially in SIDS.** Energy harnessed from oceans, 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, water desalination (see Figure S8). Offshore renewables can also provide significant socio-economic opportunities to countries with coastal areas and island territories, such as job creation, improved livelihoods, local value chains and enhanced synergies between blue economy actors, in addition to contributing to the achievement of the United Nations Sustainable Development Goals (SDGs) in islands and coastal territories (SDG 7 and SDG 14). Another key benefit of ocean energy technologies is their high predictability, which makes them well-suited to complement variable renewable energy sources such as wind and solar photovoltaic (PV).

Key messages: Pathways to address key challenges and move closer to commercialisation

- **Revenue and capital support remain crucial, as the LCOEs of ocean energy technologies are still too high to compete with other renewable energy generating technologies.** Although the LCOEs are decreasing more quickly than anticipated, they remain high. Therefore, financing opportunities must be improved and innovative finance mechanisms must be developed to support capital and revenue, which could help drive down the LCOEs.

- **A focus on the business case can help in the wider deployment of ocean energy.** Ocean energy could be increasingly perceived as an essential piece of a holistic solution. Due to its predictability and more stable generation than other renewable energy sources, ocean energy could support and stabilise grids that integrate variable renewable energy sources, such as solar PV and wind.

- **Ocean energy has the potential to position itself as a main source to power the blue economy[5].** The blue economy is gaining importance and can unlock opportunities for ocean energy to become a main source of power by making use of synergies with other offshore markets such as oil and gas, offshore wind, desalination, aquaculture, etc.

- **Islands and remote coastal areas can provide the ideal market entry avenue.** Islands – and SIDS in particular – lack land, are often in need of a more stable energy supply, and have good preconditions for ocean energy deployment and the integration of variable renewables. They also have a high need for energy to power other offshore markets such as aquaculture, desalination and cooling (see Figure S9). In addition, their grids are often carbon intensive and their energy costs are high. This market therefore possesses unique circumstances that make ocean energy a viable alternative solution to fossil fuels. Such a niche market can help to demonstrate the technology, increase investors trust and lower the LCOEs.

- **Ocean energy could be coupled with coastal defence structures.** Given the increased risks posed by climate change, including rising sea levels, ocean energy technologies could be coupled with breakwater dams, storm surge barriers and bridges, which can provide holistic business cases, addressing challenges in both climate mitigation and adaptation.

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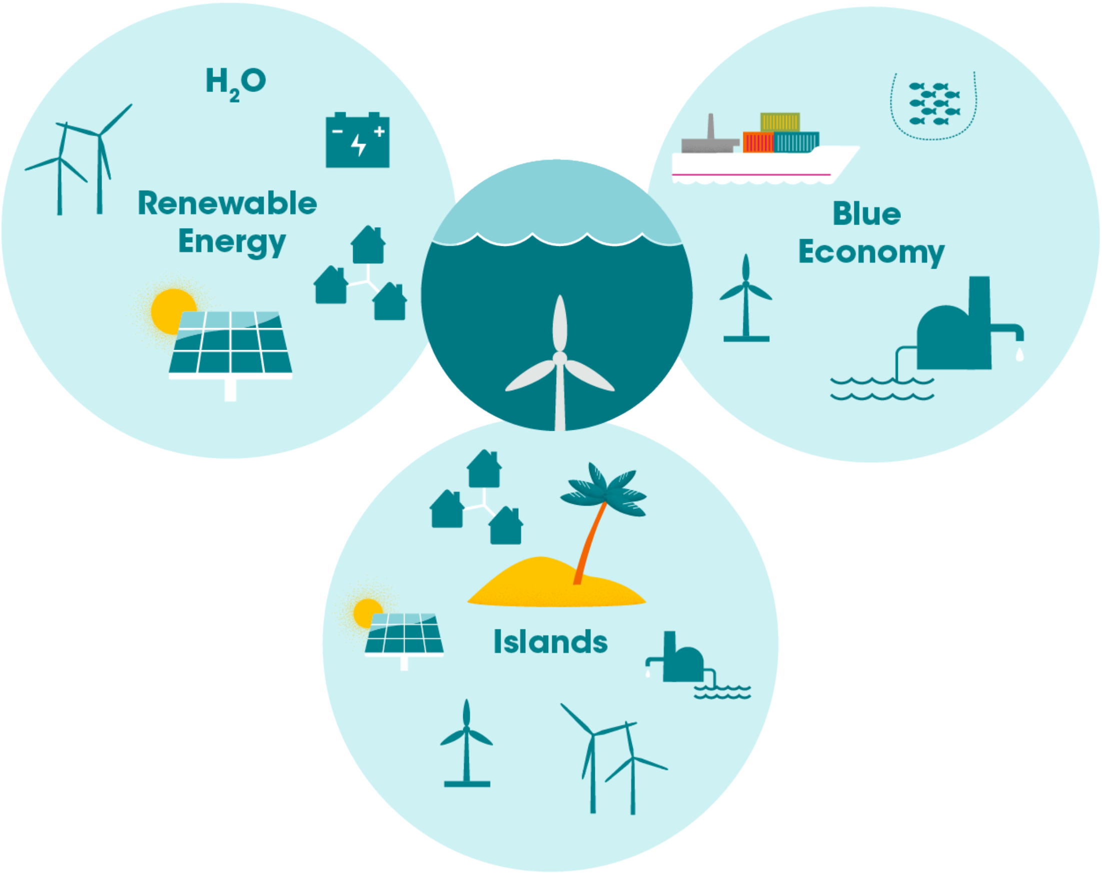
[5] The blue economy is defined by the World Bank as the "sustainable use of ocean resources for economic growth, improved livelihoods and jobs, and ocean ecosystem health", which encompasses many activities, including renewable energy, fisheries, maritime transport, waste management, tourism and climate change (World Bank, 2017).

- **Perceived risks remain high but can be lowered through standardisation, stage-gate[6] metrics and marine resource planning.** The high risks, actual or perceived, are a major issue in securing funding and therefore need to be mitigated. Tools to assist de-risking processes are standardisation and stage-gate metrics. A research gap also exists when it comes to marine spatial planning and site assessments. More emphasis on these processes is needed.

- **International collaboration and involvement of multiple stakeholders are key to advance the development and deployment of these technologies.** Joining forces and sharing knowledge and data – including among other offshore sectors such as offshore wind, oil and gas, and shipping – can help eliminate bottlenecks in know-how, supply chain management, operability improvement and de-risking the technologies (see Table S1).

- **There is a need to embed ocean energy in national energy and climate plans.** By placing ocean energy on national agendas and engaging policy makers, ocean energy gains public visibility. Providing the necessary support to research could incentivise further private investments in these technologies.

Figure S9: Coupling ocean energy with renewable energy and the blue economy in islands



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[6] Stage-gate metrics refer to breaking down the innovation process into stages (i.e., from idea to deployment) and gates, which are defined as key milestones during which decisions are made if the project continues or stops (Edgett, 2018).

Table S1: Proposed action and stakeholder identification

Proposed action	Stakeholder	Implications
Enhance the business case	Policy makers Industries Power system operators	Use ocean energy to power the blue economy and couple with other offshore sectors (e.g., ports, shipping, desalination, oil and gas, etc.)
	Power system operators Energy planners	Include ocean energy as a predictable energy source that can integrate VRE and energy storage
	Policy makers	Joint tenders with other VRE installations (e.g., wave energy and offshore wind)
	Policy makers Local municipalities	Promote application on islands, coastal communities and micro grids
	Project developers Policy makers	Quantify and consider additional benefits, avoided costs, externalities (e.g., job creation, climate change mitigation or security of energy supply, etc.)
Improve access to financial support	Policy makers Regulators Financial institutions	Create innovative financial revenue support schemes aimed particularly at ocean energy (e.g., local investments, prizes, funding based on capacity size, funding based on Technology Readiness Level)
	Policy makers	Promote blended finance which encourages private capital to invest in projects that benefit society and contribute to achieve sustainable development while also providing financial returns to investors
	Financial institutions Private investors	Invest in ocean energy technologies
	Policy makers	Improve revenue and capital support schemes across all stages of development (R&D, deployment, operation)
	Financial institutions (multilateral donors)	Increase access to finance in developing countries and SIDS
Set up and strengthen resource and site assessment	Regulators	Develop regulatory processes and frameworks for site assessment and identification
	Policy makers	Conduct effective marine spatial planning (MSP) and incorporate ocean energy on regional and national levels
		Include mapped resource potential in climate and energy strategies
	Energy planners	Use advanced modelling tools
	Data owners	Improve access and exchange to baseline data, and address need for more data
	Power system operators Developers	Include assessments of local grid capacities and requirements in site assessments
	Regulators	Provide guidance and frameworks for environmental impact assessment

Build supply chain	Private sector Coastal communities	Build upon local expertise and create supply chains (include local business)
	Established offshore industries	Adapt supply chains from related offshore industries
Boost ocean energy policy and regulatory schemes	Policy makers	Include ocean energy in long-term national and/or regional energy roadmaps and Nationally Determined Contributions (NDCs)
		Establish clear policies with national targets
		Engage and support the financial institutions
	Regulators	Remove bottlenecks in the permitting process
Minimise risks by improving reliability and efficiency of the technology	International organisations	Adoption of technical specifications and advanced development of prototype/component/type/project certifications of the International Electrotechnical Commission (i.e., power take-off system, foundation, mooring, etc.)
	Policy makers Regulators	Develop and promote the use of existing assessment frameworks to track and compare development progress, e.g., stage-gate metrics
	Utility Private sector	Develop innovative hybrid renewable energy systems to integrate and share platforms with other technologies
	Asset owner	Collect and share performance data
	Technology manufacturers Developers	Scale up manufacturing by deploying arrays
	Technology manufacturers	Use modular design that can be compatible with other renewable energy generation technologies
Develop capacity through enhanced co-operation	International organisations (e.g., IRENA)	Share best practices and lessons learned (within the ocean energy sector and with other offshore industries)
	Policy makers International organisations (e.g., IRENA)	Emphasise stakeholder partnerships and build international co-operation
	Power system operators Private sector	Collaborate with local grid operators to upgrade and adapt infrastructure to allow ocean energy connection
	Educational institutions Universities	Enhance skills in the workforce and via education programmes
	Policy makers Civil society	Consult and engage the public early on

1. INTRODUCTION

This report aims to deliver holistic insights into ocean energy and its potential, outlining the steps necessary to reach commercialisation of these innovative power generating technologies. The analysis highlights the potential of ocean energy to contribute to the energy transition across the globe by illustrating the various ocean energy technologies, providing analyses on the current and projected market, presenting ways of enhancing the business case and illustrating mechanisms to decrease costs. The report aims to support energy transitions in countries with access to the ocean, as well as on islands, and highlights specific opportunities for such markets.

While a focus on research and development was essential in the earlier stages of ocean energy technologies, there is now a gap to advance to commercialisation, a critical phase in any innovation's life cycle. Some large-scale commercial tidal energy projects have faced such issues and have not successfully completed their path towards commercial levels. In 2019, for example, the 2 MW Cape Sharp tidal stream project in Canada had its licence revoked by the government due to financial issues (Quon, 2020). While the financial issues were also caused by technical damages in the turbine that eventually led to the liquidation of developer OpenHydro, the pivotal factor here was the decision to stop investments by its parent company, Naval Energy.

Other major developers, such as the tidal developer Tocardo that has deployed a 1.25 MW commercial horizontal tidal plant in the Netherlands, and the wave developers Pelamis and Aquamarine Power, have also filed for bankruptcy due to financial issues despite successfully testing promising devices. However, Tocardo was able to recover and reacquire the plant in the third quarter of 2020. More attention therefore needs to be placed on supporting ocean energy development and improving the economic case.

This report proposes several measures to bridge the commercialisation and economic gaps.

Section 2 sets the scene on the estimated costs, their projected reduction, technology status and the prospective markets.

Section 3 sheds light on relevant challenges that the sector is facing, limiting the scale-up of deployment.

Section 4 presents three sub-sections with innovative business cases that could lead to additional revenue streams. Section 3.1 focuses on reaping benefits from complementary renewable energy sources – that is, hybrid renewable power plants linking ocean energy with other renewable energy sources – to help balance the grid and provide baseload power source. Section 3.2 presents several ways in which ocean energy can be used to power the blue economy. In Section 3.3, hybrid renewable power plants and the blue economy are combined with an emphasis on powering islands (in particular SIDS), which have a number of unique characteristics and face several challenges that can be mitigated by ocean energy.

Section 5 discusses other pathways to bridge the commercialisation gap. Section 4.1 presents several revenue and capital support mechanisms that could facilitate the implementation of ocean energy technologies. Section 4.2 provides risk mitigation and assessment tools, including standards, stage-gate metrics and resource assessments.

Finally, **Section 6** presents an overview of recommendations and proposed action based on what is discussed throughout the report.

Due to its early development stage, tracking cumulative and annual deployments of ocean energy is not a practical method because most projects that have been deployed in the water are for limited testing or demonstration purposes only, and annual deployments are thus not equal to annual capacity additions.

The emphasis of this analysis is therefore not on past and cumulative deployment, as is often done in other analyses, but rather on currently active (deployed) projects as well as projected (planned) projects, particularly those of commercial scale, where applicable (Table 17 in Appendix I).

However, planned projects in the pipeline come with different degrees of uncertainty, which means that while these projects are possible, it is not certain that they will be implemented. The driver behind this analysis is to provide a picture of the current ocean energy market. The project analysis in the following sub-sections only includes open-water projects that deliver power to the grid or to other purpose-built applications. Small-scale tank-testing or wet tests without delivery of electricity are not included.

Illustration by Ling Ling Federhen

2. GLOBAL OUTLOOK: TECHNOLOGY AND MARKET

With nearly 2.4 billion people, or 40% of the global population, living within 100 kilometres of the coast (UN, 2017), ocean energy presents a convenient solution to tackle climate change while contributing to a more sustainable future. Ocean energy has been recognised by the Intergovernmental Panel on Climate Change (IPCC) as a means of mitigating climate change (IPCC, 2019). Ocean energy can also be an important key to advancing numerous United Nations Sustainable Development Goals (SDGs) that go beyond SDG 7 (affordable and clean energy) and SDG 13 (climate action) and could impact a wide array of SDGs including SDG 1, SDG 2, SDG 5, SDG 6, SDG 8, SDG 9, SDG 14 and SDG 17 (see Figure 1).

Ocean energy technologies are commonly categorised based on the resource utilised to generate energy. Tidal stream and wave energy converters are the most widely developed technologies across geographies, aside from tidal range, which is only suitable in limited locations. Other ocean energy technologies that harness energy from the differences in temperature or from the difference in salinity, or that make use of ocean currents, may become increasingly relevant over longer time horizons.

The theoretical resource potential of ocean energy is so vast that it could meet present and projected global electricity demand well into the future. The potentials differ among technologies, and an analysis from the International Renewable Energy Agency (IRENA) based on more than a dozen sources assesses the aggregated value for all ocean energy technologies combined at between 45 000 terawatt-hours (TWh) and potentially well above 130 000 TWh of electricity per year. This means that ocean energy could cover more than twice the current global demand for electricity[7].

Figure 2 presents the mean values that are assessed as most probable for each generating source. More than half of the potential comes from ocean thermal energy conversion (OTEC), followed by wave energy, salinity gradient and tidal energy[8].

Figure 1: Sustainable Development Goals that are impacted by ocean energy

Note: *The thickness of the borders indicates the level of the expected impact, i.e., the thicker borders indicate a higher impact of ocean energy on SDG 7 and SDG 13.*

Source: *Adapted from UNDP, 2020*

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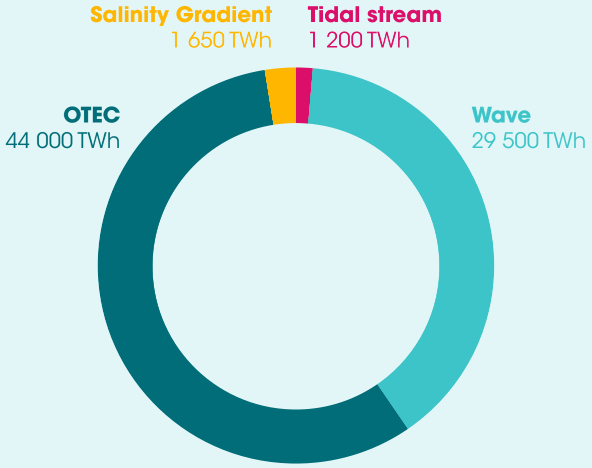
[7] Global electricity demand was 25 814 TWh in 2019 (Ember, 2020).

[8] Further research is needed to assess the potential of ocean current energy technologies.

Figure 2: Ocean energy resource potential (TWh/year)



Based on Nihous, 2007; Mørk et al., 2010; Skråmestø et al., 2009; OES, 2017

Key benefits of ocean energy technologies

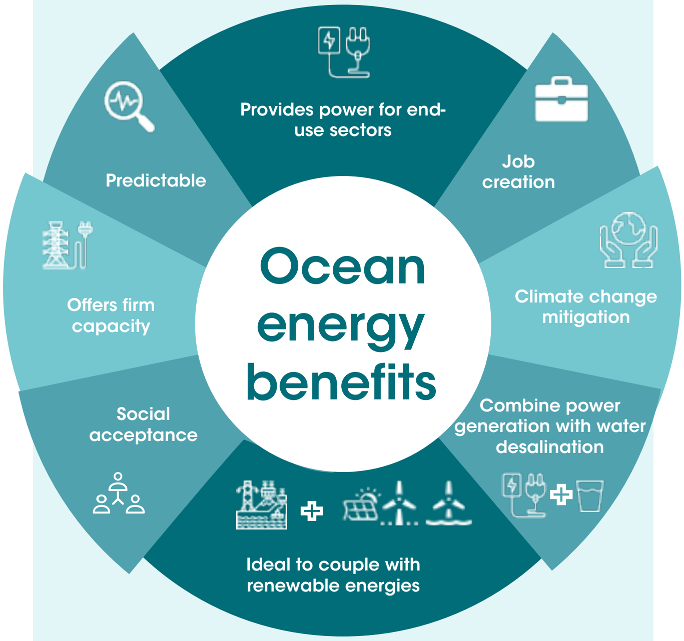
Technological benefits: Ocean energy is considered a renewable energy source, meaning that there is an abundant amount of unlimited energy waiting to be used. Such technology is characterised by greater predictability than other variable renewable energy (VRE) sources, which gives it a technical edge over solar PV and wind electricity. The predictability is driven mainly by the location and movement of the moon, which is well known. Ocean energy acts as a complementary source offering firm capacity that in turn can increase the uptake of VRE sources such as solar and wind. Therefore, ocean energy is well-suited to form hybrid renewable electricity generation systems. Especially when coupled with offshore wind energy, ocean energy technologies can continue to supply electricity since the waves last much longer following the reduction in wind speeds. What distinguishes ocean energy is its applicability and availability for both onshore and offshore deployment. Due to its modularity and scalability it can provide electricity for a variety of end-use sectors (for example, tourism, ports, cooling, desalination, etc.).

Socio-economic benefits: Ocean energy is a key component of the blue economy (IRENA, 2020a) and could provide several socio-economic benefits. Although currently these technologies are not cost competitive with mature renewable technologies, with increased uptake of ocean energy projects, costs are expected to decrease. As this is a relatively new industry, it could create new job opportunities in the fields of research and development (R&D) and technology deployment, but also engineering procurement and construction (EPC) as well as operation and maintenance (O&M) of ocean energy power plants. Moreover, given that ocean energy technology is submerged, it does not impose any visual impairments that affect the natural landscape, so it could benefit from increased social acceptance.

Climate change mitigation: The benefits of ocean energy extend beyond technical and socio-economic benefits. Because ocean energy is a renewable energy source, it contributes to offsetting emissions from conventional greenhouse gas-intensive electricity generation sources. It therefore has the potential to contribute to the mitigation of climate change.

Additional benefits for SIDS: SIDS are positioned to become the main beneficiaries of a blue economy driven by offshore renewables and ocean energy technologies, helping to address some of their most pressing and specific needs,

Figure 3: Key benefits of ocean energy technologies



including 1) *affordable and reliable access to electricity*, replacing costly generation using imported diesel, and reducing the need for land to deploy other energy sources onshore, as well as reducing disruptions of energy imports via maritime transport; 2) *sustainable transport of goods*; and 3) *access to freshwater* through water desalination powered by renewable energy sources. For example, the grid-parity equation is different in SIDS where ocean energy is competing with costly fossil fuel imports.

Current and future deployment

The deployment of ocean energy technologies was anticipated long before the need to decarbonise the power sector became evident. Growth in the sector has been slower than expected, however. The last decade has shown a modest progress for ocean energy technologies, especially for wave and tidal energy. Tidal energy is getting one step closer to commercialisation with the convergence towards one technology (horizontal-axis turbines) and with several large-scale multi-turbine tidal farms under construction. Wave energy is less mature and is at a scale-testing to demonstration stage.

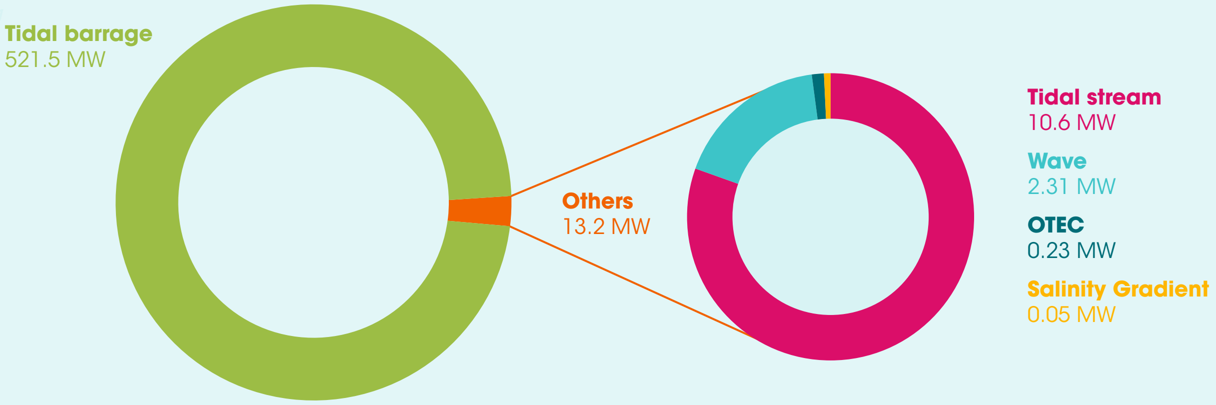
Numerous different wave energy technologies are being pursued, and unlike tidal energy that aims at large-scale arrays, wave energy converters are currently following two parallel paths: one aimed at the deployment of large-scale devices above 1 megawatt (MW) and eventually arrays of these, and the other aimed at purpose-built smaller full-scale devices for specific offshore applications. OTEC and salinity gradient technologies are still in early development stages with limited deployed demonstration projects and various challenges before reaching commercial scale. Although ocean current technology presents a fifth means of harnessing the ocean's energy, not much research has been conducted in this area and thus little emphasis is placed on ocean current technologies throughout the report.

The current cumulative installed capacity across all ocean energy technologies is 534.7 MW, with a large majority of it being tidal barrage (or tidal range) technology (see Figure 4). Due to the different level of maturity, but also because of little development in the past decade, tidal barrage is often not included in modern discussions of ocean energy. On the contrary, the other ocean energy technologies receive more attention due to the dynamic project development. Figure 4 therefore also presents an overview of installed capacity excluding tidal barrage, amounting to 13.2 MW, with more than three-quarters of this being tidal stream.

As an increasing number of companies, research institutes, universities and investors are allocating resources to the development of all ocean technologies, substantial growth in deployment and installed capacity is expected in the coming years.

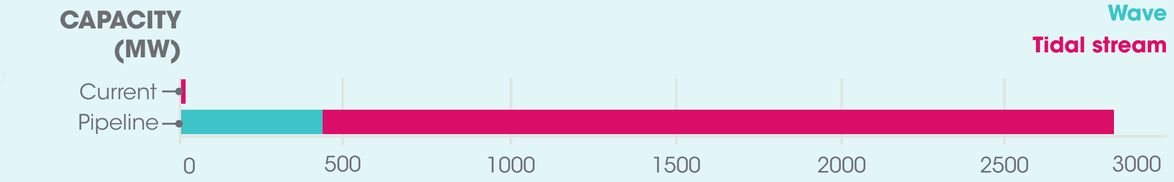
The sector will continue to grow as the cumulative tidal stream and wave projects in the pipeline will account for almost 3 gigawatts (GW) (see Figure 5), which can be expected over the coming years. While not all projects in the pipeline will eventually be implemented, this figure gives an order of magnitude of the developers' activity.

Figure 4: Ocean energy deployment (MW)



Source: *IRENA ocean energy database*

Figure 5: Active and projected tidal stream and wave capacity beyond 2020



Note: *While their capacity is too small to appear on this chart, additional projects are planned for the other ocean energy technologies beyond 2020. For example, a 2 MW ocean thermal energy conversion plant and a 1 MW salinity gradient energy plant are planned in the Netherlands (Johnson, 2019).*

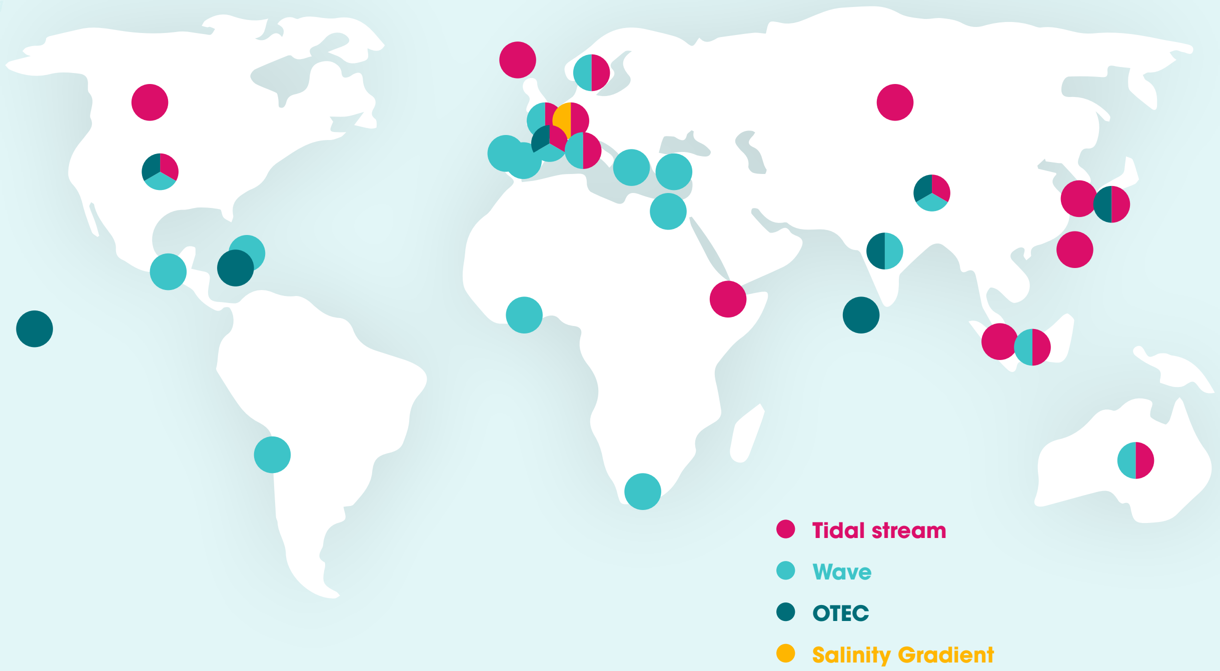
Source: *IRENA ocean energy database*

IRENA estimates that ocean energy could exceed 10 GW of installed capacity by 2030, if certain challenges discussed in this report are overcome.

In terms of geographic distribution, ocean energy is being pursued in 31 countries across the globe. Figure 6 indicates countries that are deploying and planning to deploy projects, as well as the different sources of ocean energy.

Although ocean energy is globally distributed, European countries such as Finland, France, Ireland, Italy, Portugal, Spain, Sweden and the United Kingdom (UK), rounded up with Australia, Canada and the United States (US), have been at the forefront of the ocean energy market, with the largest number of projects tested, deployed and planned and the most project developers and device manufacturers.

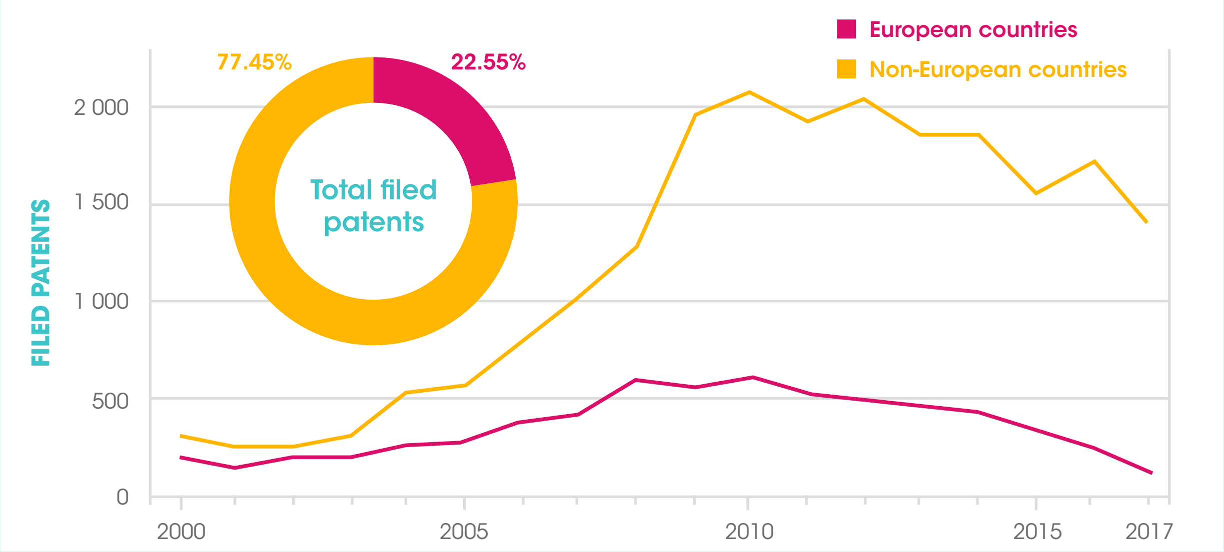
Figure 6: Geographic distribution of ocean energy projects



Boundaries and names shown on this map do not imply any endorsement or acceptance by IRENA

Source: *IRENA ocean energy database*

Figure 7: Number of ocean energy patents filed (2000-2017)



Source: *IRENA, 2020b*

Canada, for example, is supporting the funding of its first floating tidal energy array of 9 MW, which is planned to be connected to Nova Scotia's power grid. The total investment is estimated at USD 21.7 million (EUR 18.4 million) (Renewable Energy News, 2020).

Europe aims at retaining its leadership in this renewable technology area, maximizing the benefits for the region. In this context, the European Commission is giving offshore renewables a prominent role within its plans to realize the European Green Deal as part of the COVID-19 recovery package. The offshore renewable energy strategy of the European Commission released on 19 November 2020 (European Commission, 2020a) sets ambitious plans, which include:

- 60 GW of offshore wind by 2030 (from 12 GW today);
- 300 GW offshore wind by 2050;
- 1-3 GW of wave and tidal energy by 2030; and
- 60 GW of wave and tidal energy by 2050.

The focus is now spreading from the western world as increasing interest is observed in many other locations, most dominantly China, Japan and the Republic of Korea.

Two parallel trends are being observed. On the one hand, western countries with more experience are increasingly exporting the technologies and developing projects outside of their borders – including to developing countries, with a particular interest in SIDS (for more on ocean energy on islands and SIDS see section 3.3). On the other hand, innovation is increasingly being conducted outside of Europe, which can be observed by analysing filed patent data. Figure 7 shows the innovative efforts outside of European borders, which account for around three-quarters of all globally filed patents.

2.1 Levelised cost of electricity

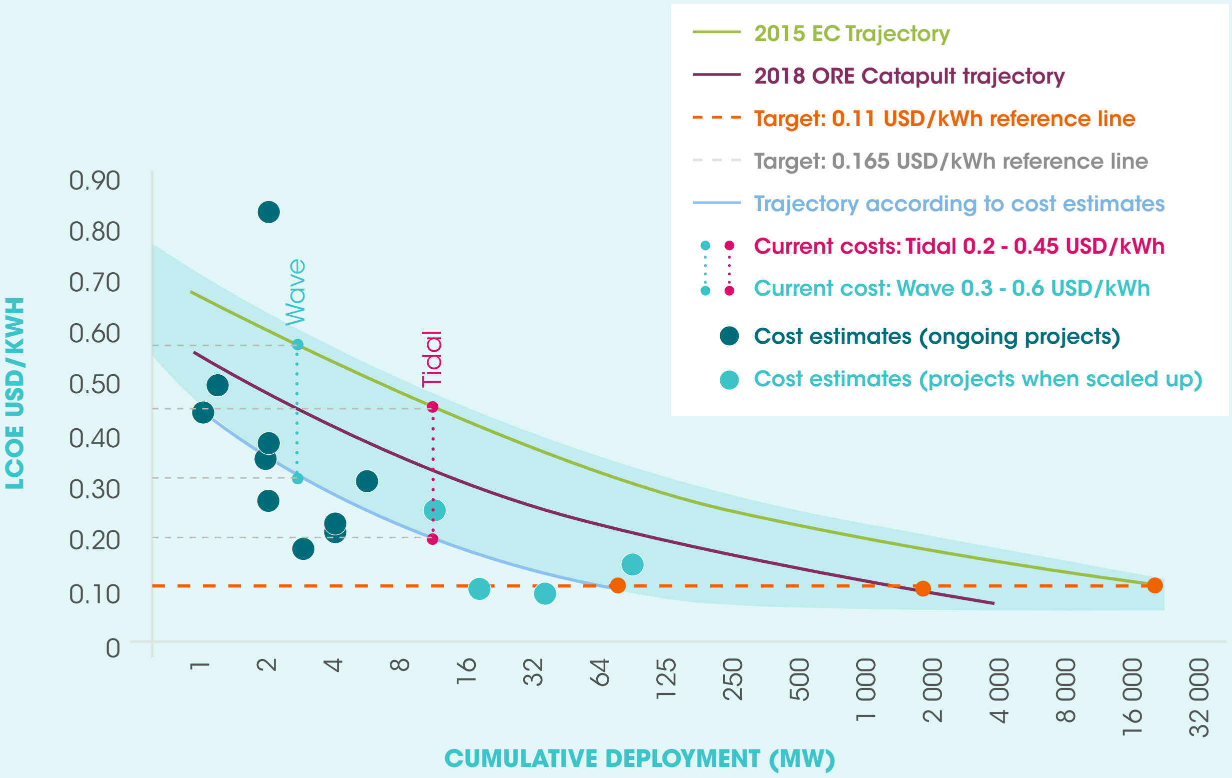
Due to the relatively early life-cycle stage of all ocean energy technologies, their levelised costs of electricity (LCOEs) are difficult to predict and uncertain. Several assessments have been performed, and this analysis is based on three previous datasets that are visualised in Figure 8. They include a cost reduction assessment for wave and tidal energy performed by the European Commission in 2015 (European Commission, 2016a), a cost reduction assessment based on cost data provided by developers of the UK tidal market by ORE Catapult from 2018 (ORE Catapult, 2018) and an analysis by the European Commission's Joint Research Centre based on LCOE estimates from developers (Magagna, 2019a).

In 2015 the European Commission proposed targets for LCOE values that have since been used widely as reference aims. The European Commission's LCOE targets for tidal energy were USD 0.165/kWh (EUR 0.15/kWh) by 2025 and USD 0.11/kWh (EUR 0.10/kWh) by 2030, while the costs for wave energy would lag five years behind and would be expected to reach USD 0.22/kWh by 2025 and USD 0.165/kWh by 2030 (European Commission, 2016a). Although the target costs of USD 0.11/kWh are still higher than cost projections for other renewables, the extra charge could be justified if these technologies would enable other benefits such as predictability and a steady energy supply.

While the target is not within the margins of competitive energy prices, ocean energy technologies could be competitive in niche markets such as islands, which depend on relatively costly fossil fuel imports. The study further assessed that the main reasons for decreasing costs in recent years were volumes (*i.e.*, economies of scale), engineering validation, experience and improved commercial terms. Accordingly, and assuming a learning rate of 12%, a cost reduction curve was created that moves quickly towards cost parity with other renewable energy sources (see *2015 EC Trajectory* in Figure 8) (European Commission, 2016a).

A more recent study employed the Cost Reduction Monitoring Framework methodology for the UK market and used cost data provided by developers and estimations that were weighted according to deployment level, size, etc. The study assessed that the current LCOE of tidal stream is USD 0.40/kWh and that costs will drop significantly when volumes increase, with the LCOE for tidal stream energy expected to fall to USD 0.20/kWh at 100 MW of installed capacity, to USD 0.12/kWh at 1 gigawatt (GW) and to USD 0.11/kWh at 2 GW (see *2018 ORE Catapult Trajectory* in Figure 8) (ORE Catapult, 2018). The study outlines that further cost reduction can occur through *initial accelerated reductions* (mainly economies of scale, turbine size, volume and accelerated learning), *industry learning* (through test

Figure 8: Target cost reduction curve (EC and ORE) and recent LCOE estimates



Note: *EC = European Commission; ORE = ORE Catapult*

Source: *Adapted from Magagna, 2019a; ORE Catapult, 2018* outcomes regarding technology, supply chain, O&M, weather data, site familiarity, etc.) and through *innovation* (regarding reliability, mooring, electrical connections and offshore costs) (ORE Catapult, 2018).

Figure 8 also illustrates the cost estimates of 10 ongoing ocean energy projects and their projected costs with increased deployment. All but one project have substantially lower costs than initially anticipated (Magagna, 2019a). The new trajectory that is derived from these projects shows lower LCOEs than the other two studies (see *Trajectory according to Cost Estimates* in Figure 8).

When applying the current installed capacity of 10.6 MW of tidal stream and 2.3 MW of wave energy to the trajectories (see Figure 8), one of the three aforementioned datasets, the current LCOE for tidal energy can be estimated to be between USD 0.20/kWh and USD 0.45/kWh and for wave energy to be between USD 0.30/kWh and USD 0.55/kWh. This implies an expected learning rate of 45% to 75% for tidal energy and 63% to 82% for wave energy. With the least optimistic projections (*EC Trajectory*), the targeted USD 0.11/kWh (see *Target: 0.11 USD/kWh reference line* in Figure 8) should be reached with a deployment of 20 GW, which can be anticipated in the early- to mid-2030s. The more recent study, however, shows a much more optimistic image presenting USD 0.11/kWh already at less than 100 MW of deployed cumulative capacity, which can be expected in around 2022 for tidal and in 2024 for wave.

LCOE learning curves, notably, involve a degree of uncertainty, particularly when forecasting costs of new technologies with low deployment and limited available data. In addition, the concept of learning curves postulates an increase in deployment, which can only be achieved with sufficient financial support mechanisms. When looking at the learning curves of other renewable energy sources – for example, between 2010 and 2019 offshore wind costs fell 29% to USD 0.115/kWh and solar PV fell 82% to USD 0.068/kWh – it can be seen that remarkable cost reductions have happened in the past. However, both of these technologies had a large increase of cumulative installed capacity in the same period: from 3 GW to 28 GW for wind and from 40 GW to 580 GW for solar PV. Although reaffirming that larger capacity deployment leads to significant cost reductions, assumptions of cost reductions with relatively low deployment may be too optimistic and need to be viewed with caution.

2.2 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 energy. This can be done either by harvesting the potential energy of the difference in the water level or by making use of 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 potential increases with the range, but it can only be harnessed in a limited number of countries that possess the necessary resources.

Resource potential

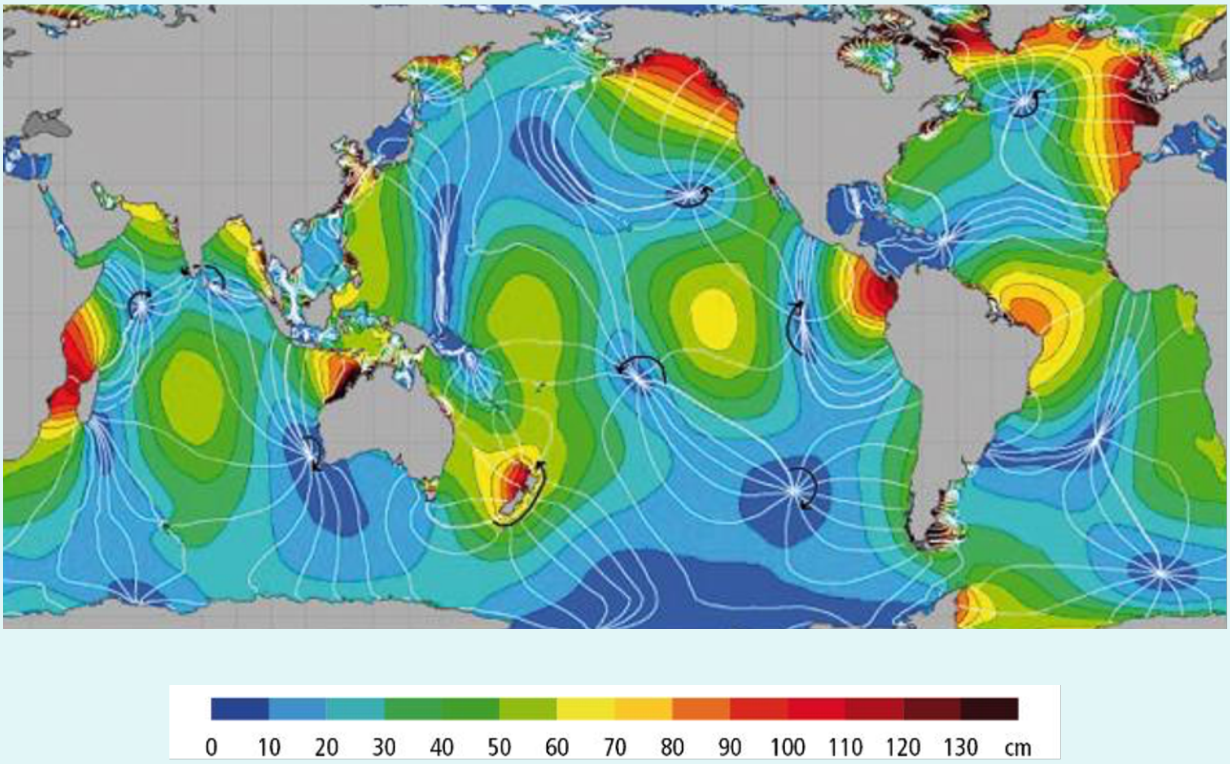
Due to the geographical limitation, the theoretical potential of tidal energy is the smallest of any ocean energy technology at 1 200 TWh per year (OES, 2017). Tidal energy has a much lower potential than other renewable resources such as solar irradiation or wind, but its main advantage over these technologies is that tides are not influenced by weather but by cyclical constellations. They can therefore be predicted well in advance for the short and long term.

Figure 9 demonstrates the considerable variations of tidal range resource potential on a global scale. 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 currents are strongest in regions with high tide ranges but are further enhanced by the topography. This is particularly the case in narrow straits or between islands, where the streams are naturally funnelled and speed is thus enhanced. The test centres in the Bay of Fundy in Canada and in the Orkney islands in Scotland lie among such favourable areas.

Technology

A distinction is made between tidal barrage (or tidal range) and tidal stream (or tidal current) technologies. Tidal barrage makes use of the tidal range – the actual height difference between high and low tide – and harnesses the potential energy. This technology is relatively more mature than other ocean energy technologies having

Figure 9: Global distribution of water level differences due to tidal forces (in centimetres)



Source: *Lewis et al, 2011*

reached a Technology Readiness Level[9] (TRL) of 9, and such power plants have been in operation since the 1960s. However, tidal barrage technology now faces various deployment challenges related to limited site availability, high capital investment and environmental impacts. It is therefore being pursued only to a limited extent.

Tidal stream technologies, on the other hand, make direct use of the incoming and outgoing flow in open water. They are approaching maturity and are expected to become more prominent than tidal barrage in the future. Several technologies to make use of tidal currents are under investigation, and although a convergence towards horizontal-axis turbines has been observed in recent years, other technologies that may greatly increase the global resource potential are also being pursued. Whereas a few years ago a single tidal turbine had a capacity of only 100 kilowatts (kW), turbines of 1.5 MW have now been successfully deployed by a handful of deployers, and they are being scaled up further.

Notably, turbines of 100 kW might still be very suitable in certain locations and therefore have a market of their own. A collection of different tidal energy technologies is presented in Table 1, and their respective TRLs, where testing has occurred, are indicated.

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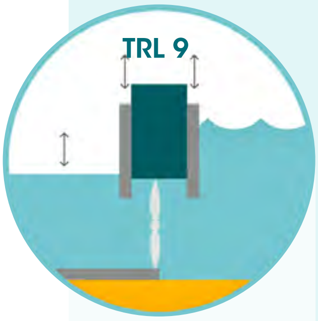
[9] TRL is a scale from 1 to 9 where 1-3 represent the research phase, 4-5 the development phase, 6 the demonstration phase and 7-9 the deployment phase (with 7 representing prototype demonstration and 9 a fully deployed, proven and operational technology).

Table 1: Different tidal energy technologies



Barrage
Water that entered an enclosed tidal basin with high tide is released in low tide and generates electricity by passing through turbines.

Horizontal-axis turbine
The tidal currents flow past blades that are radially attached to a horizontal shaft and cause rotation, thus generating power, much like a wind turbine underwater. Either the hub or blades need to turn 180 degrees to accommodate a reverse flow direction.

Vertical-axis turbine
The tidal currents flow through a set of blades parallel to a rotating shaft, generating power irrespective of the direction of the flow.

Enclosed tips (venturi)/ open-centre
The tidal stream’s velocity is increased by concentrating it in a funnel or duct, in which a turbine is placed to generate energy.

Reciprocating device/ oscillating hydrofoil
the tidal flow lifts an oscillating hydrofoil attached to an arm. This up-and-down movement drives a shaft or pistons to generate energy.

Archimedes screw/ spiral
a tidal stream passes through the spiral of a helical-shaped impeller. The device starts to turn, and the rotation is converted into energy.

Tidal kite
A kite connected to the sea bed or to a floating platform moves through the tidal stream in an eight-shaped or linear trajectory. The relative velocity is increased and with it the electricity output.

Other
Other technologies have been investigated that either fit in none of the categories or incorporate various aforementioned characteristics.

Based on IRENA, 2014a and EMEC, n.d. a; TRL based on Magagna, 2019a

Market

Global overview

The highest share (98%) of all installed ocean energy is of the tidal barrage technology. Several such projects have been in operation for years, with three projects accounting for nearly all the capacity: the 254 MW Sihwa Lake Tidal Power Station in the Republic of Korea (which came online in 2011), the 240 MW Rance Tidal Power Station in France (1966) and the 20 MW Annapolis Tidal Station in Canada (1984). Other countries that have smaller tidal barrage power plants in operation are China and the Russian Federation, but no such power plants of relevant scale have been developed in almost 10 years and there is relatively low resource potential to be explored, compared to the other ocean energy technologies.

The installed capacity of tidal stream is the second largest of all ocean energy resources, at 10.6 MW. Whereas tidal barrage's installed capacity is considerably larger than that of tidal stream, the number of deployed projects is greater for tidal stream technologies (see Figure 10) and is also projected to continue to grow much faster in the coming years (see Figure 11). Figure 11 shows projects with a predefined completion date, whereas the total capacity in the pipelines is 2.4 GW for tidal stream and up to 5.5 GW for tidal barrage.

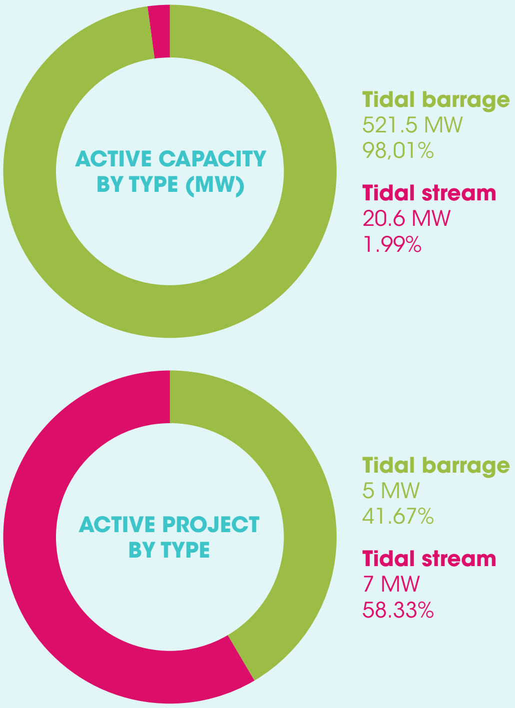
The tidal barrage capacity mainly includes projects in the Republic of Korea and the UK, and the Cardiff and Swansea lagoons in Wales have been most prominent. They are, however, progressing only slowly and face numerous challenges. The UK government has not yet approved the plans, which makes realisation of the projects soon rather unrealistic. The tidal stream pipeline capacity, on the other hand, is composed of over 40 projects in 15 countries, meaning that even if not all were to be realised, a substantial increase is expected. Figure 12 presents the locations of currently active tidal barrage and tidal stream technologies.

The currently installed capacity of tidal stream power generation comprises projects at different stages of maturity. Whereas a large amount belongs to a first phase of larger commercial tidal farms (7.8 MW), a small share belongs to smaller completed commercial projects (1.7 MW), full-scale demonstration plants (1 MW) and sub-scale test plants (0.1 MW). This demonstrates a clear trend towards commercialisation, particularly because the 7.8 MW is part of four planned tidal arrays with a potential total capacity of up to 570 MW. Such a multi-device tidal power array is explained in more detail in Box 1.

Many more such large-scale tidal farms are being planned or considered, totalling more than a dozen projects. Most of these are to be deployed in the UK, the clear frontrunner in tidal energy, but other countries such as Australia, Canada, Djibouti, France, Indonesia and the Republic of Korea also have large tidal energy ambitions. Figure 13 illustrates the locations of all currently planned projects with rated capacities above 9 MW, separated by the vertical lines. They add up to a combined capacity of 2.45 GW. Other countries that have tidal projects in the pipeline but that are still testing and demonstrating smaller devices include China, France, the Faroe Islands (Kingdom of Denmark), Italy, Japan, the Netherlands, Norway, the Philippines and the US.

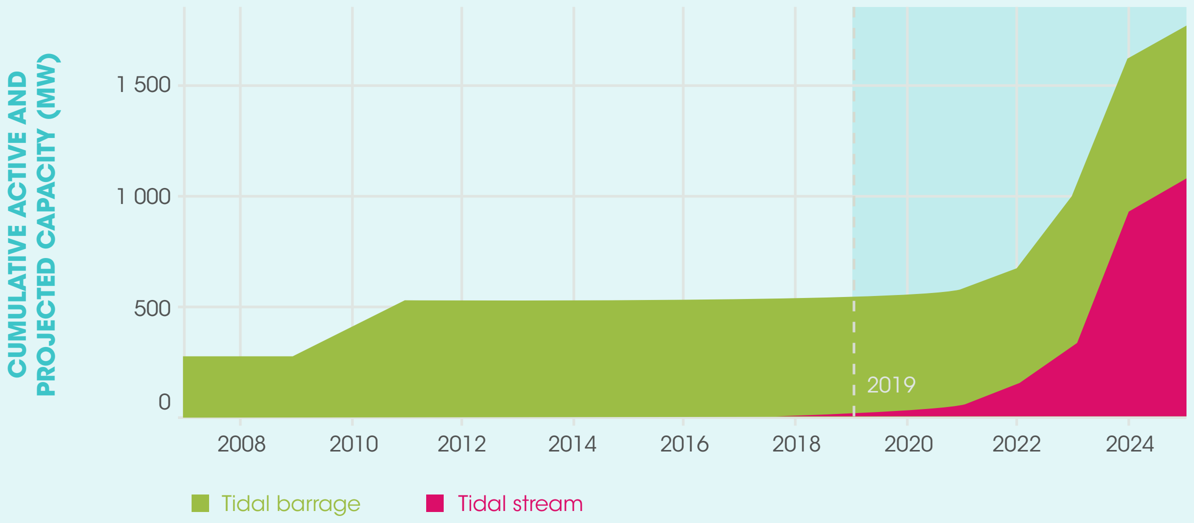
Although deployments are planned in only 15 countries, many more countries are active in innovation and research on tidal energy devices. When looking at the patent activity of the number of filed patents in the tidal energy sector (CPC class Y02E 10/28) in Figure 14, it can be

Figure 10: Share of active capacity and number of projects by tidal technology



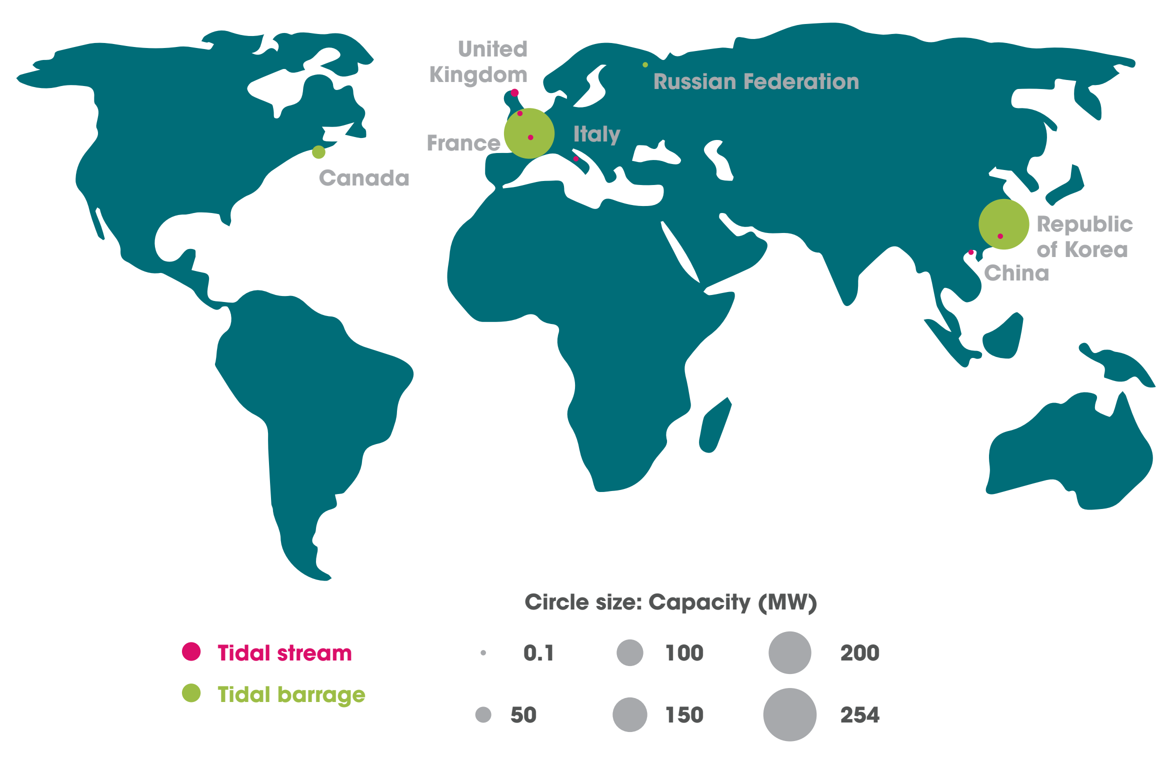
Source: *IRENA ocean energy database*

Figure 11: Active and projected cumulative tidal energy capacity



Source: *IRENA ocean energy database*

Figure 12: Global distribution of active tidal power generators



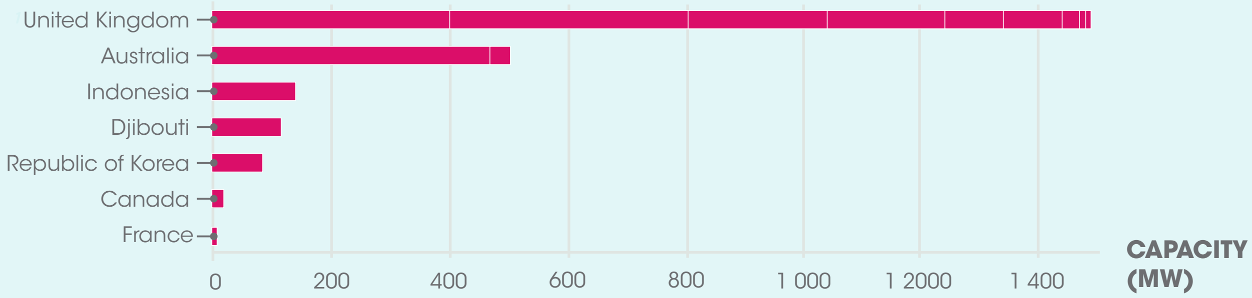
Boundaries and names shown on this map do not imply any endorsement or acceptance by IRENA

Source: *IRENA ocean energy database*

seen that the countries with the largest number of active projects as well as those planning large deployments are not the countries with the highest number of filed patents. A first aspect to be considered is that the patent analysis presented in Figure 14 is not limited to tidal stream but also includes patents for tidal barrage, which among other factors may explain the Republic of Korea's prominent role. Patents are a good tool to trace innovation and R&D, but there is a time lag between the filing of a patent, its approval and the actual conceptualisation, let alone the actual manufacturing and deployment of the product.

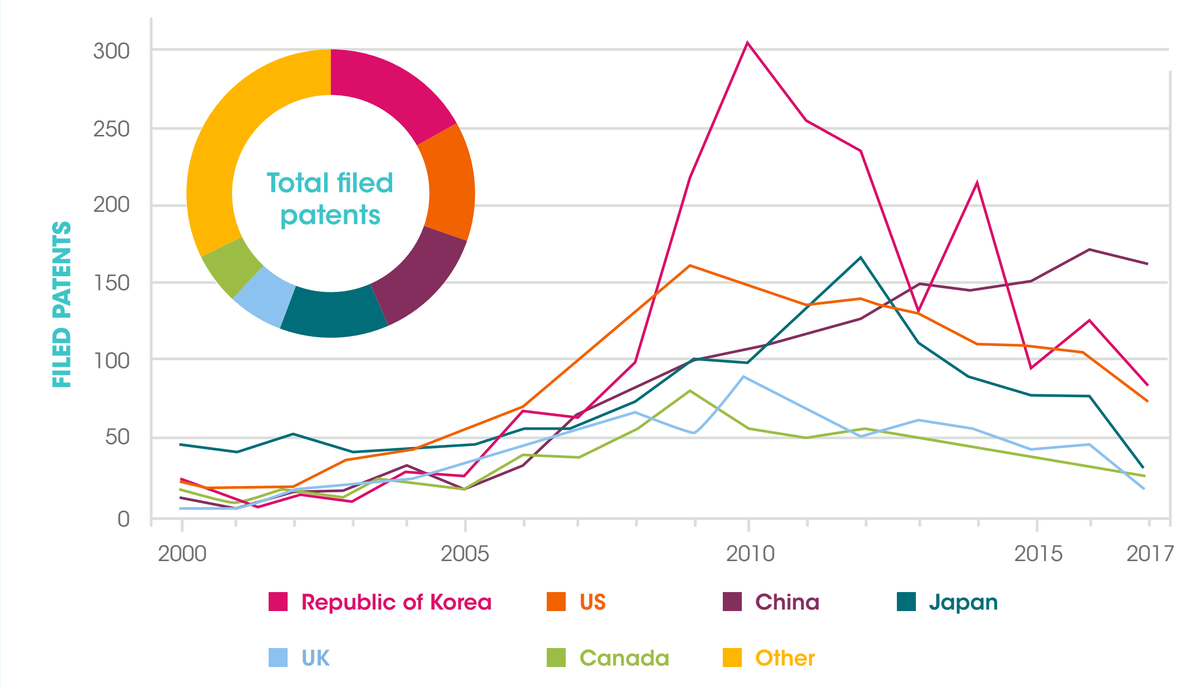
The annual patent filing in the UK peaked in 2010 and in Canada in 2009, and because fewer patents have been filed each year, the Republic of Korea filed significantly more patents between 2009 and 2012, which is now starting to show in the increased deployment of these technologies. China's filed patents have been increasing steadily since 2005, which hints towards an increased deployment of these technologies in the coming years. In other countries such as the US, a high number of projects have been announced and cancelled or suspended in the last decade, for a number of different reasons.

Figure 13: Location of the largest tidal stream projects in the pipeline



Source: *IRENA ocean energy database*

Figure 14: Total filed tidal energy patents by country (2000-2017)



Source: *IRENA, 2020b*

BOX 1: THE MEYGEN PROJECT: A MULTI-DEVICE TIDAL ARRAY

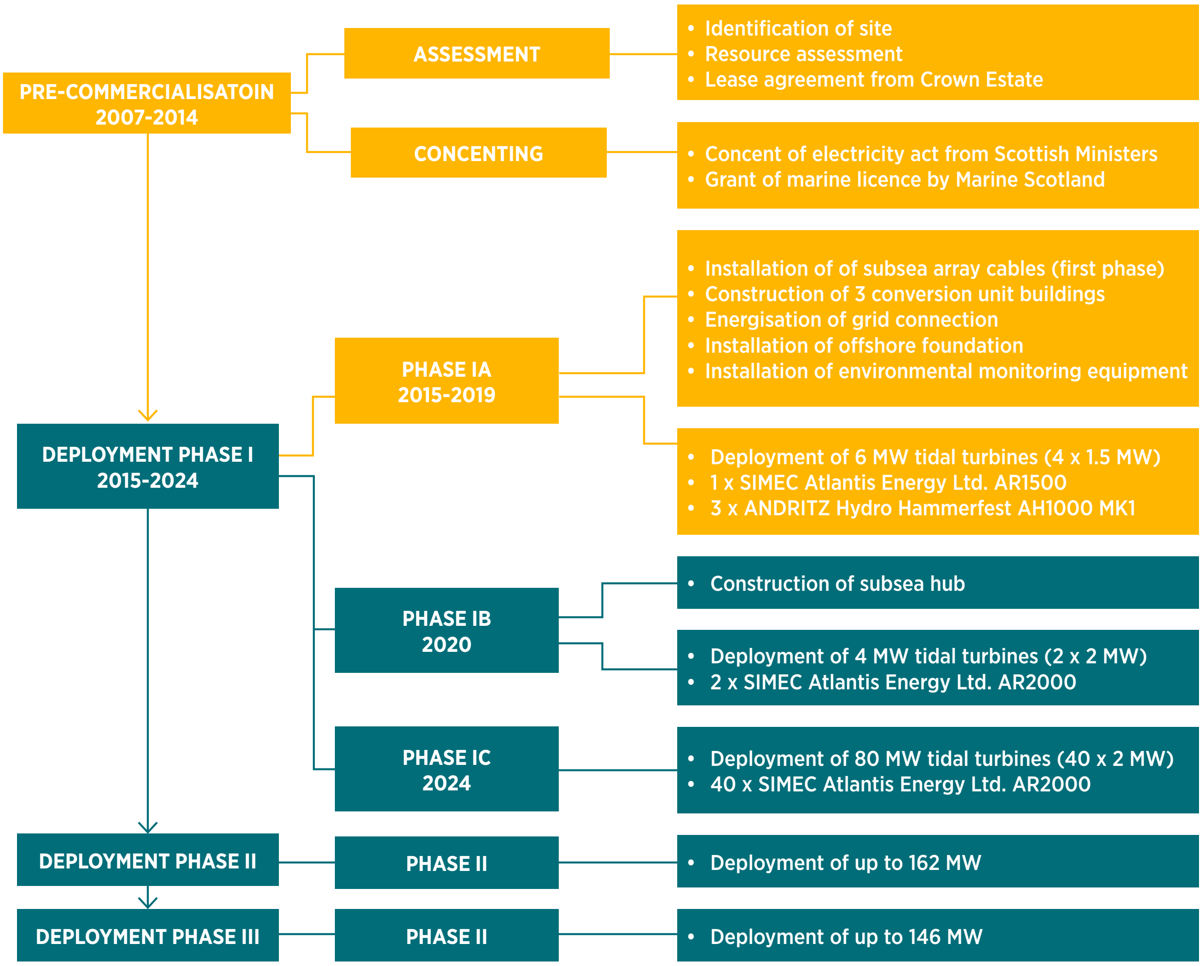
MeyGen is the first commercial multi-device tidal power array to be deployed and has already achieved a long period of uninterrupted generation from a multi-megawatt array. The natural channel between the Scottish mainland and the island Stroma, the medium water depth and the proximity to the mainland set the ideal preconditions. In phase 1 a "deploy and monitor" strategy is being applied, where phase 1A was aimed at demonstrating the commercial viability and technical feasibility of the technology and learning from first findings. Figure 15 shows one of the tidal turbines implemented in phase 1A (Figure 16). In phase 1B, a subsea hub is being added to drastically reduce cable length, conversion equipment, horizontal drilling and vessel/installation time. Phase 1C plans to include the powering of a commercial-size data centre.

Figure 15: Tidal turbine of 1.5 MW

***Image source:** Simec Atlantis, n.d.*

- **Device type:** Horizontal axis turbine
- **Developer, owner, operator:** MeyGen Ltd. (86% owned by SIMEC Atlantis Energy Ltd.)
- **Total capacity:** 398 MW permitted, 252 MW grid capacity, 90 MW consented
- **Electricity generation:** 26 gigawatt-hours (GWh) (as of March 2020), 13.8 GWh in 2019
- **Other service providers:** GE Power provides turbine generators and power converters

Figure 16: MeyGen project phases



Source: Simec Atlantis, n.d.

Trends by technology

As presented in Figure 17, of the 16 currently operating tidal stream devices, 13 are horizontal-axis turbines, 2 are tidal kites and 1 is a vertical-axis turbine, indicating that a large majority of devices use the horizontal-axis turbine technology. Of the roughly 30 companies that are working on devices with a TRL of at least 6 (Magagna, 2019b), over two-thirds focus on these turbines as well, a convergence in technology that can also be seen in the pipeline projects (see Figure 17). Almost all large tidal stream developers that have done the most extensive testing and that have the majority of projects in the pipeline (*i.e.*, DP Energy/Andritz, Hydroquest, Nova Innovation, Orbital, Sabella, SIMEC Atlantis, SME and Tocardo) use this technology.

Further, most projected multi-device arrays have also settled on horizontal-axis turbines. The relative maturity of this technology reflects its similarity to well-established wind turbines. But it is also favoured due to its easy scalability and its universality, as some developers focus on hydrokinetic turbines that can also be deployed in rivers. However, 2019 saw more devices other than the horizontal-axis technology deployed. One vertical-axis turbine developer and two tidal kite developers were testing their devices, and the deployment of an Archimedes screw device was planned for 2020. This is portrayed in Figure 18.

The market is therefore taking an interesting turn. On the one hand, the technology of horizontal-axis turbines is actively being pursued and pushed as the core of

Figure 17: Active tidal stream capacity by technology

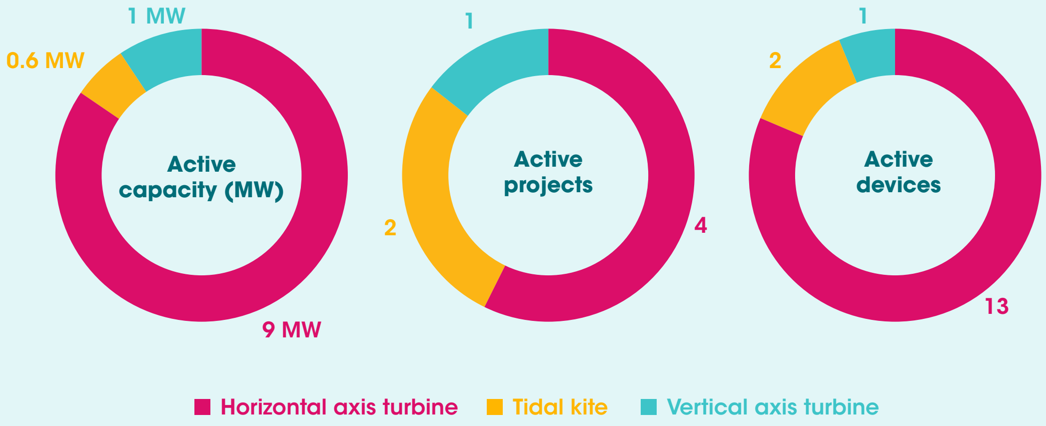
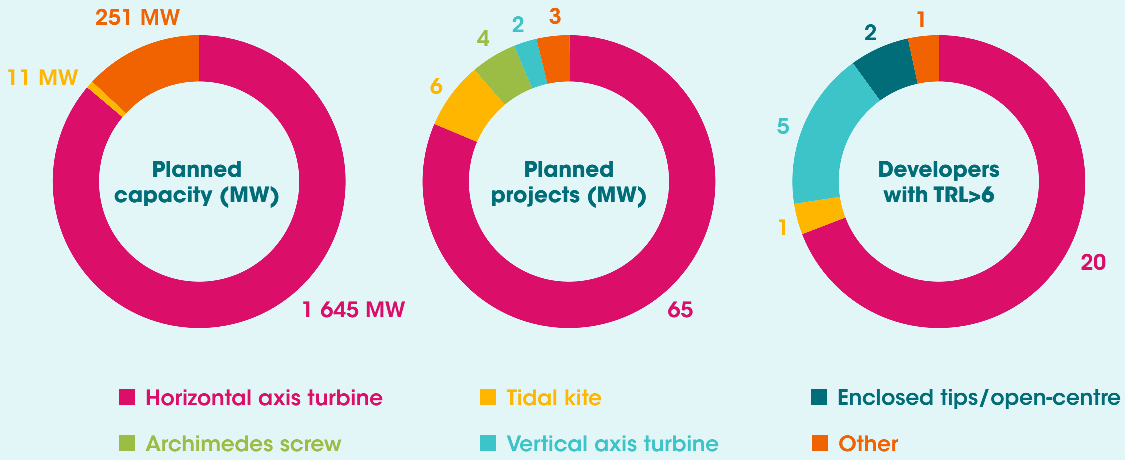


Figure 18: Projected tidal stream capacity and developers by technology



Source: *IRENA ocean energy database*

many large first-generation commercial tidal farms. On the other hand, products with varying characteristics are being tested and deployed in parallel at a faster rate than before. This is unusual, as once a certain technology positions itself as viable, other developers tend to follow, taking advantage of the R&D and marketing efforts done by the pioneers.

One explanation could be that horizontal-axis tidal turbines, despite countless attempts and an increasingly positive outlook, still have not managed to properly commercialise and thereby show their viability. With highly anticipated players repeatedly filing for bankruptcy while having successfully deployed large turbines and having hundreds of MW in the pipeline, the case arises that the value proposition of tidal stream technologies and horizontal-axis turbines, in particular, may not be strong enough. This could explain the lack of revenue support, among others.

Turbine technologies are, logically, being questioned, and alternatives for potentially more viable and cost-effective solutions are being sought and invested in. In addition, there is an increasing pool of competition as many developers are working on broadly comparable products. Distinguishing oneself with a different and potentially even better product may therefore be the tactic for developers of the less conventional technologies to draw competition aside and penetrate the market.

Although the non-horizontal-axis turbines are still much smaller in scale and number, the race towards market convergence is not yet finished, and there may soon be larger competition. An example of such an alternative technology and developer is presented in Box 2.

2.3 Wave energy

Wave energy converters are devices that harvest the energy that is contained in ocean waves and uses it to generate electricity. When wind blows over the ocean it transmits some of its kinetic energy to the ocean's surface creating wave energy, a form of energy that contains both kinetic and gravitational potential energy. Wave energy converters can be conceptualised to absorb either the kinetic energy, mainly through moving bodies, the potential energy, through overtopping devices or attenuators, or both, through, for example, point absorbers.

Resource potential

Waves are most powerful in latitudes between 30 degrees and 60 degrees and are influenced by the wave height, wave speed, wavelength (or frequency) and water density. Wave energy resources are more spatially distributed than tidal, which can be seen in wave energy's large potential.

The global theoretical potential of wave energy is 29 500 TWh per year[10], which means that wave energy alone could meet all global energy demand (Mørk et al., 2010). Although varying seasonally and in the short term, waves can be well forecasted and are widely considered a reliable energy source. The global distribution of wave power levels is presented in Figure 21, which shows that mid-latitude regions have lower resource levels and that the latitudes between 30 and 60 degrees deliver more powerful waves, particularly in the southern hemisphere.

Technology

Wave energy technologies have not seen a convergence towards one type of design as has been observed for other renewable technologies such as wind energy. Over the years three main working principles to harness energy from waves have emerged: *Oscillating water columns (OWC)* compress air to drive an air turbine, *oscillating bodies (OB)* converters use different conceptualisations to transform wave motion between bodies (up/down, forwards/backwards, side to side) into electricity, and *overtopping devices (OD)* use the potential energy of water that spills into a closed reservoir to subsequently drive a hydraulic turbine (IRENA, 2014a).

There are various additional ways to differentiate wave energy conversion technologies. They can be related to the location (shoreline, near-shore or offshore), the mooring and foundation structures (fixed, floating, submerged), the power take-off system (PTO) (air turbines, hydraulic turbines, hydraulic engines), the conversion technologies (rotation, translation), the motion (heaving, surging, pitching) and the water depth (deep, intermediate,

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[10] Calculated for areas with latitudes lower than 66.5 degrees and excluding areas with power levels lower than 5 kW per metre.

BOX 2: MINESTO: A TIDAL KITE TECHNOLOGY

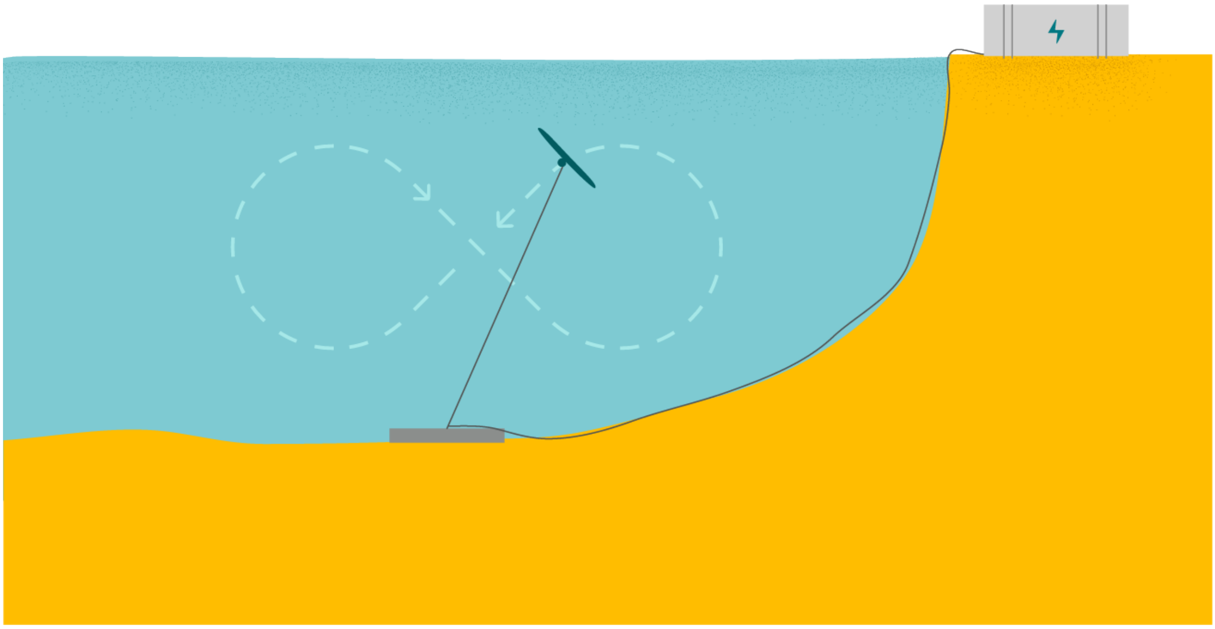
Image source: Minesto

Figure 19: Minesto's tidal kite device

Minesto is the market leader of tidal kite developers. It has recently scaled up its tidal kite device to 500 kW, the largest such device ever deployed, and claims to have reached commercial phase with projects scheduled in the Faroe Islands and Wales. In the Faroe Islands, Minesto is installing two commercial 0.1 MW units, and in Wales it plans to install 10 MW and to potentially scale up to an 80 MW plant. Its devices are also growing in size, as the developer is looking into 0.5-3 MW turbines with wingspans of 12-24 metres. An example of Minesto's tidal kite device is shown in Figure 19.

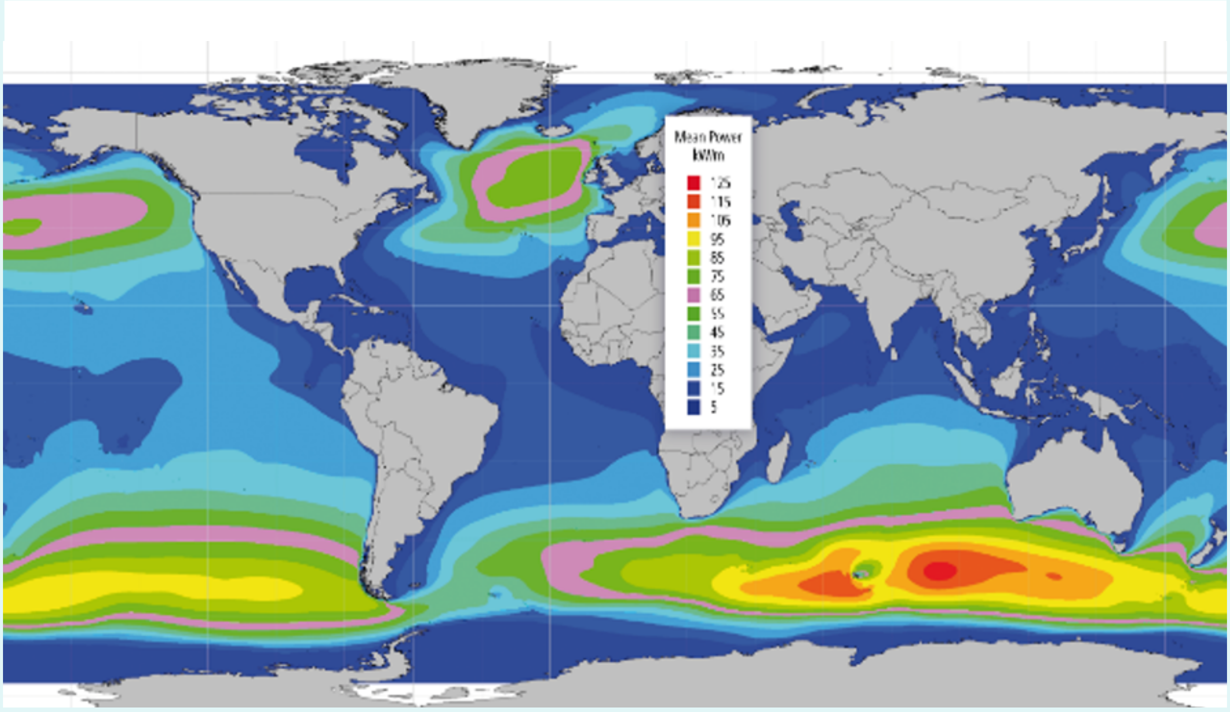
Minesto kites look like little submarine planes, a resemblance that comes from the company's origin as a spin-off of an aircraft manufacturer. Due to their particular design, the tidal kite can produce higher power because the relative speed of the kite is multiplied with the actual stream speed. They can therefore operate at lower absolute velocities and as such have the potential to open the global ocean current market. Minesto claims that it can take the potential of tidal stream technology so much further that the overall tidal resource potential needs to be redefined, possibly going above 600 GW. The kite's lower weight additionally aids deployment and maintenance. An illustration of Minesto's tidal kite in operation is shown in Figure 20.

Figure 20: Illustration of Minesto's tidal kite device in operation



Source: Minesto, 2020

Figure 21: Global distribution of wave power level in kW per metre



Boundaries and names shown on this map do not imply any endorsement or acceptance by IRENA

Source: *Lewis et al., 2011*

shallow) (IRENA, 2014a; Lewis *et al.*, 2011; WEC, 2016). The combination of these characteristics has resulted in over 50 different technology types (Lewis *et al.*, 2011).

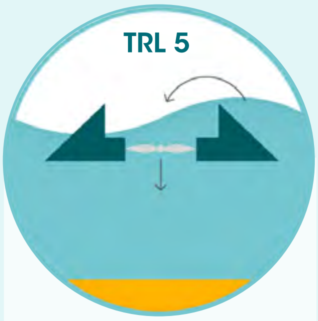
Due to the numerous ways to distinguish the technologies and the large resulting numbers of systems, the distinction is often made less systematically; instead, technologies that are being pursued are simply described. The most common such categories are presented in Table 2. The table further shows a classification among the three main working principles as well as the Technology Readiness Level (TRL), where testing has occurred. The large number of different technology types can serve in part as an explanation for why the TRL for wave energy is still relatively low. The differences in the TRLs among technologies nevertheless show that some devices are more advanced than others. The most promising technologies for commercialisation include oscillating water column (OWC), oscillating water surge converter (OWSC) and point absorbers. Rotating mass devices are at a similar technology stage, but the application is more niche and only a few developers are pursuing it.

Table 2: Different wave energy technologies

OWC

Oscillating Water Column (OWC)
Passing waves raise the water level within a hollow, demi-submerged structure, causing the enclosed air to compress and flow to the atmosphere, driving a turbine.

OD

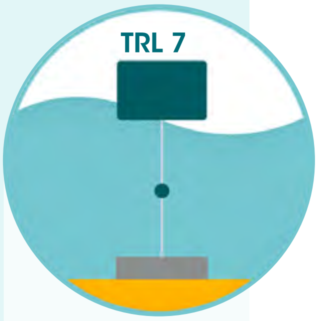


Overtopping deivce
Water of passing waves is captured in a reservoir and released through a shaft. A turbine is located in the shaft that generates energy when water passes.

OB

Attenuator
The attenuator consists of multiple connected segments or a single long and flexible part that extracts energy from waves by following the parallel motion of the waves.

OB



Point absorber
This floating or submerged buoy generates energy from the buoy's movement caused by waves in all directions relative to the base connection.

OB

Oscillating Water Surge Converter (OWSC)
This structure uses the surge movement of the wave (back-and-forth motion) to capture energy in an oscillating arm.

OB

Submerged Pressure Differential (SPM)
The rise and fall of passing waves cause a pressure differential in the structure to trigger pressure pumps and generate electricity.

OB

Bulge wave
A device is placed parallel to the waves, capturing energy from its surge. Water flows through the flexible device and passes through a turbine to exit.

Other

Rotating mass
The heaving and swaying in the waves cause a weight to rotate within this device. This rotation drives an electric generator.

Other
Certain technologies have other unique, not commonly used ways of capturing energy from the waves.

**Only attempted but not achieved.*

Based on IRENA, 2014a and EMEC, n.d. a; TRL based on Magagna, 2019a

Market

Global overview

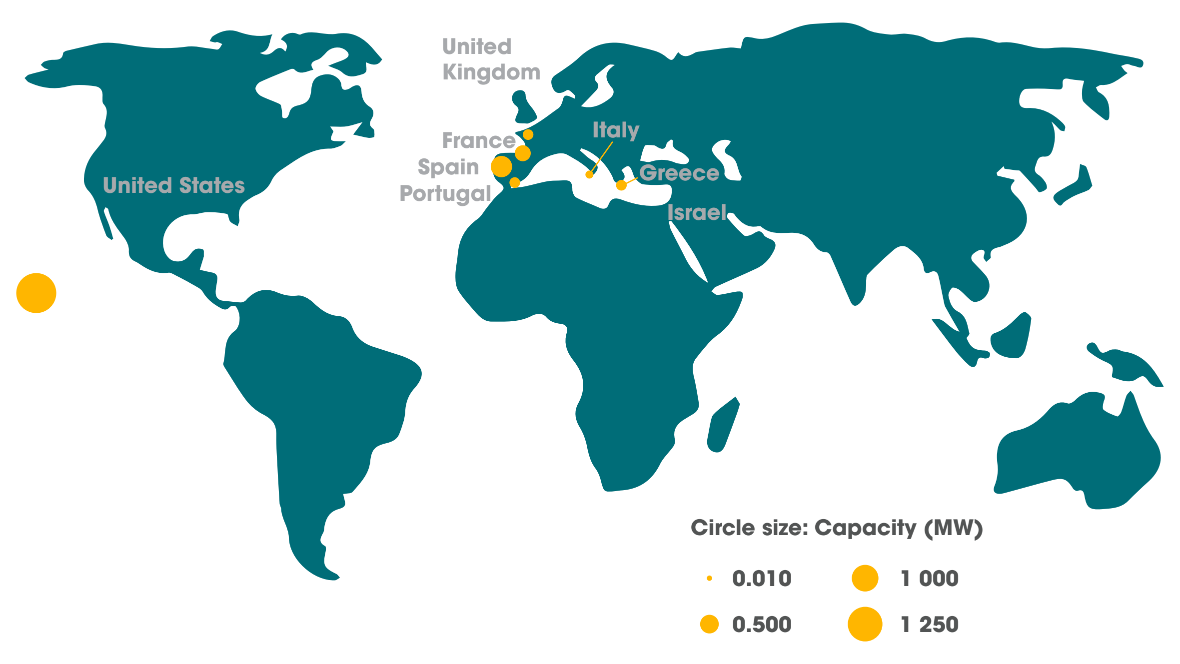
Currently, 33 wave energy converters with a combined capacity of 2.3 MW are deployed in 9 projects across 8 countries and 3 continents. The only active project with a capacity above 1 MW is located in Hawaii and was deployed in early 2020. Other locations with active projects include France, Gibraltar, Greece, Israel, Italy, Portugal and Spain. Figure 22 presents an overview of the locations and capacities of currently installed projects. Since many more devices have been tested, decommissioned, adapted and redeployed over the years, the current distribution is only to a certain extent representative of countries that are actively pursuing the technology.

The UK, for example, has historically deployed the most projects (partly due to its test sites), even though no such devices were in UK waters at the time of publication of this report. The largest test site globally is the European Marine Energy Centre (EMEC) in Scotland. This location has hosted a large share of the developers that are close to reaching commercialisation (for example, Wello Oy, Bombora Wave Power, Aqua Power Technologies, AW Energy). It has several promising projects lined up, and the UK will therefore reappear shortly on such future maps.

Figure 23 displays the diversity of countries where wave energy deployments are anticipated. The countries in blue represent locations where projects were planned for 2020, and the countries in orange are locations for projects deployed after that. While Europe, particularly France, Italy, Portugal, Spain and the UK, as well as the US, remain at the forefront, an increasing interest in the deployment of wave energy converters is now arising in Asia (particularly China), Australia and even Africa and South America.

Similar to tidal energy, when looking at the filed wave energy patents, there seem to be discrepancies at a first glance. Figure 24 demonstrates the filed patents for wave energy technologies (CPC classes Y02E 10/32 and Y02E 10/38) since 2000 by country. China's patent activity has also been growing for wave energy since 2005, far outnumbering all other countries. This reaffirms the previous statement that China is one of the emerging countries in the market. The Republic of Korea and the US both filed many wave energy patents with sharp growth in the late 2000s but have added fewer patents annually

Figure 22: Global distribution of active wave power generators



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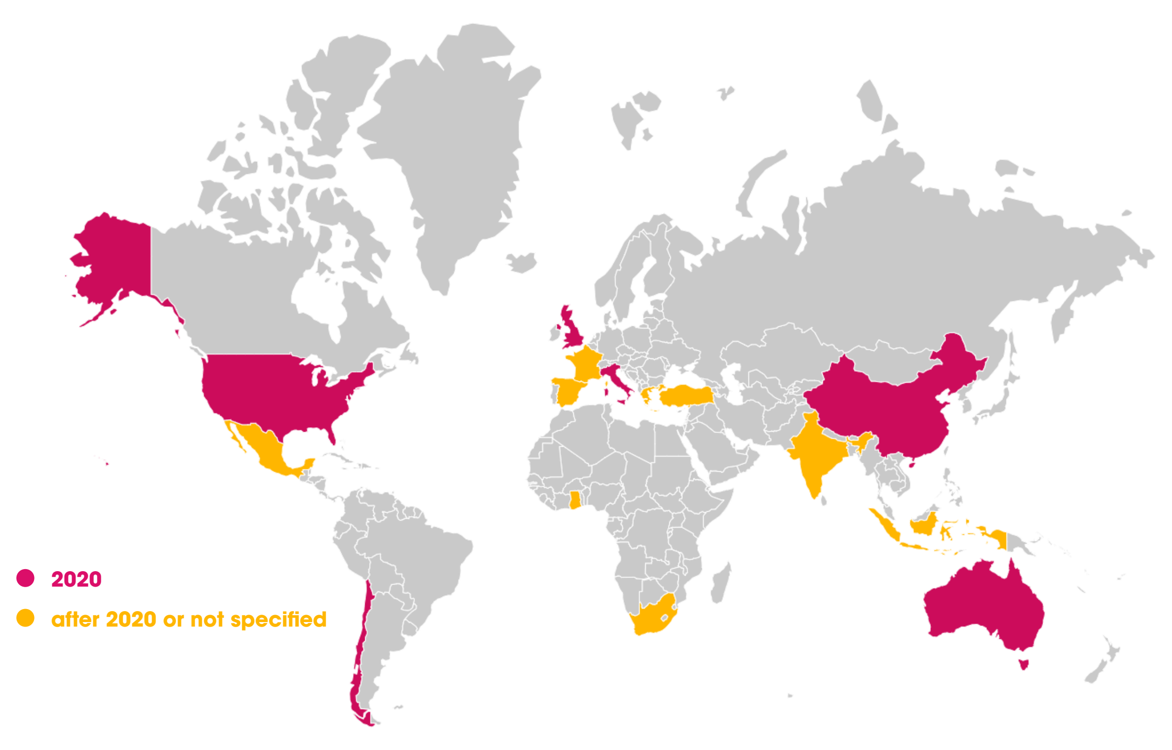
Source: *IRENA ocean energy database*

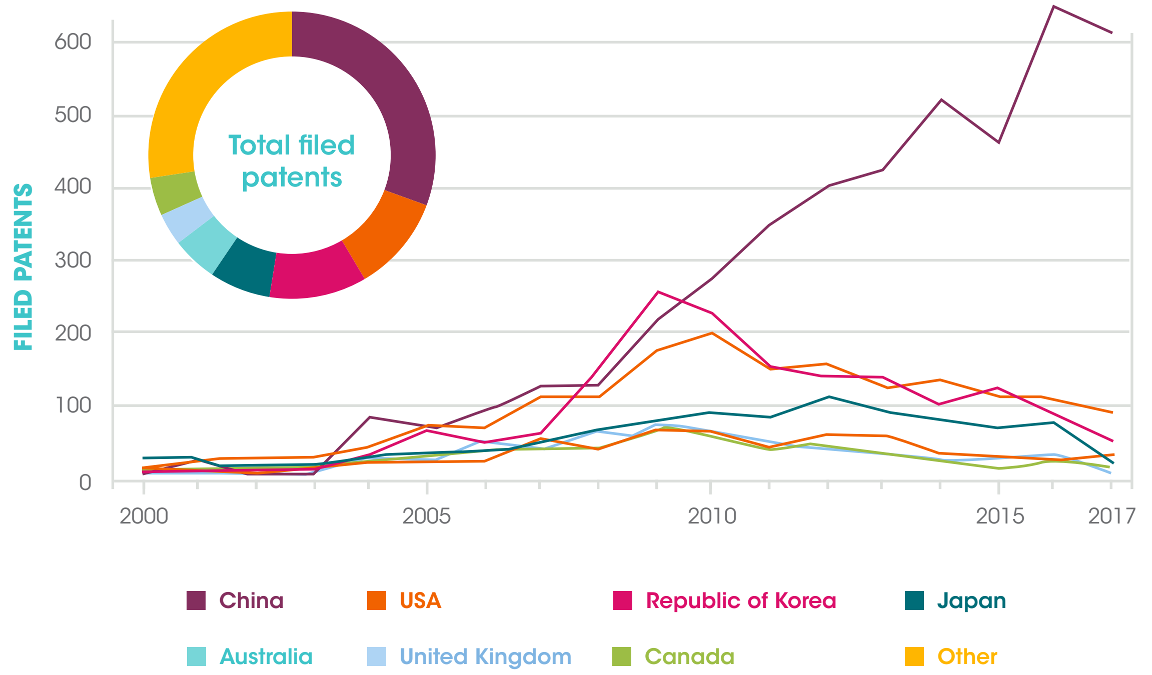
Figure 23: Global distribution of active and projected wave energy projects



Boundaries and names shown on this map do not imply any endorsement or acceptance by IRENA

Source: *IRENA ocean energy database*

Figure 24: Total filed wave energy patents by country (2000-2017)



Source: *IRENA, 2020b*

since their peaks in 2009 and 2010 respectively. Whereas this activity shows in the deployment of wave energy and its well-equipped test centres in the US, the Republic of Korea's market entry is still in an early stage, as the country is just in the process of setting up a test site with the help of EMEC, which indicates that increased activity can be expected. As with tidal energy, Canada and the UK both peaked in the number of filed patents in 2010 and 2009 and have since continued to file fewer new patents.

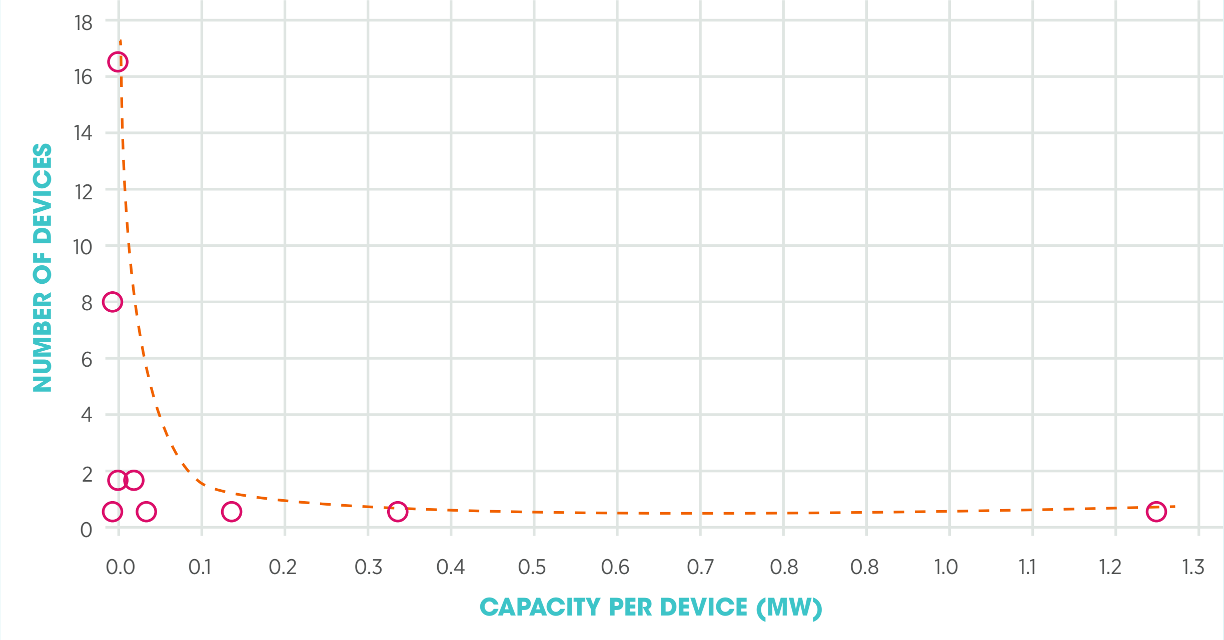
Trends and technologies

The lower maturity level of wave energy in comparison to tidal can be seen clearly when taking a closer look at the 2.3 MW installed capacity. Unlike tidal turbines, where several first phases of large-scale projects are being deployed and expected shortly, wave energy is still very much in the testing and demonstration phase with many small-scale projects. Three multi-device projects make up 25 of the 33 grid-connected devices, all of which have been generating energy for several years (deployed between 2011 and 2016). They are the closest to commercial installation that has been observed in the sector so far, although they have relatively low capacities of less than 20 kW per unit. In the last two years the other eight devices have been deployed and consist of projects of a single or maximum two devices at a time, and seven of them are of relatively small scale with maximum capacities of 350 kW. Most are sub-scale devices, thus in the testing phase, but for some this already is the desired scale as a trend towards smaller-scale devices is visible.

An increasing number of wave energy converter developers are dropping the vision of designing large utility-scale devices and are moving towards smaller purpose-designed devices for niche markets such as the oil and gas industry, aquaculture, etc. Various developers even go a step further with hybrid wave energy converters that include other power generating technologies such as solar PV systems and floating wind turbines. More information on markets of the blue economy as opportunities for ocean energy and on hybrid devices can be found in sections 3.1 and 3.2. The final and latest installation has a noticeably larger capacity of 1.25 MW and is moving closer to maturity. All installed projects are presented in Figure 25 with relation to the unit size. It can be seen that a relatively large number of small-scale devices and only few large-scale devices are deployed.

Wave projects of around 400 MW are currently in the pipeline, but a majority of them are not yet clearly defined with vague or no specifications on technology type, deployment date, capacity or even technology. Although the number of full-scale projects in the pipeline is increasing, most devices remain rather small and only a

Figure 25: Number of installed devices by single unit size



Source: *IRENA ocean energy database*

few multi-device arrays are being pursued for deployment in the near future. Nevertheless, less than 100 MW can be expected in the coming years. This includes several new full-scale devices of at least 1 MW per unit (for example, Wello Oy, Bombora Wave Power) but mostly encompasses devices that are significantly smaller. They can be as small as 3 kW in full scale, showcasing again the parallel pathways of utility and specialised devices.

Due to the different requirements for the respective applications of wave energy converters, as well as their lower maturity level compared to tidal, a large number of different wave energy conversion technologies are still being pursued. A breakdown of currently deployed projects according to technologies, categorised by number of projects, number of devices and installed capacity, can be seen in Figure 26. Given the low number of installed projects, only five different types are currently in the water. These projects are relatively representative of past and current wave energy development, with oscillating water columns dominating the current deployments.

In the future, however, a wider variety and different distribution of technologies can be expected, as oscillating bodies are expected to play a more important role. This is in line with Figure 27, which also presents the cumulative active and planned projects by capacity and number of projects as well as the technologies pursued by the roughly 30 wave energy converter developers with

Figure 26: Active wave energy capacity by technology

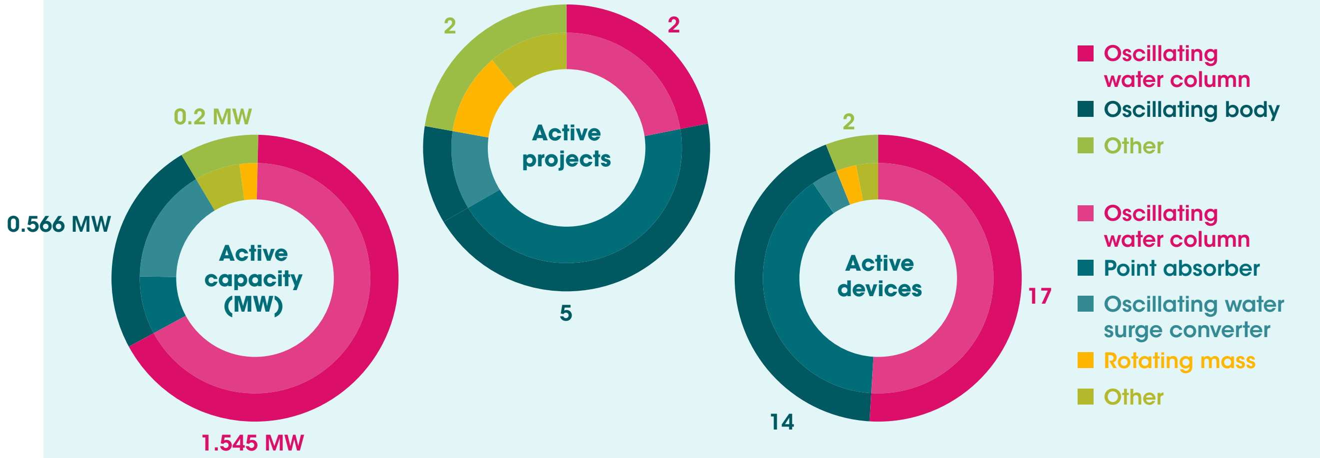
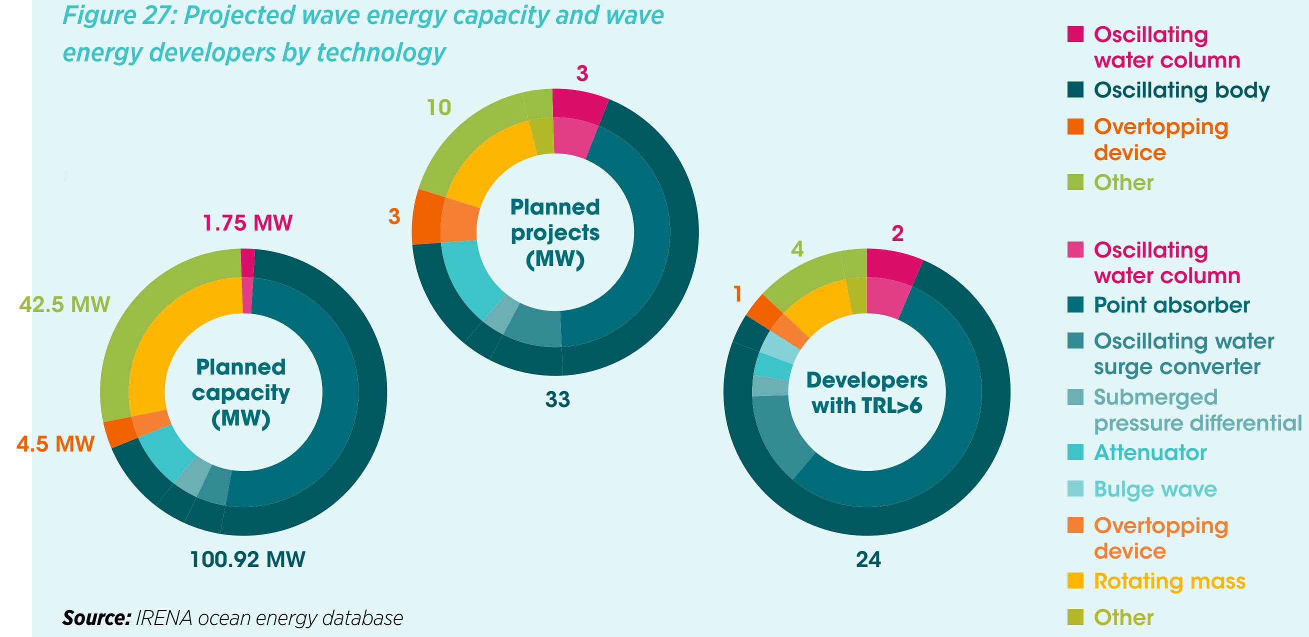


Figure 27: Projected wave energy capacity and wave energy developers by technology



Source: *IRENA ocean energy database*

devices of TRL 6 and above. Figure 27 is not exhaustive and the forecast does not represent all planned projects, as for many the technology, capacity and/or device number is not yet defined. The developers only include those classified by the Joint Research Centre as having reached a relatively high maturity (Magagna, 2019a).

Oscillating water columns, although dominating the installed capacity, account for only three projects of three developers (Voith Hydro, Ocean Energy Ltd and REWEC3), which have little in common besides their mutual classification. The 17 Voith Hydro devices are of an early generation and have low capacities of 18.5 kW each, whereas Ocean Energy Ltd's OE35 device is a cutting-edge deployment and the largest wave energy device ever operated so far, with a rated capacity of 1.25 MW. Oscillating water column technology is one of the earliest researched wave energy technologies and has been pursued for a long time.

This was the specific wave energy technology that first delivered electricity to the grid (in Scotland in 2000) and was deployed as the first commercial wave array (in Spain in 2011), both led by Voith Hydro. Although the company has ceased to operate in the wave energy market, the breakwater wave plant in Mutriku, Spain is still operational. While oscillating water columns are still being researched and used in larger devices, few companies are focusing on the technology.

Of the **oscillating body** category, currently 5 projects and 14 devices, or 566 kW, are operational. The largest share (4 projects, 13 devices, 216 kW) are point absorbers (Sinn Power, Eco Wave Power). Point absorbers is the technology that has been tested and deployed with the most operational projects in the water. This is due in part to their universal nature, as they can be scaled down to very small few-kW, purpose-built projects (e.g., Ocean Power Technologies) up to large-scale units of 1 MW (e.g., Carnegie Wave). Therefore, more than half of the wave energy converter developers with high TRLs focus on such point absorbers, and most current and planned projects are of this technology. Future projections point towards it being the technology to dominate the market.

Oscillating water wave surge converters is the other technology of the oscillating body type that is currently deployed, with one project consisting of one 350 kW device. AW-Energy's WaveRoller is the leading device of this technology, with plans to deploy commercial plants in Portugal. Extensive know-how about the technology was gathered through Aquamarine Power's repeated testing of its Oyster device; however, the company has ceased operation.

Other technologies within the oscillating body family that have been tested are attenuators and submerged pressure differential devices. Attenuators gained high prominence through Pelamis' repeated grid-connected deployment between 2004 and 2014. Before going into administration, the company had tested devices as large as 750 kW, the largest wave energy device ever deployed at the time. Submerged pressure differentials are mainly being pursued by Bombora Wave Power, which was planning to deploy a 1.5 MW device later in 2020 and has additional projects in the pipeline.

Overtopping devices have so far only been tested in sub-scale and are not widely being pursued. In Naples harbour in Italy an embedded over-topping has been operational since 2016 (Iuppa, 2016).

Of the ***other*** technology types that do not fit into the three main working mechanisms, rotating mass devices are among the largest. Wello Oy is leading the way with its Penguin that has been proven on multiple occasions with devices of up to 1 MW. Wave for Energy's ISWEC device is also being tested extensively with a currently deployed device, albeit on a smaller scale of 50 kW. Both developers were deploying new devices in 2020. Additionally, Wello Oy has other multi-device arrays in the pipeline. A few other devices that fit into neither category are also being trialled.

2.4 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. 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 (IRENA, 2014b).

Resource potential

As seen in Figure 28, such conditions are only present in tropical regions between latitudes of around 30 degrees north and 30 degrees south. 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, the global technical potential of OTEC is the largest of all ocean energy sources at 44 000 TWh per year of steady-state power (Nihous, 2007), which is partly thanks to the exceptionally high capacity factor.

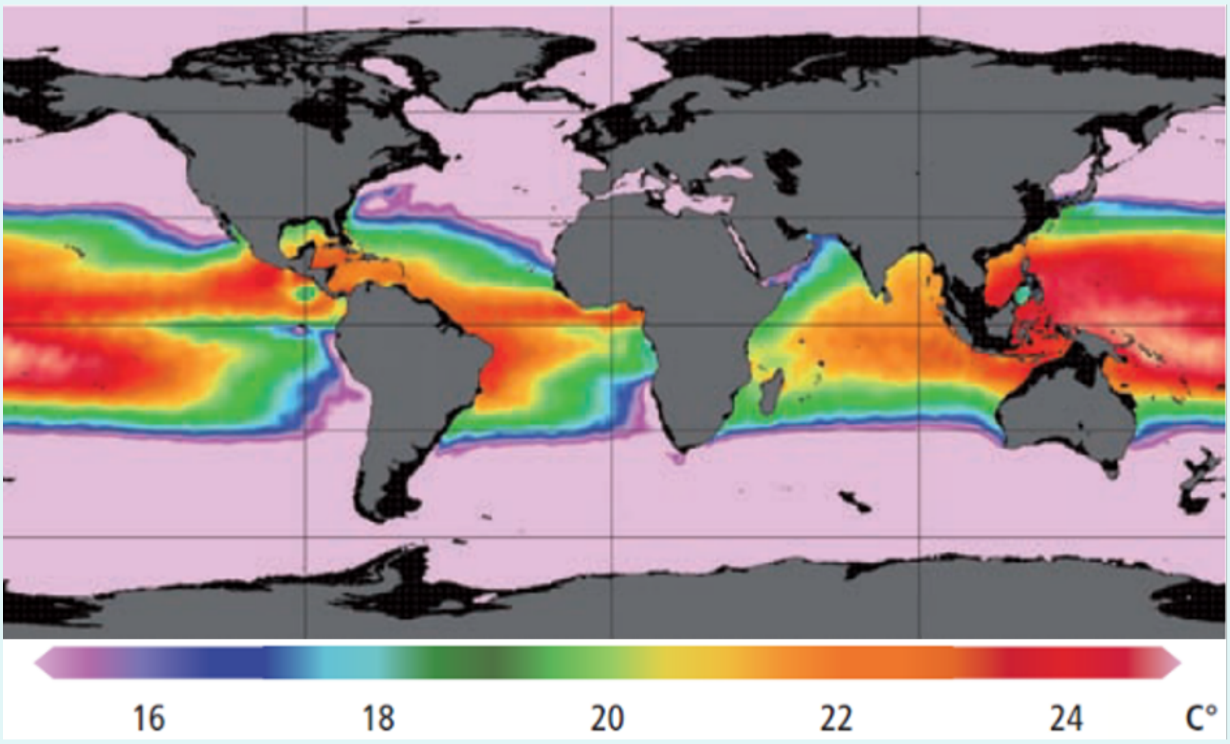
Besides its uniquely large potential, OTEC's main advantage is its ability to provide non-intermittent, continuous baseload power around the clock. OTEC can further be coupled with technologies such as seawater air conditioning (SWAC) to provide cooling and seawater reverse osmosis (SWRO) to produce fresh water, and the waste water of the electricity generation can be repurposed for aquaculture use. This opens new revenue streams and business models for the technology and makes it particularly interesting for applications in tropical islands such as SIDS. For more on such business models see section 3.2, and for more on ocean energy applications on islands see section 3.3.

Table 3 shows the theoretical exploitable resource potential for OTEC compared to various offshore wind technologies for a selection of SIDS located in the Caribbean Sea. While some constraints may further reduce such estimation, it nevertheless shows that the potential of offshore and ocean energy greatly surpasses the average electrical demand in each of the countries shown. At the same time, conducting such a resource mapping exercise allow policy makers to understand which technologies have the highest potential, and which ones should not be actively pursued. For example, Barbados seems to have no potential to deploy fixed offshore wind for technical reasons.

Technology

Three thermal energy conversion processes are being pursued to harness thermal ocean energy; they are open-cycle, closed-cycle and hybrid devices and are presented in Table 4. Several adaptations of these three cycles exist where, for example, working fluids differ slightly or additional turbines and other devices are added.

Figure 28: Global distribution of ocean temperature differences (°C) between 20 and 1 000 metre water depth



Source: *Lewis et al., 2011*

Market

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. Nevertheless, the first OTEC test plants were developed in the late 1970s, starting with a 15 kW offshore barge in Hawaii in 1979 and followed by several land-based plants in Nauru in 1982 and in Hawaii in 1987 and 1993. Demonstration projects have continued to be conducted in France (La Réunion), Hawaii, India, Japan and the Republic of Korea, with many of them investigating additional functions such as SWAC, desalination or aquaculture. In recent years, several companies have signed memoranda of understanding indicating their intention to deploy OTEC. Other projects have been announced and started preparation works, but reality has shown delays in the development of OTEC plants, and several projects lack a clear timeline.

France, Japan, the Netherlands, the Republic of Korea and the US (Hawaii) are among the countries that are most extensively researching and testing the technologies (in the case of France in its tropical oversea territories), while small-island states in the Pacific, the Caribbean and also regions in the Indian Ocean are showing a particular interest in deploying the technology. This is reflected in the operational projects, as presented in Figure 29. Hawaii, Japan and Réunion island each have small running projects in their respective test sites, and the Republic of Korea is installing a 1 MW project in Kiribati in the Pacific Ocean. It will be the largest project of its kind and is expected to evaluate OTEC's high potential in island applications (see Box 3).

2.5 Salinity gradient energy

Salinity gradient energy, also known as osmotic energy, makes use of the pressure potential in the difference in the ocean's salt concentration and transforms it into usable energy with the help of membranes.

Table 3: Theoretical exploitable resource potential for each technology in Caribbean SIDS

Country	Maximum technically exploitable resource (MW)					Average electrical demand (MW)
	Fixed offshore wind	Floating offshore wind – conventional	Floating offshore wind – deep sea	OTEC	Total	
Antigua & Barbuda	4 935	1 477	11 718	100	18.230	38
The Bahamas	10 955	6 321	16 723	220	34 219	220
Barbados	0	112	7 063	140	7 315	104
Grenada	2 618	476	7 196	110	10 400	25
Jamaica	1 211	1 848	9 709	180	12 948	498
Saint Kitts & Nevis	399	196	9 135	40	9 770	24
Saint Lucia	105	224	4 025	90	4 444	46
Saint Vincent & the Grenadines	3 227	385	3 017	70	6 699	17
Trinidad & Tobago	16 597	12 460	4 963	50	34 070	1 064
Total	**40 047**	**23 499**	**73 549**	**1 000**	**138 095**	**2 036**

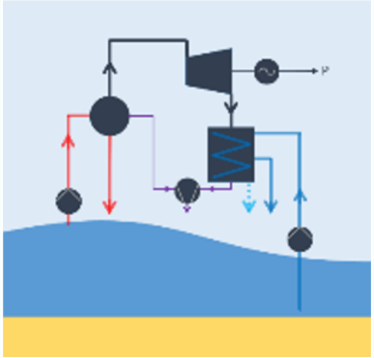
Source: *Johnston, 2019*

Resource potential

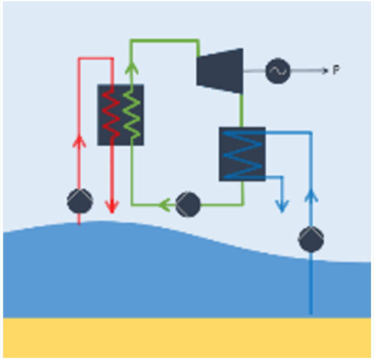
The salinity of the ocean is not homogenous across the globe, as can be seen in Figure 31. Its concentration is lower in the proximity of the poles, which is due mainly to the melting ice. Other factors such as river runoff or melting glaciers as well as heavy or lack of precipitation also impact the salinity in certain regions. Although the salinity levels vary, the presence of river beds, where fresh water discharges into the sea, is most important to harness salinity for energy generation purposes. This is because the amount of energy that can be generated is proportional to the difference in salt concentration, making a freshwater-saltwater system extremely efficient. Estuaries can be found globally, and salinity plants can in theory run continuously to provide baseload power. In comparison to other ocean energy technologies, however, the geographical requirements pose strong limitations to the overall potential, making it comparably small at 1 650 TWh per year (Skråmestø *et al.*, 2009).

In addition to the stand-alone way of harnessing the "natural" differences of salt contents in the ocean, salinity gradient technologies can be applied as a hybrid system

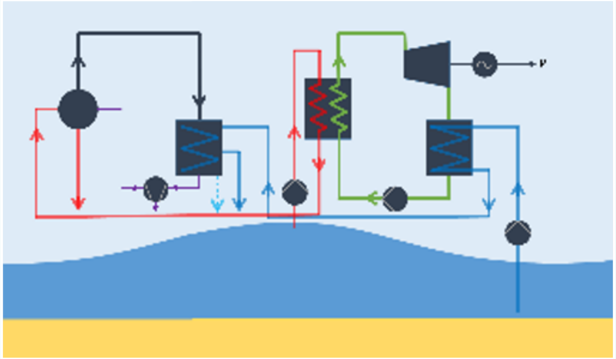
Table 4: Different OTEC working principles



Open-cycle:
Open-cycle processes use warm surface water that is flash-evaporated under low pressure as the working fluid. The vapour is used to drive a turbine that drives a generator to create electricity. Cold deep-sea water is then used to condense the vapour. This cycle generates desalinated water as a by-product, or it can bypass the electricity generation completely for freshwater production through a low-temperature thermal desalination (LTTD) system. The cold seawater used to condense the vapour can be re-used for cooling purposes and is also well suited for aquaculture.



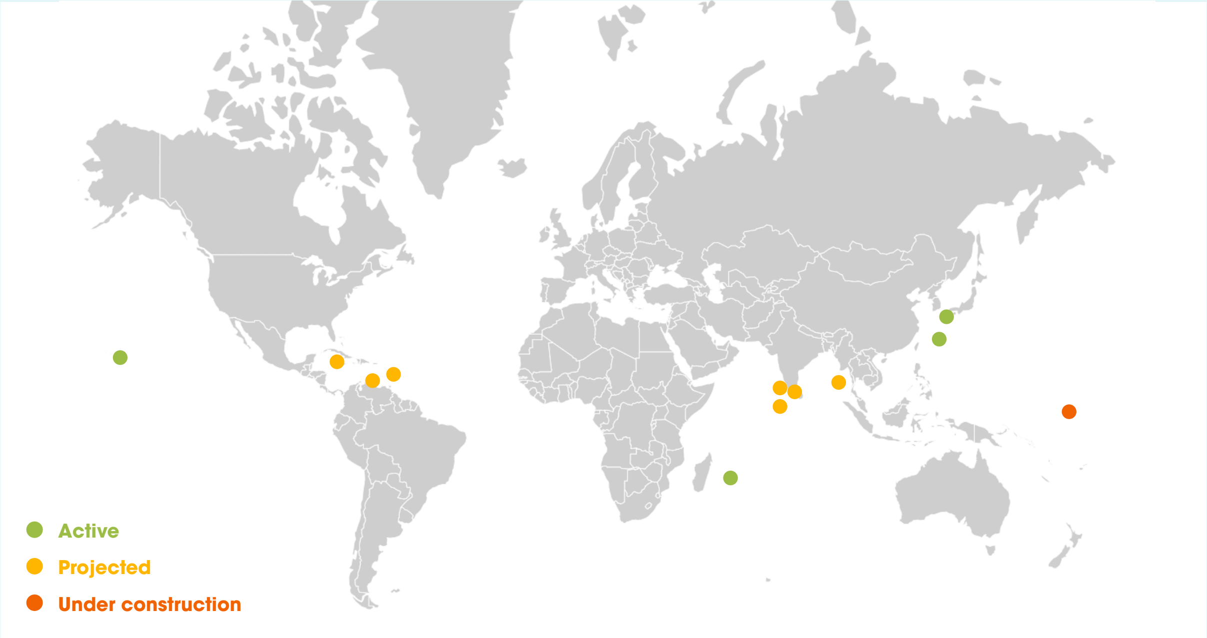
Closed-cycle:
In closed-cycle systems the warm water is not evaporated directly but is used to flash-evaporate another working fluid with lower boiling temperatures than water (e.g., ammonia) in a heat exchanger. The working fluid drives a turbo-generator, is condensed by coming into contact with cold deep-sea water and is pumped back into the closed system. This cycle is more efficient but is better suited for smaller applications. The cycle can be reversed to use cold water to cool a working fluid through heat exchangers to provide seawater air conditioning (SWAC) instead of electricity.



Hybrid:
In a hybrid system both closed and open cycles are used successively. First electricity is generated through a closed-loop system as described above. The warm seawater is, however, not discharged but is flash-evaporated and passes through an open cycle, generating more electricity and/or desalinated water.

Based on IRENA, 2014c

Figure 29: Global distribution of active and projected OTEC power plants



Boundaries and names shown on this map do not imply any endorsement or acceptance by IRENA

Source: *IRENA ocean energy database*

BOX 3: KIRIBATI OTEC PROJECT

Figure 30: Kiribati OTEC Project

Although the Republic of Korea successfully runs successfully running a 20 kW OTEC plant in the Republic of Korea, today's OTEC technologies can only operate in the country in during the summer months in the Republic of Korea. The South Pacific poses better preconditions for year-round operation with temperature differences of 24 °C, which is one reason why the Korea Institute of Ships and Ocean Engineering (KRISO) is now delivering a 1 MW OTEC plant to South Tarawa, Kiribati, in the South Pacific, with planned operation to begin in 2021. Figure 30 shows the Kiribati OTEC project deployed in the South Republic of Korea's waters.

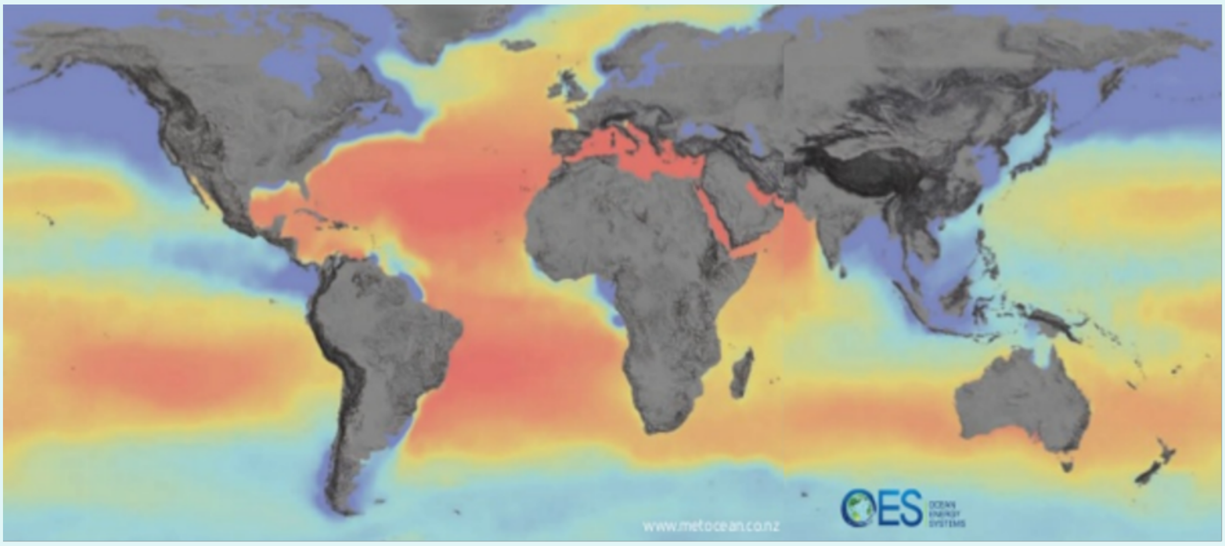
The project, that is funded by the Ministry of Oceans and Fisheries of the Republic of Korea, has been granted all necessary environmental and planning permissions by the Kiribati government. KRISO is furthermore also collaborating with the Korea International Cooperation Agency (KOICA), the University of the South Pacific, (USP), the Pacific Community and the Sustainable Seawater Utilization Academy (SSUA) to build local capacity for operation and maintenance. The current funding is aimed at the initial phase, and if successful, KRISO will apply for longer-term funding with an aim at increasing the OTEC capacity to 5-50 MW in the future. The design and building of the initial plant costs USD 20 million.

Kiribati's total installed electricity capacity is around 6 MW, making the OTEC plant a substantial part of the country's electricity mix. The OTEC project would displace significant large amounts of diesel generation and it has the potential to make a contribution towards increasing Kiribati's share of renewables by 26% by 2025.

Source: *IRENA et al., 2017; KRISO, 2017; Petterson and Kim, 2020*

Image source: *Petterson and Kim, 2020*

Figure 31: Global distribution of the annual mean salinity concentration in the ocean



Boundaries and names shown on this map do not imply any endorsement or acceptance by IRENA

Source: *Huckerby et al., 2012*

in industrial energy recovering purposes, where instead of seawater saturated brine is used (for example, from desalination or wastewater treatment) (IRENA, 2014d). While such applications would not be included under the ocean energy category, they can help to prove the technology viable before scaling it up for ocean purposes.

Technology

Currently two main processes to make use of this potential energy are being tested and applied: *pressure retarded osmosis* (PRO) and *reversed electro dialyses* (RED). Descriptions of both operation principles are presented in Table 5.

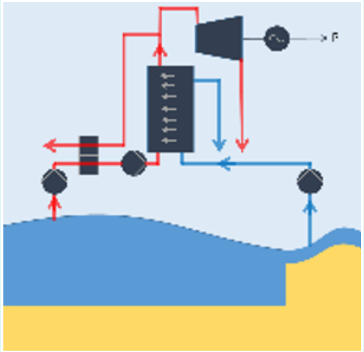
The membranes are the critical components and technology bottlenecks of the plants. The required properties are unique as they must have highly efficient ion rectifiers as well as high ionic flux with long-term robustness in seawater. In addition, the vast required quantities are commercially unavailable, and regular replacement would be necessary. A scale-up of the technology to increase viability is thus often thought to be challenging (Chen *et al*., 2020).

Market

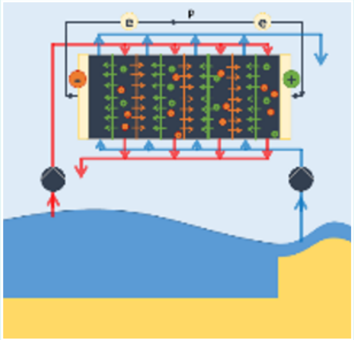
The technology remains in conceptual stage and is significantly less mature than tidal, wave or OTEC, but research is being conducted intensively, data are being collected, and laboratory testing is ongoing. In 2019, researchers from Australia and the US published a study presenting the development of a novel nanocomposite membrane for salinity energy purposes (Chen *et al*., 2020), and that same year researchers at Stanford University successfully deployed the first electrochemical battery to harness this energy (Ye *et al*., 2019). Research is ongoing at other universities as well, such as at EPFL in Switzerland (researching nanotechnologies to increase the power density for RED membranes), at the Universidad del Norte in Colombia (analysing the resource potential for salinity gradient across Latin America) and at Yamaguchi University in Japan (analysing ways to use the RED technology to produce hydrogen).

Only one plant using the RED technology is currently operational: a demonstration plant on a test rig in the Netherlands by REDstack, classified with a TRL of 7. The company's plans to install a larger project near The Hague have been placed on hold due to issues in securing funding. The PRO technology is being pursued by SaltPower, a Danish company that is focusing on enhancing the business case and is thereby looking into using salt domes as salinity sources and reusing salt caves to store hydrogen or carbon. Such niche markets can play a role in proving the technology before moving to ocean resources. SaltPower plans to install its first commercial unit (80-100 kW) in 2021, while REDstack's next goal is the installation of a 1 MW station with a TRL of 8.

Table 5: Different salinity gradient technologies



Pressure-Retarded Osmosis (PRO):
In a PRO system a freshwater and seawater chamber are separated with semi-permeable membranes. When the fresh water flows into the seawater, it increases the pressure within the chamber which is compensated to spin a turbine and generate electricity.



Reversed Electro Dialyses (RED):
The RED system makes direct use of the salt ions in the seawater and bypasses the need for a turbine. It uses perm-selective membranes to separate the ions and arrange them in RED stacks to increase the chemical potential difference. Through this, voltage is created across the membranes and thus electricity is generated.

Based on IRENA, 2014c

2.6 Ocean current energy

In addition to the ocean movement caused by rising and falling tides, the ocean currents are other movement mechanisms in the oceans. These large circulations are initiated by an interplay of wind, temperature and salinity across the globe.

Resource potential

The locations of these currents are well known and studied, as presented in Figure 32. The streams with the highest velocities include the Gulf Stream (off North America), the Agulhas Currents (off South Africa), the Kuroshio Current (off East Asia) and the East Australian Current (Lewis *et al.*, 2011). There have been few studies, however, on the potential ocean power that could be harnessed from such streams. Research has shown that, for example, the Florida Current has a potential of 20 GW across its cross-section, but it remains open how many of these cross sections could be harnessed and what impact it would have on overall flow (Hanson, 2014). The currents are usually slower than tidal streams, but volumes and magnitudes of these currents are considerably higher. Another advantage is that unlike tidal streams, which have bidirectional flow, these currents flow unidirectionally and continuously with few fluctuations. They are therefore ideally suited to be harnessed for baseload power generation.

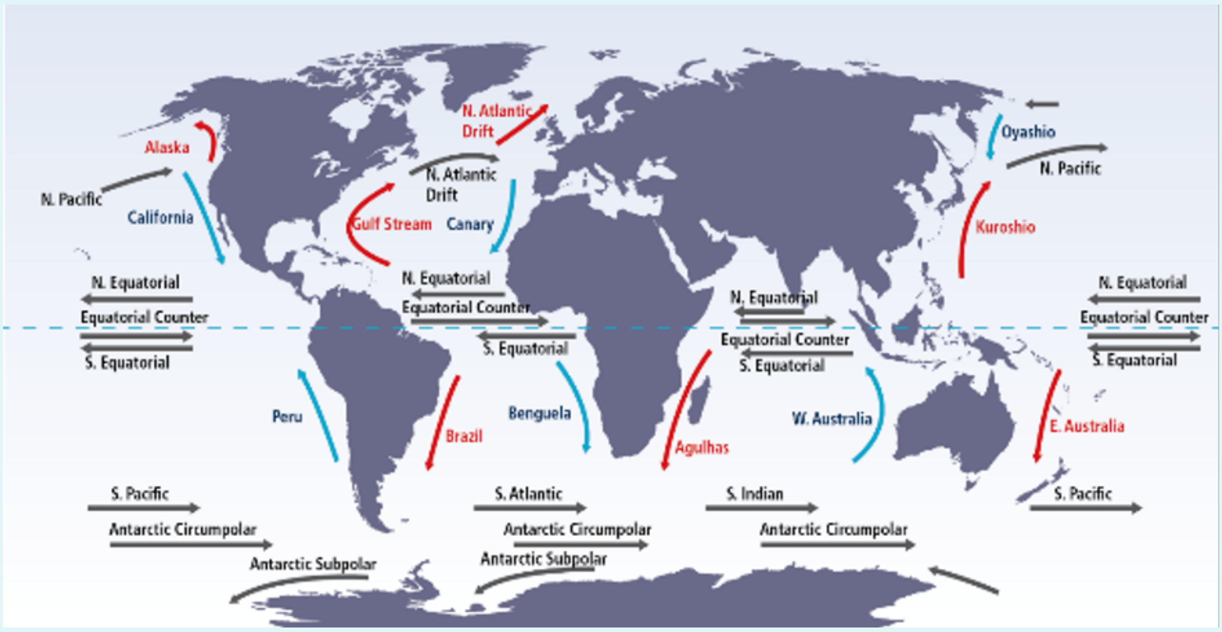
Technology

Although barely tested so far, the technologies to harness ocean currents are expected to be similar to those to harness tidal streams presented in section 1.2.2. The focus has specifically been on hydrokinetic devices that are adapted to the lower current speed. However, new tidal technologies are emerging that are suited for lower speeds by default. Minesto (see Box 2), for example, claims that its tidal kite could be well used for ocean currents as well. It therefore remains unclear which technology will be used when ocean currents will be harnessed for electricity generation.

Market

The Florida-based South National Marine Renewable Energy Centre (SNMREC), a marine energy R&D centre with close collaboration with local universities, has small-scale test berths for ocean current deployments in the nearby Gulf Stream. Equipped with a deep-sea anchor bases at 350 metres below the surface, the devices are suspended at 90 metres depth. A first 24-hour test of an ocean current device in such a berth was successfully conducted in May 2020. Besides this, relatively little attention has been devoted to extracting energy from ocean currents, which can be attributed mainly to the fact that open ocean currents are often in much deeper waters and much further offshore, which complicates the deployment and mooring technology. In addition, the environmental impacts are largely unknown, and assessment is complicated. The stage of development is therefore lower than that of any other ocean energy technology. It can be expected that more attention will be given to ocean current energy extraction once tidal energy is fully commercial and long-term studies are available.

Figure 32: Global distribution of the major ocean currents



Boundaries and names shown on this map do not imply any endorsement or acceptance by IRENA

Note: *Red = warm currents, Blue = cold currents*

Source: *Lewis et al., 2011*

3. CHALLENGES OF OCEAN ENERGY DEVELOPMENT AND DEPLOYMENT

Ocean energy technologies still face several challenges that have so far hindered large-scale deployment. They are closely linked to the relatively low maturity of most of the technologies. Research into the risk analysis for ocean energy has indicated essential gaps in gathering and analysing data about resource characteristics; life-cycle costs; project macro environment and device characteristics as well as project execution procedures (Martins, 2014). The uncertainties and related challenges of these areas can be grouped into five categories as presented in Table 6 and described in this section. Even though the development stage varies among the different ocean energy technologies, most barriers apply to all to a similar extent.

Table 6: Existing challenges in the ocean energy sector

Technology	Harsh offshore environment (salinity, extreme forces)
	Concerns about technology maturity and performance
Infrastructure	Poor grid-connection infrastructure
	Poor or non-comprehensive site assessment
Financial	High initial capital costs
	Funding shortage
	High LCOE
	Difficulty in securing funding due to high perceived risks
	Lack of insurance and guarantee
Market	Low cost-competitiveness compared to other renewable sources
	Lack of established supply chains
Regulatory and policy	Lack of regulatory frameworks for ocean energy technologies
	Poor reinforcement of standards
	Inadequate revenue support instruments
	No clear framework to include ocean energy in Nationally Determined Contributions (NDCs)
Environmental	Uncertainties about environmental impact
Socio-political	Ocean governance
	Social acceptance and community readiness for implementation
	Weak awareness and knowledge of technology by all involved stakeholders (governments, end users, investors, etc.)

3.1. Technology

Due to continuous water movement and salinity the subsea marine environment is harsh and poses numerous technical challenges. There is a need for the structures to sustain vastly energetic settings, as the locations are chosen for their high energy potential. In addition, they have to withstand extreme atmospheric conditions such as heavy precipitation, strong winds, heat waves and abrupt temperature changes. Therefore, all components need to be amply stress-resistant. The salinity of seawater poses additional challenges on the materials as they need to withstand corrosion for extended periods of time. In addition, the subsea environment complicates grid deployment and connection as well as maintenance efforts.

Historically, numerous wave and tidal devices faced such challenges when first deployed in the ocean, even leading to bankruptcies. Technical challenges must therefore be identified and determined at the R&D stage, with improvements being made through tank testing before wider deployment. This further helps to address stakeholders' concerns about the technologies' maturity level and can minimise risks. Moreover, given that these are relatively new technologies, their reliability needs to be assessed and improved over time.

3.2 Infrastructure

Infrastructural barriers apply to the grid, supply chain and spatial planning. Due to the offshore nature, the grid connection is typically not already in place and the cable connection needs to be laid out first, which is associated with high capital costs. In comparison to other energy sources the grid capacity for ocean energy often poses additional challenges because grids in ocean energy markets can be small and unstable especially in islands or sparsely populated coastal areas. The construction and improvement of onshore and offshore grid capacity is therefore central to fully exploit the resources (Scottish Government, 2015).

In addition to the technical infrastructural barriers, the site assessment poses other challenges. The finding of an adequate site to place the device is a complex process; high-resolution maps are not yet largely available, and although research on tidal and wave patterns has progressed enormously, there are still research gaps relevant to sourcing sites for ocean energy. Where data are available, they are not always open-source, are often not accessible to the relevant institutions and, if available, their existence may not be widely known. More on resource assessment can be found in section 4.2.

3.3 Financial

Some of the major barriers towards commercialisation of ocean energy are of an economic nature. The levelised costs of energy for ocean energy are in most cases significantly higher than for other renewable energy carriers due to high upfront costs. The initial installation, research and development costs as well as the manufacturing costs are also high due to the novelty and a lack of economies of scale. The technology is perceived as high risk due to uncertainties that arise from a lack of familiarity and operational experience with the technology. These uncertainties span the entire value chain and make it extremely challenging to find appropriate investors and funding. Education and outreach are thus crucial for advancement of the technology, and revenue and capital support mechanisms are needed, as presented in section 4.1. Another means to bypass funding limitations is by creating new business models such as hybrid renewable electricity generation units or powering the blue economy, as described in section 3.

3.4 Market

Challenges also appear across the supply and value chains. No ready supply chains and few standardised components are available, which means that developers often have to take on more roles than initially expected – for example, some developers had to opt to develop part of their power electronic components. However, developers are increasingly seen to be adopting parts and entire sub-systems from established manufacturers, often components originally developed for other purposes such as the shipping industry.

Due to a lack of operators across the value chain many technology manufacturers also function as project developers and power producers. An unbundling could increase the efficiency and help advance the technology as the limited resources can be channelled to build capacity in a specific area. This may also facilitate market entry for new actors and play a significant role in broadening the market.

Agreements for co-operation between developers and power producers or utility companies have already been made and are increasing with the growing number and scale of commercial projects.

Particularly in tidal projects, it can be observed that such a consortium often includes technology developers, technology manufacturers, power utilities and/or local or regional councils. Wave energy projects, where the majority are still in prototype phase, are often still solely implemented by the technology developers. OTEC, salinity and other less mature technologies tend to be developed by universities or other research institutes. While such collaborations are crucial to mitigate challenges, the different players are often geographically disconnected, often due to the distances between R&D, manufacturing and adequate deployment sites. This leads to additional difficulties and increasing costs.

Such issues are present not just across the value and supply chains but also across development levels because the transition from demonstration to commercial stage or from prototype to full-scale testing cannot always be carried out by the initial developer. Liaisons with larger, established companies could play a significant role in helping to successfully cross the technology readiness steps.

3.5 Regulatory and policy

On numerous levels regulatory and policy frameworks that are needed to adopt ocean energy into a nation's energy mix are not adequately available. Developing such frameworks requires early engagement with policy makers. There is, however, a lack of ocean energy networks and umbrella organisations that have the resources and experience in developing such regulatory frameworks and discussing potential policies with authorities. In addition, there is often unclarity and a lack of information on the permitting process.

Strategic government plans and policy mechanisms are further lacking to enhance the grid, obtain investments, support revenue streams and conduct marine spatial planning, because of the novelty of these technologies. In some countries, strategies have been developed through a joining of forces of the government and relevant stakeholders (see, for example, Scottish Government, 2015), but efforts to include ocean energy in country-specific energy roadmaps or Nationally Determined Contributions (NDCs) are lacking.

3.6 Environmental

Relatively little is known about the impact of ocean energy technologies on marine life due to the early stage of technology deployment. Negative impacts could arise in the form of habitat loss, animal-turbine interactions, noise and electromagnetic fields produced by sea cables, which may have effects on aquatic species. While key lessons can be learned from other offshore activities, such as conventional oil and gas as well as offshore wind operation, this is yet to be studied in-depth for ocean energy technologies.

An additional issue is that studies are very location specific, and findings cannot be easily transferred to other sites. Also, the increased vessel traffic due to deployment and maintenance can further intensify environmental effects. It has been indicated that learning-by-doing, which is often practiced when developing other technologies, cannot be applied as simply for ocean energy because risk mitigation needs to be demonstrated before a project can be performed (IRENA, 2014e). Nevertheless, major deployment sites have numerous monitoring devices attached to their turbine to continue researching the impacts on the environment. The main objectives that are analysed are collision risk, mainly of marine mammals, fish and birds; acoustic impacts; and impact on currents, erosion and sediment transport. Hydrophones, sensors, cameras, acoustic Doppler current profilers (ADCPs) and land-based observation are common tools to do such analyses, and developers often collaborate with universities for data analytics and to develop appropriate tools and software.

Despite the risk potential, research has shown positive outcomes so far. Underwater noise, for example, usually remains below hearing thresholds for most species and has little impact. Collision also does not show a high risk for tidal plants, because observation has shown that when tidal streams gain speed, much of the sea marine population vacates the site regardless of the turbines. A recently published extensive study on the environmental effects of ocean energy has concluded that impact is likely much smaller than perceived, as no harms through collision, noise or electromagnetic fields and no significant change in habitat due to ocean energy have ever been observed (Copping and Hemery, 2020). However, research remains limited and no large farms have been deployed so far. The extent to which animals and the environment would respond to larger arrays remains uncertain, and more research and studies on the environmental impact will have to be conducted in parallel to the industry development.

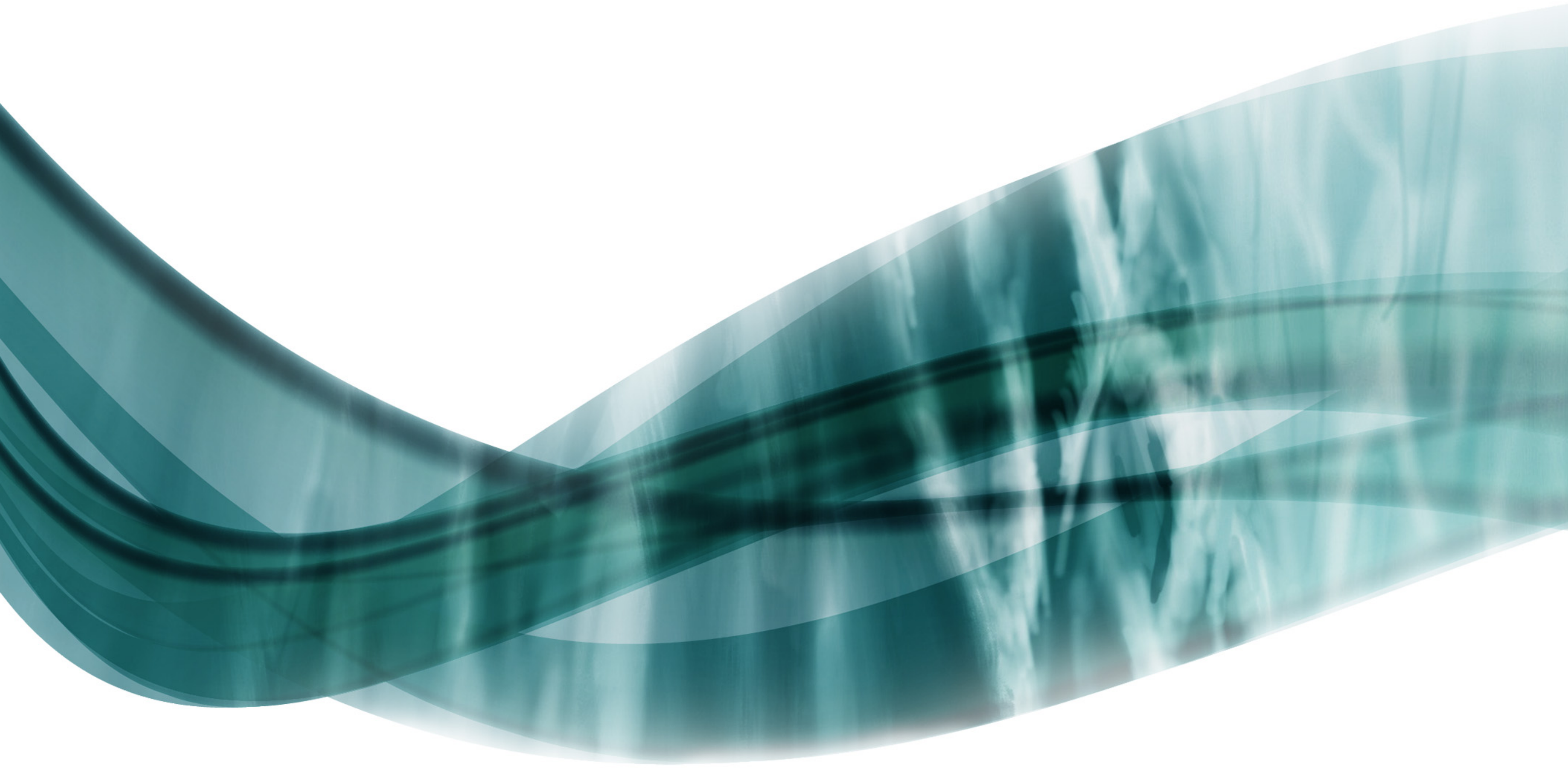
Besides the perceived risks, some research has also shown positive impacts such as an increase in biodiversity where ocean energy systems act as artificial reefs or where ocean energy leads to the absence of fish aggregation devices (Inger *et al.*, 2009). In other offshore renewable technologies, particularly wind farms, it has also been observed that due to the absence of vessels an increase in marine mammals could be determined.

3.7 Socio-political

Socio-political issues such as those of *sharing* the oceans are also becoming more prominent with increased focus on the blue economy. More than two-thirds of the oceans are not governed by specific nation-governments but are part of the so-called global commons (Ocean Unite, 2019), leaving much room for uncertainties that can lead to ownership disputes among communities, countries and sectors, particularly in areas where fishery, conservation, shipping and defence is already in place. In the context of offshore wind energy, some countries have started to co-operate via collective initiatives to avoid such disputes. Through the North Seas Countries' Offshore Grid Initiative, for example, 10 countries formalised a political declaration on energy co-operation in the North Sea that focuses on further interconnection among the countries and on jointly building subsea cables (European Commission, 2016b).

Ocean energy and other offshore sectors should be included in future initiatives. It needs to be considered that regional ecosystems differ considerably and are vastly complex, and therefore no generic roadmap is available to approach such co-operation. Careful marine spatial planning, as described in section 4.2.3, is thus essential for the deployment of ocean energy technologies.

Particularly for near-shore installation, community readiness must also be taken into consideration. The above-mentioned conflicts of ocean use as well as potential visual impacts and the unfamiliarity with the emerging technology are prone to lead to rejections from the public. The public's opinion can have a significant impact on the development of the technologies, and consulting and consenting processes should therefore be sufficiently considered early on. Additional risks emerge when the needs and interests of the population are not fully understood and too much emphasis is placed on quickly deploying the technology.



4. ENHANCING THE BUSINESS CASE OF OCEAN ENERGY

The ocean plays a key role in the global economy with an estimated value between USD 3 trillion and USD 6 trillion per year (UN, 2017) that is expected to continue to grow substantially. This places increased attention on the blue economy, a term that focuses on the economic growth of offshore industry sectors through the sustainable use of ocean resources. New market pathways are emerging that could be significant to enhance the economic case of ocean energy and to drive it into new business models with additional revenue streams. Such models that leverage the synergies with other markets can help ocean energy reach commercialisation levels and enable wider deployment. A visualisation of technologies that can be coupled with ocean energy is shown in Figure 33.

When ocean energy works in harmony with other offshore technologies and when innovative business models are applied, the levelised costs of energy can be reduced drastically through the creation of economies of scale and the formation of additional revenue streams. This can allow access to new markets such as islands and as such could be the urgently needed game-changer for ocean energy. Synergies can not only benefit economically but also contribute to making energy systems more reliable.

This section distinguishes between three business opportunities as presented in Figure 34. Firstly, ocean energy can be coupled with other renewable energy sources to optimally complement each other and create hybrid electricity generating systems (left bubble); secondly, it can be used to power established and emerging offshore sectors and benefit from synergies (right bubble); and thirdly, it can generate electricity on islands, where it can deliver numerous benefits and also profit from the first two business models (bottom bubble). These three mechanisms are described further in the following sub-sections.

4.1 Innovative business models: Hybrid electricity generating systems

Ocean energy should not necessarily be regarded as a stand-alone source of power but should be assessed by its capability to interact with other renewable energy sources at the same location. Ocean energy technologies must be developed in harmony with other renewables, and *vice versa*, in order to increase the predictability and

Figure 33: Ocean energy coupled with other renewable energy sources to power the blue economy

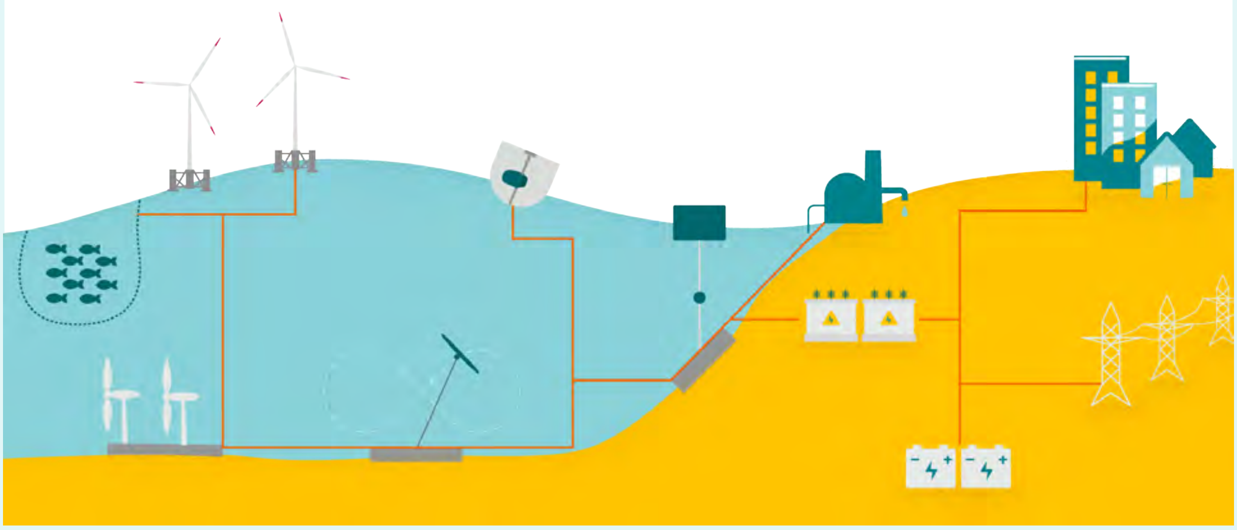
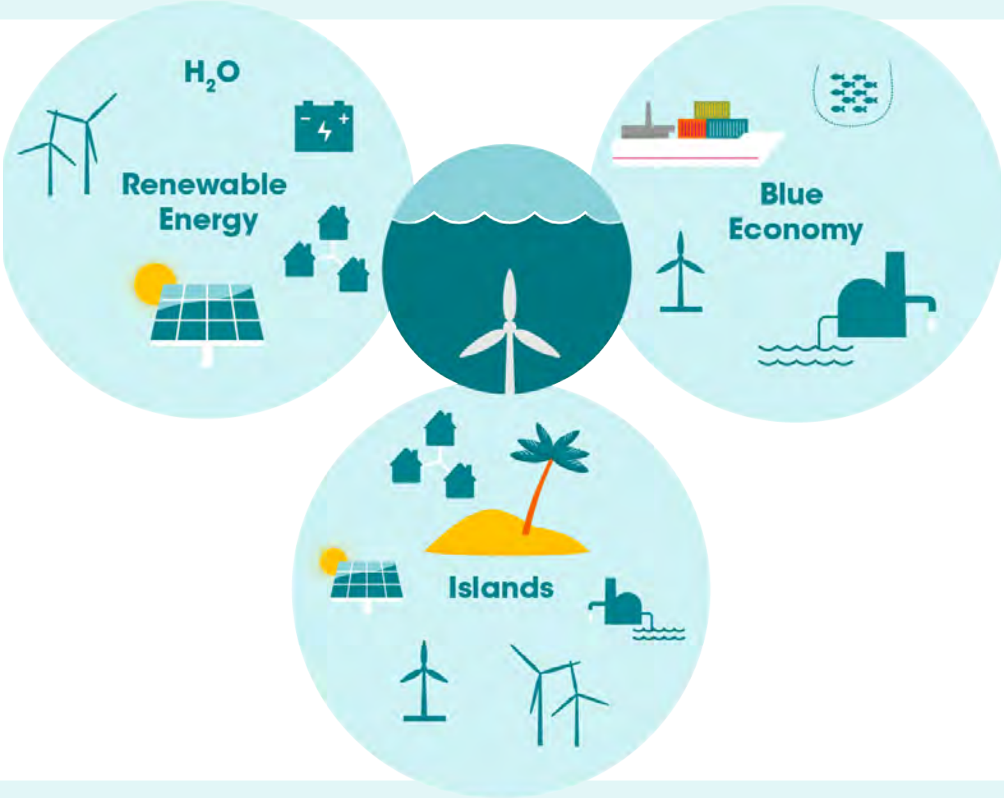


Figure 34: Coupling ocean energy with other renewable energy sources (left), other offshore markets (right) and islands (bottom)



reliability of the entire system and to help balance the grid, especially if also coupled with energy storage. Table 7 shows an example where a wave energy converter is coupled with offshore wind to power a coastal city. Such syncing of different renewable energy technologies can play an important role in scaling ocean energy to a commercial level.

As some renewable energy sources generate intermittent, non-dispatchable energy, coupling them with a predictable ocean energy source could make a power system more reliable and sustainable. Several hybrid projects that link different renewable energy sources with ocean energy have already been investigated, planned or even deployed. Table 7 summarises some existing and proposed systems that use ocean energy to complement other renewable energy sources. As can be seen these projects are planned on a wide geographical spectrum, showing a global interest in the field.

The motivation and reasons for the deployment of the projects presented in Table 6 vary widely. In some cases the projects aim at responding to site-specific needs and available resources, and the entire infrastructure needs to be built new (for example, the potential for pumped hydropower near the shore in the KIOST microgrid project). Other projects were developed in response to the availability of excess energy from the tidal plants (for example, Shetland and Orkney using storage and electrolysers), while yet others aim at integrating ocean energy with existing energy infrastructure (for example, a high renewable share in microgrids in Garden Island and San Antonio) or at decarbonising an existing system (for example, Ushant Island to replace diesel generation; see Box 4). The business model of coupling different renewable energy sources can thus, in addition to creating a market for ocean energy, solve and mitigate pre-existing issues on different scales.

In addition to coupling ocean energy with other energy sectors there is increasing interest in combining multiple technologies into one device. Different such hybrid technologies are emerging, mainly with wave energy converters, where they are for example equipped with solar panels or are paired with a wind turbine. Some examples of projects under development are presented below.

Table 7: Projects coupling ocean energy with other renewable energy sources

	SOLAR	WIND	FLOATING WIND	PUMPED HYDRO	STORAGE	MICROGRID	HYDROGEN	Examples	Country	Status
Tidal		✓					✓	BIG HIT / Surf 'n' Turf	Scotland	In operation
Tidal					✓			Bluemull Sound Shetland	Scotland	In operation
Tidal	✓				✓			San Antonio	Philippines	Research
Tidal	✓	✓			✓	✓		PHARES Ushant Island	France	Planning
Tidal				✓				KIOST	Republic of Korea	R&D
Wave	✓	✓			✓	✓		King Island	Australia	Planning
Tidal					✓	✓		KIOST	Republic of Korea	R&D
								Dent Island	Canada	Test completed
Wave	✓				✓	✓		Garden Island	Australia	Planning
								KIOST	Republic of Korea	R&D
Wave			✓					Canary Islands	Spain	Research
								Bombora and MEECE	Wales	Research
Salinity							✓	REDstack	Netherlands	Planning
Wave	✓							GEPS Techno		Full-scale testing
								Eco Wave Power		Installed (Gibraltar and Israel)
								Wave for Energy		WEC full-scale testing completed
								GIEC		Open-sea testing completed
Wave	✓				✓			Ocean Power Technologies		Full-scale deployment announced
Wave	✓	✓						SINN Power		WEC prototype testing completed
Wave		✓						Floating Power Plant		Previous model testing completed
								Marine Power Systems		WEC 1:4 scale testing completed
								Seabased		WEC tested, wave-wind resource assessment conducted
								Havkraft		WEC full-scale testing completed
Wave					✓			BOLT Lifesaver		Small-scale testing completed
Tidal					✓		✓	HydroWing (Tocardo Turbine)		Patenting

Note: *WEC = wave energy converter*

Source: *IRENA ocean energy database*

BOX 4: PHARES (PROGRESSIVE HYBRID ARCHITECTURE FOR RENEWABLE ENERGY SOLUTIONS IN INSULAR SYSTEMS)

Renewable energy producer AUKO Energy and tidal developer Sabella (horizontal-axis turbines) have joined forces to develop a multi-energy pilot project on Ushant Island in the French Channel Islands to replace the high carbon energy carriers (now 100%) with a hybrid renewable power scheme.

The pilot project hopes to showcase the integration of variable resources with ocean energy in the island setting of Ushant Island, where ideal topographic and bathymetric preconditions for tidal energy are available. Figure 35 provides an illustration of the proposed hybrid renewable power scheme

Features:

- 1 MW tidal power (2 x 500 kW Sabella D12)
- 0.9 MW wind power (1 x 0.9 MW)
- 0.5 MW solar PV power
- Energy storage system (EDF SEI)

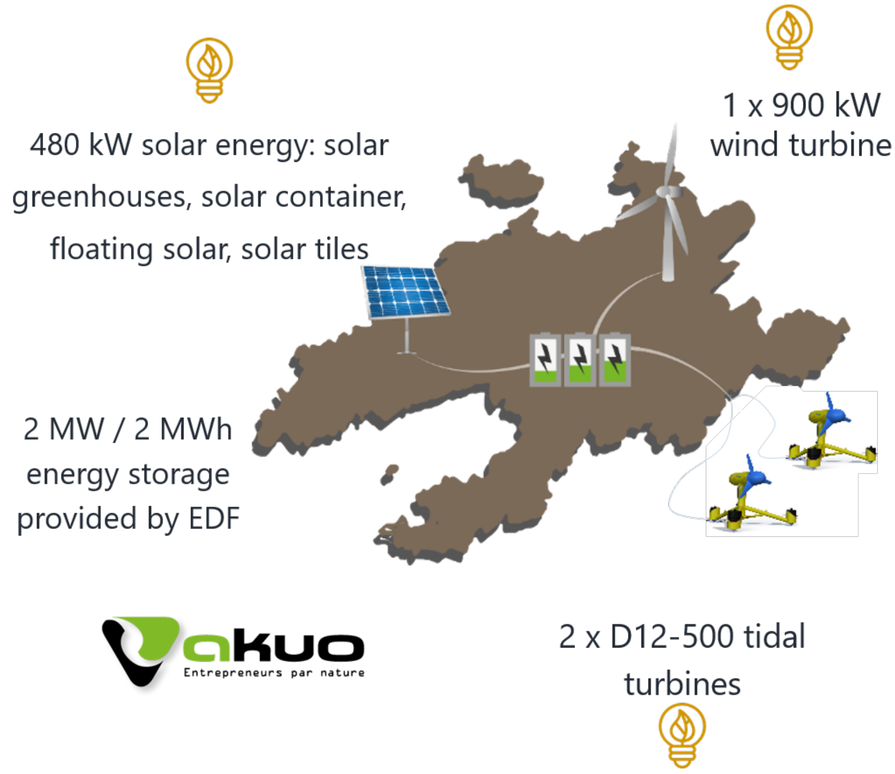


Figure 35: An illustration of a hybrid renewable power scheme

Image source: *Akuo*

Wave-solar

The most common hybrid devices are wave energy converters that are equipped with solar arrays. These devices are popular due to their simplicity. They are often devices, deployed or in research stage, where the solar panels do not make up core components of the wave energy converter and their addition was sometimes not initially intended but added somewhere along the way. Numerous wave energy converter developers have now started to include such PV arrays on the surface of their devices. With the recent upgrade of Eco Wave Power's wave energy converters in Gibraltar and Israel, a first hybrid ocean energy technology is now commercially operating (see Figure 36).

Wave-wind

A more complex and very promising hybrid model consists of floating offshore wind and wave power. Such generators can not only increase revenue streams due to the higher energy yield, but the platform and crucial infrastructure such as subsea cables and grid connection as well as installation and deployment practices can be shared. Costs can thus be reduced, and project resources can be utilised in a more effective way, making commercialisation more viable. In addition, wave power could have a shielding effect and cover the necessary energy supply in periods where wind turbines are not operational or not generating power.

Figure 36: Eco Wave power plants upgraded with solar PV panels

Source: *Ridden, 2019; Eco Wave Power, 2020*

BOX 5: FLOATING POWER PLANT

A company called Floating Power Plant is developing its P80 unit, a platform that hosts a floating wind turbine and a wave energy converter. Some units have already been successfully tested on a smaller scale. Led by DP Energy, several projects are under development in Wales and Scotland with the aim of commercial availability by 2021/2022. The technology for the mooring system is taken from the oil and gas industry. Figure 37 provides an example of the floating platforms being developed by Floating Power Plant.

Image source: *Floating Power Plant (n.d.)*

Key features:

- 5 - 8 MW floating wind turbine
- 2 - 3.6 MW wave power

Figure 37: Floating Power Plant's P80 platform combining floating wind turbines and a wave energy converter

Wind resources often appear at the same location as wave energy resources, albeit not always equally strong. A recent assessment of a location in Ireland analysed wind and wave profiles over the course of two weeks and found that the resource curves of wave and wind complement each other well. While standalone wind baseload power was 3 MW and standalone wave was 8 MW the combined power had a baseload of 15 MW, a higher value than the simple addition of both sources (Albert, 2020).

However, some effort needs to be placed in the optimal spacing. Marine Power Systems is therefore pursuing three separate technologies in its portfolio: a stand-alone platform with wave energy converter, stand-alone

BOX 6: THYPSO: TIDAL HYDROGEN PRODUCTION, STORAGE AND OFFTAKE

Tidal developer HydroWing is creating a floating platform that houses multiple Tocardo horizontal-axis tidal turbines, an electrolyser and storage tanks. The electricity is not delivered to the grid but used to transform seawater into hydrogen, which can be stored on the unit for up to two weeks.

Challenges with external factors such as grid capacity can be avoided, and time and costs connected to consenting can be saved. Costs are further reduced significantly by the elimination of subsea infrastructure associated with grid connection and by easy deployment. The abundance of seawater in direct proximity also facilitates the hydrogen production process.

Source: *HydroWing, n.d.a*

floating wind units as well as the DualSub, a wind and wave combined unit. In this way, the company can assure the most efficient spacing for a hybrid ocean energy farm. Other developers such as Havkraft only develop the wave energy converter part themselves but design the platform in such a way that it is suited to be integrated in a hybrid wave-wind solution.

Other

There are several other ways to combine different energy sources on one unit. Some wave energy converters have integrated batteries to enable continuation of operation in short periods with less powerful waves, while others are working on tidal turbines that have an integrated electrolyser on their platform. Yet others are moving away from solely developing the energy technologies and are instead focusing on modular multi-purpose platforms that provide space for, for example, wave, wind, solar and beyond.

4.2 Innovative business models: Powering the blue economy

In recent years a significant increase in discussions on the blue economy has arisen. The alarming findings of the IPCC's latest report on oceans (IPCC, 2019) have put an emphasis on the sustainable use of oceans – that is, on the blue economy. In this context the immense potential of marine renewables is often highlighted, as was seen when the European Council called on Member States of the European Union (EU) to commit to quadrupling Europe's offshore renewable energy capacity in the next 10 years (Council of the European Union, 2019).

Ocean energy has the potential to position itself as a leading source of energy to power the blue economy, a sector where both the emerging and established markets have high energy demands. Even though offshore wind is a mature technology and floating PV is gaining momentum and on the pathway of maturity, ocean energy has a chance of competing in this sector due to its better predictability and higher power density compared to other offshore energy sources.

The blue economy consists of many different sectors such as shipping, aquaculture and fishing, offshore oil and gas, ocean observation, tourism, desalination, cooling, coastal protection, etc. They can either function alone or be coupled with each other. Some projections even show that multi-purpose platforms may be common in the future that include many of these sectors, in conjunction with hydrogen electrolysers and solar, wind and ocean energy generators. In such cases, on-site synergies can be used and excess energy can be converted directly into other forms such as hydrogen (DNV GL, 2019).

Powering offshore markets

A significant number of ocean energy developers are already focusing specifically on electrifying one or more of these sectors. Some examples are presented in Table 8.

The potential to power the blue economy with ocean energy is increasingly being recognised. OTEC in particular has high potential to be utilised to generate power not only for the grid but also for desalination, cooling and aquaculture processes. Figure 38 illustrates how this can be done.

Table 8: Examples of ocean energy developers focusing on powering the blue economy

	POWER	DESALINATION	COOLING (SWAC)	OIL AND GAS	AQUACULTURE	SHIPPING/PORTS	AUV CHARGING	Developer
Wave	✓				✓			SINN Power
								AWS Ocean Energy
								WavEC
								Albatern
								Aqua Power Technologies
								GIEC
								Japanese Consortium
Tidal	✓				✓			Sustainable Marine Energy
Wave	✓			✓	✓			Ocean Harvesting
Wave	✓			✓				Wave for Energy
								Hann-Ocean
								Floating Power Plant
Wave	✓			✓			✓	Ocean Power Technologies
Wave	✓	✓						Resolute Marine Energy
								Carnegie Clean Energy
								Wavepiston
								GIEC
Wave		✓						Atmocean
								NRELUS National Renewable Energy Laboratory
Tidal	✓					✓		EMEC (through hydrogen)
OTEC	✓	✓						NIOT OWC
OTEC	✓		✓					Makai
OTEC	✓	✓	✓					Bardot Ocean
								Bluerise
OTEC	✓	✓	✓		✓			Bretagne Ocean Power
Other						✓		GEPS Techno

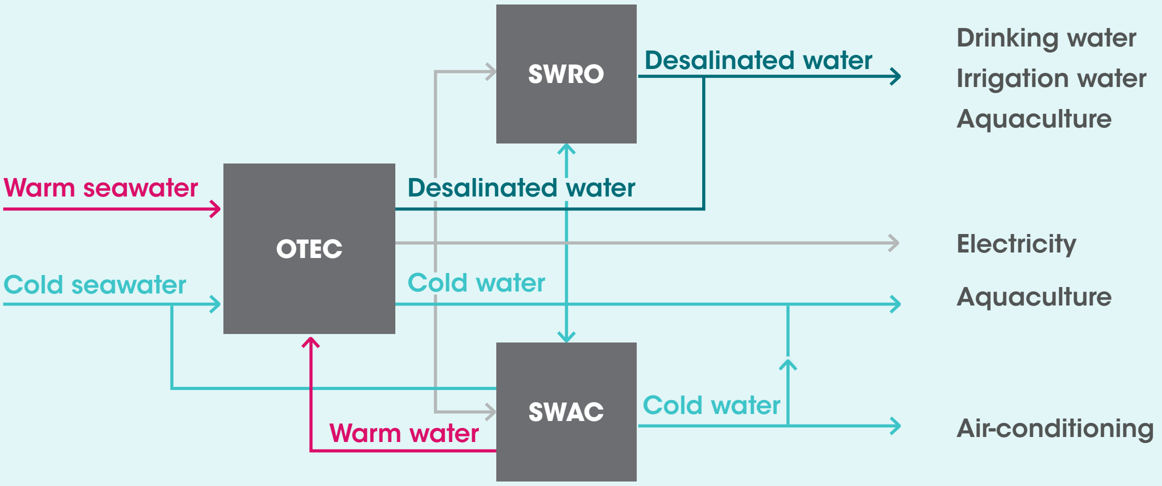
Note: *SWAC = seawater air conditioning; AUV = autonomous underwater vehicle*

Source: *IRENA ocean energy database*

Shipping and port activities

Around 90% of global trade is carried out at sea by container traffic (IMO, 2019). Maritime shipping and port activities are collectively responsible for almost a quarter of all ocean-related industry value, and the sectors are projected to continue to grow (OECD, 2016). Greenhouse gas emissions associated with the shipping sector currently account for 3% of global emissions and were as high as 667 million tonnes in 2017 (IRENA, 2019a). The global trade volume is expected to grow 3.8% in the next five years, and the International Maritime Organization (IMO) stated that if business as usual continued, the shipping sector

Figure 38: Ways of coupling OTEC, desalination, cooling and aquaculture



could grow 26% within the next 10 years, and between 50% and 250% by 2050 (DNV GL, 2019; IRENA, 2019a). Port activities are also expected to grow simultaneously.

Market challenges

Given the goals of the Paris Agreement, decarbonisation is needed in the shipping sector. The IMO has set targets to reduce global greenhouse gas emissions from shipping by at least 50% by 2050 (IMO, 2018). This poses many challenges across the industry, particularly because alternative ways to power the sector are not yet competitively available. In attempts to decarbonise the sector, renewable heat and biomass, synthetic fuels and feedstocks (for example, hydrogen) produced from renewable electricity, direct use of renewable electricity and reduced energy demand, as well as improved energy efficiency are being considered, but obstacles remain (IRENA, 2020c).

Opportunities for ocean energy

Ocean energy can be deployed in proximity to harbours to provide green electricity for ships as well as activities within the ports; this is mainly suited for smaller ports and auxiliary services as the power demand for shipping cannot yet be reached from this technology. Unlike other power sources, however, ocean energy can not only provide clean electricity on shore but is also ideally suited to provide energy offshore. This is particularly interesting in the context of battery-powered shipping and offshore charging stations. Through such charging platforms, range issues for smaller ships can be overcome and auxiliary power can be provided for vessels that spend long times at sea. Ocean energy can further be used to produce green hydrogen, which is highly suited to power ships (see Box 7).

Aquaculture

Overexploitation and climate change have reduced the number of fish available for commercial fishing, and many high-productivity fishing areas are shifting to higher latitudes. Projections show that fish availability will further decrease in the future and the range of species will drastically shrink (particularly in tropical regions) (IPCC, 2019). This has significant impacts on the economies, livelihoods and food security of communities around the globe. To adapt to these issues, aquaculture, a way of domesticating and controlling the growth of ocean species, has gained in significance. In its latest ocean report the IPCC called for more attention towards the aquaculture sector, which is expected to grow 2.1% per year in the next decade (IPCC, 2019). Aquaculture requires energy to power circulation, fish feeders and waste disposal. It also needs power for its infrastructure such as sensors, cameras and light, and for monitoring and maintenance equipment.

Challenges

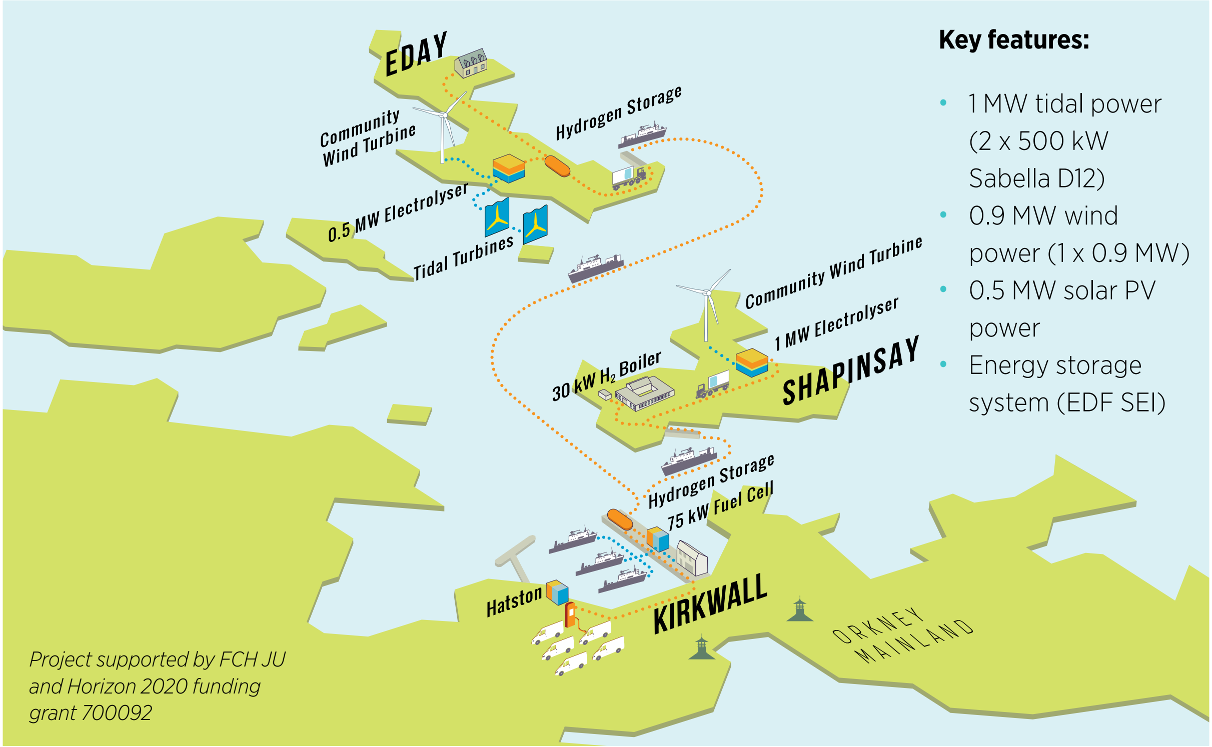
Whereas aquaculture is traditionally conducted near shore, it is now increasingly being moved farther offshore due to increasing sizes and economies of scale. This poses additional challenges and costs as the required energy

BOX 7: BIG HIT ORKNEY

The BIG HIT project in the Orkney Island in the north of Scotland is using electrolysers and innovative approaches with hydrogen storage and distribution to overcome local grid capacity constraints. Green hydrogen is produced using tidal power with a 0.5 MW electrolyser at the European Marine Energy Centre (EMEC) test site on Eday, together with a 1 MW electrolyser on the island of Shapinsay to overcome local wind power curtailment. Green hydrogen is shipped from Eday and Shapinsay to the Orkney mainland town of Kirkwall by hydrogen trailers, with some also used in on Shapinsay for community heating. The hydrogen trailers are moved by ferry between the islands, which distributes hydrogen locally as well as providing significant hydrogen storage buffer capacity.

About 50 tonnes per year green hydrogen can be produced on Eday and Shapinsay from existing curtailed renewables, with a total continuous rated supply capacity of ca. 200 tonnes per year. Additional hydrogen production from tidal energy is expected to be achieved on Eday by the installation of a 1.5 MWh flow battery.

Green hydrogen is used in Kirkwall for local mobility and for a fuel cell at Kirkwall harbour to provide auxiliary heat to a harbour building, as well as auxiliary power for up to three local ferries (cold ironing). There are plans to introduce hydrogen ferries (HyDIME and HySEAS III projects) and in the future for hydrogen planes (HyFlyer) that will enable Orkney to use green hydrogen for decarbonising 'hard to treat' parts of the local energy system. Figure 39 illustrates the envisioned BIG HIT project.



Key features:

- 1 MW tidal power (2 x 500 kW Sabella D12)
- 0.9 MW wind power (1 x 0.9 MW)
- 0.5 MW solar PV power
- Energy storage system (EDF SEI)

Project supported by FCH JU and Horizon 2020 funding grant 700092

Figure 39: BIG HIT project in Orkney

Image source: *BIG HIT Orkney*

BOX 8: GUANGZHOU INSTITUTE OF ENERGY CONVERSION (GIEC)

GIEC is upgrading its Sharp Eagle device to deliver the world's first semi-submersible open-sea aquaculture platform. The Penghu device not only provides wave-generated power to the aquaculture system but simultaneously solves some of aquaculture's typical problems regarding wave and wind resistance and integration of modern equipment.

The technology has been granted patents from China, the EU and Japan, and a first pilot device was built and delivered in 2019.

cannot be taken from conventional onshore grids. Instead most floating farm systems are heavily reliant on diesel and other fossil fuels (FAO, 2015), which is carbon-intensive and leads to high shipping and maintenance costs.

Opportunities for ocean energy

The trend to move aquaculture farther offshore increases its exposure to more energy-intensive sites. Wave energy converters traditionally perform better in higher swells, but novel wave energy converter designs are being developed that also function in less energetic waters, which is where aquaculture has traditionally been deployed. Ocean energy systems are therefore well suited to be located in proximity of aquaculture farms either way. Since wave energy converters often consist of a floating structure that is commonly tethered to the seafloor, they could be directly integrated into the aquaculture system (see Box 8). As the mooring systems are complex and are currently responsible for roughly 10% of a wave energy converter's capital expenditure, sharing the mooring with aquaculture could reduce these costs by up to 50% (OPERA, 2016).

Not only wave energy conversion but also OTEC is well suited for aquaculture as its waste cold water contains valuable nutrients. The many advantages of co-locating aquaculture and ocean energy could lead to ocean energy positioning itself as the leading technology to power such processes.

Desalination

Globally, fresh water accounts for only a small percentage of all available water, and around 1.6 billion people, nearly a quarter of the world's population, have issues with economic water shortage. This means that they lack the infrastructure to access fresh water they need for drinking and agriculture. In addition, a decline in freshwater availability is expected due to climate change (UNESCO WWAP, 2020). Clean Water and Sanitation is therefore a top priority on the agenda of international organisations and is one of the United Nations' SDGs. Today, a large amount of drinking water comes from precipitation, but weather patterns are changing and regions increasingly cannot rely on this source of fresh water anymore. In addition, some areas have limited or no ground and surface water and are forced to draw on other measures to access drinking water.

Desalinating seawater has become a common practice to produce potable water in such areas and is also increasingly being used elsewhere due to its more resilient nature. Desalination is a process of removing salt and other unwanted content from seawater to provide fresh water for human consumption or agriculture. The global desalination market is growing considerably and is anticipated to surpass USD 4.5 billion in capital and USD 5.2 billion in operational expenditures by 2020 (LiVecchi *et al.*, 2019).

Challenges

Reverse osmosis is the main process of desalination. The process of pressurising water to direct it through a membrane against its natural flow is energy intensive. About 36% of the operating expenses in a seawater desalination plant come from its energy consumption (LiVecchi *et al.*, 2019). In addition, capital expenditures are high as water intake pipelines and ocean pumping systems need to be installed.

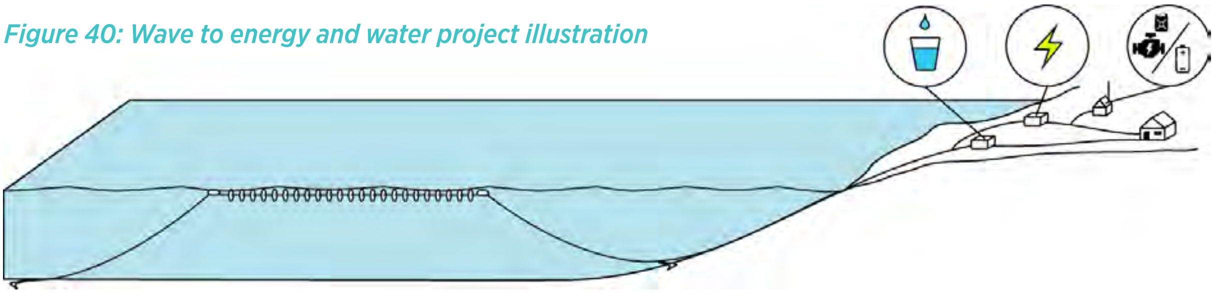
Opportunities for ocean energy

Coastal areas that lack a reliable grid infrastructure often simultaneously lack a reliable drinking water supply – or vice versa. Near-shore ocean energy has the ideal prerequisites to deliver solutions for both issues as they

BOX 9: WAVE TO ENERGY AND WATER (W2EW)

The Horizon 2020 project W2EW aims at demonstrating an integrated system that generates clean energy and fresh water for an insular smart grid (Figure 40). Energy intermittency is managed through water storage. The project is led by a complementing consortium of a wave energy developer (Wavepiston), a sea mooring specialist (Vryhof), a hydraulic pump designer (Fiellberg) and a renewable energy supplier and smart grid developer (Ener.Med). Prototypes at a 1:2 scale have successfully been tested.

Figure 40: Wave to energy and water project illustration



Key Features:

- **Location:** Isola Piana, Italy, 0.21 km2
- **Timeline:** 32 months
- **Budget:** EUR 4.9 million, EUR 3 million from EU grant
- **Wave Energy:** Attenuator, 100-150 kW
- **Desalination:** Reverse osmosis, 15 000 – 30 000 cubic metres

Source: *Henriksen et al., 2019*

Image source: *Wavepiston*

are located where seawater is abundant and in proximity of populated areas. A desalination plant can furthermore provide demand response and thus increase the reliability of local grids (see Box 9).

Wave power plants that have their power take-off units on shore deliver high-pressurised water to shore by default. When reusing this water and using wave energy for the desalination process, costs of both energy and desalination technologies are driven down and additional revenue streams are created. Another way to use ocean energy for freshwater production is being evaluated where the step of generating electricity is skipped altogether as pressurised seawater is directly delivered to the reverse osmosis cycle. This process, known as a wave-powered desalination system, has large potential. Besides omitting energy demand, studies have shown that the costs are comparable.

Costs for producing fresh water through a wave-powered desalination system can be as low as USD 0.7 per cubic metre (Folley and Whittaker, 2009), which is similar to traditional desalination plants but guarantees greater flexibility and less carbon emissions. The US National Renewable Energy Laboratory (NREL) (Yu and Jenne, 2017) adjusted these values for inflation and conducted a similar study more recently to conclude that costs for desalination through wave energy converters without electricity generation are 12% higher than typical costs of water in the same area (California). This is due to the high capital costs for wave energy converters, but as these costs are projected to decrease it will make the system even more viable in the future.

Like wave energy conversion, OTEC also moves water to shore. Depending on the OTEC process, fresh water is produced as a by-product from evaporated warm seawater or it can be obtained through condensation. Other technologies such as dehumidification or low-temperature thermal desalination can also produce fresh water from OTEC (IRENA, 2014c). While 2012 analyses found that combining OTEC with desalination on a 100 MW scale could reduce the costs of fresh water significantly to USD 0.24 per cubic metre (IRENA, 2014c), a number of knowledge gaps regarding OTEC and its costs remain, making it challenging to make accurate cost predictions.

The potential of coupling ocean energy with desalination is also being addressed by NREL's water and power systems unit that focuses on zero-emission desalination, among others. To accelerate development, NREL called for a competition dubbed the Waves to Water prize, where companies, researchers and investors are encouraged to demonstrate desalination systems powered by wave energy.

Cooling (SWAC)

Cooling is an energy-intensive process, and the energy demand for cooling is projected to further increase globally as more people in developing countries have the resources to afford air conditioning and as countries in moderate climate zones increasingly see heat waves due to climate change (IRENA, 2016a). Cooling will be one of the key drivers of electricity demand growth and is expected to triple by 2050 (IEA, 2018).

Challenges

While modern technologies with high co-efficients of performance exist, a vast majority of cooling systems are inefficient and powered by carbon-intensive fossil fuels. In addition, many developing economies lack proper cooling infrastructure as well as the means to import expensive fossil fuels.

Opportunities for ocean energy

Seawater air conditioning (SWAC) is an often-discussed technology that can not only provide efficient cooling but also reduce and balance electricity demand and peak electricity. It is a concept that uses cold water from the depth of the ocean as the refrigerant fluid to cool a freshwater distribution system by means of heat exchangers. The SWAC technology is widely mature, and it already powers air conditioning systems in large parts of entire cities, such as Stockholm. SWAC is very efficient because it uses less electricity than conventional air conditioning, it reduces the need for refrigerants, and by adding a pumping station and a water intake pipeline, it is easily compatible with conventional, already installed cooling units. SWAC can provide up to 90% savings in comparison to conventional air conditioning's electricity costs (Ocean, 2020).

The water that is used in the electricity generation process of OTEC can be re-used in an air conditioning system because smaller temperature differences are needed for SWAC than for OTEC. In current SWAC installations water is solely pumped up for cooling purposes and not combined with OTEC. By combining the two technologies to produce power and provide air conditioning, the efficiencies of both technologies can be further enhanced, and installation, deployment, power and maintenance costs can be shared, as OTEC uses pumping stations and water intake pipelines by default. Adding a SWAC unit could create additional revenue streams for OTEC and can thereby make the technology more feasible and aid its commercialisation. This hybridisation could even be taken further to produce fresh water or support aquaculture (as presented in Figure 38).

Another way of coupling cooling with ocean energy has been demonstrated by Microsoft and EMEC in Orkney where a data centre is directly cooled through ocean water with the aim to be powered by wave and tidal energy.

BOX 10: OCEAN POWER TECHNOLOGIES (OPT)

OPT's PowerBuoy harvests ocean energy from waves with a focus on supplying continuous power to nearby equipment, mainly of the oil and gas industry. It has partnered with oil and gas companies such as Eni and Premier Oil. The latter installed a 3 kW OPT PowerBuoy wave energy converter at the Huntington field in the North Sea where a trial is ongoing to power a surveillance system at the abandoned oil field. The buoy is equipped with a small battery to balance supply and demand.

Key features:

- Modular and scalable
- 8.4 kWh/day
- 3 kW peak
- 50 kWh battery

Oil and gas

The burning of oil and gas is not only carbon emission intensive, but their extraction is energy and carbon intensive as well, with gas or diesel generators often being used to produce and process oil and gas. This makes oil and gas extraction responsible for the largest share of offshore carbon dioxide (CO2) emissions (DNV GL, 2019). Although there is a global effort to decarbonise the world's most energy-intensive sectors, oil and gas demands have continued to rise and are predicted to keep doing so (IRENA, 2020d). To nonetheless comply with emission targets, countries and companies are seeking to decarbonise the extraction, production and transport processes. The Norwegian petroleum company Equinor, for example, has plans to reduce greenhouse gas emissions for its offshore fields and onshore plants 40% by 2030 and to reach net zero by 2050 (Equinor, 2020).

Market challenges

Decarbonising the oil and gas extraction sector has been challenging due to the remote nature of oil and gas wells. On occasions, subsea cables have been installed to reduce a country's carbon footprint by delivering onshore renewable energy to the platforms (for example, in Norway), but the installation of such cables is complex and costly.

Opportunities for ocean energy

To avoid long subsea cables a more economic option is to generate power locally. Ocean energy fulfils the requirements to be used in such conditions, and some wave energy developers have already started to specialise in providing power for this specific sector (see Box 10). Commonly used technologies are point absorber buoys, but other novel uniquely purpose-designed technologies are emerging as well. Currently such ocean energy focuses on providing power to monitoring and other supplementary devices (for example, for data analysis) located on and around oil and gas platforms. With a scale-up and wider deployment of ocean energy technologies, it can be expected that ocean energy will be utilised to provide power directly for the extraction process in the future.

Others

There are several other emerging offshore markets within the blue economy that could be powered by ocean energy. Table 9 presents a list with some further possibilities.

Table 9:Examples of ocean energy developers focusing on powering the blue economy

Market	Role of ocean energy
Coastal tourism	Deliver energy to different sectors in the tourism industry
Hydrogen	Power electrolysers to produce green hydrogen
Marine algae	Deliver power for marine algae production to, for example, make biofuels more carbon neutral
Data centre	Provide energy to run data centres (see Box 11)
Ocean observatories	Power observation sensors, subsea inspection vehicles, navigation markers, etc.
Underwater vehicle / autonomous vehicle charging	Charge underwater docking stations and recharge vehicles
Seawater mining	Pump seawater, power machinery for mineral extraction and power monitoring equipment
Disaster relief and recovery	Provide quick and scalable power in emergencies

BOX 11: MEYGEN SUPERCOMPUTING HUB

As part of the MeyGen project (see Box 1) a supercomputing hub will be developed in the north of Scotland to deliver power to the first ocean-powered data centre. With the help of a USD 2 million government grant, MeyGen plans to combine its tidal power with onshore wind power and other renewable energy sources to create a virtual 80 MW power plant. MeyGen has completed a concept study and is now working closely with Celtic Norse to develop a subsea fibre optic cable and is exploring international fibre optic cable options.

Using synergies among offshore markets

In addition to physically syncing offshore technologies, ocean energy can benefit from synergies through knowledge transfer. Several offshore markets such as oil and gas and offshore wind power are much further developed and have overcome barriers similar to those that ocean energy is facing today. Established actors in these sectors not only possess knowledge in engineering and development, but also have experience across the entire value chain, for example in resource and impact assessment, supply chain, installation, operation, etc. Such experience can also be used to influence standardisation, as was seen in the development of offshore wind standards. Offshore wind's standardisation for foundations and platform structures as well as health and safety aspects in particular were heavily influenced by the oil and gas sector (IRENA, 2018a).

In section 2, numerous barriers and challenges for the wider deployment of ocean energy were identified. By using synergies between sectors, there is potential to mitigate challenges and reduce risks in all identified categories. Table 10 presents potential ways in which the four categories Environmental and Social, Technology, Infrastructure and Regulatory and Policy could be positively impacted by leveraging synergies. The category Economic and Market is not included in the list, as the four presented areas all lead to lower capital costs and lower LCOE; it thus represents the desired outcome and not a means of reaching it.

Ocean energy developers can benefit from such synergies on three levels: by forming partnerships, using in-house synergies and transferring knowledge and procedures (Figure 41).

Partnerships

By forming partnerships or building joint projects the costs can be reduced significantly and ocean energy can leverage extra value. An example is the Cooperative Research Centre in Australia that has brought together experts from the seafood industry, renewable energy and offshore engineering fields to do joint research in novel offshore sectors such as ocean energy. Another example is the partnership between the wave energy converter developer Bombora and the Marine Energy Engineering Centre of Excellence (MEECE), a collaboration itself between ORE Catapult and universities. MEECE is highly active in the offshore wind industry, and together with Bombora it aims to investigate the feasibility of co-locating floating wind and wave systems. Similar arrangements between wind and tidal energy have been made for the MeyGen plant in Scotland to improve utilisation of grid networks.

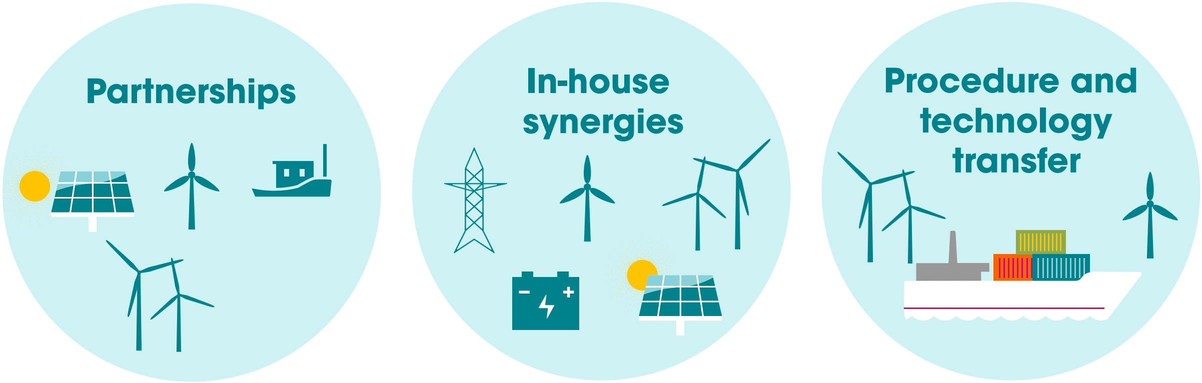
In-house synergies

Another way to leverage synergies is to use in-house synergies. It can be interesting for established offshore companies to broaden their portfolio to include ocean energy. This is particularly the case for the offshore wind sector, where 42% of the costs could find synergies with wave and tidal (Magagna and Uihlein, 2015), or for the offshore oil and gas sector. An example for such a market entry is the oil and gas provider Eni, which is setting up a separate company that fully focuses on developing wave energy converters. Other examples of in-house synergies are DP Energy, which is active in the tidal, wind, solar and storage sector; Guinard Energies and ORPC, which both provide adapted versions of their hydrokinetic turbines for tidal as well as run-of-river applications; and Andritz, which provided tidal turbines as well.

Table 10: Potential fields of co-operation between ocean energy and other offshore sectors

Technology	Exchange expertise on materials that sustain the harsh offshore environments Share R&D processes and best practices Use subsea sensors and monitoring equipment as well as maintenance equipment from other industries Use generic components such as mooring, balancing, foundation, subsea cabling, power take-off, etc., from other industries (e.g., oil and gas or wind) Collaborate to develop solutions for challenging components (e.g., floating structures in deep water) Use standardised parts from other industries such as shipping
Infrastructure	Share vessels and port space for transport, deployment, installation and maintenance of the technology Share knowledge on impact on other marine infrastructures from, for example, fisheries and shipping Use supply chain of other industries, for example turbine manufacturing from the automotive industry Share grid connection, cables and subsea structures with offshore wind and grid integration practices Use joint resources to develop an internationally interconnected grid and increase local grid capacity Exchange expertise on resource mapping, for example co-location with other offshore technologies such as offshore wind and wave
Regulatory and policy	Use key regulatory frameworks and policies of other industries Create joint regulatory frameworks and policies (e.g., feed-in tariff, auctions, etc.) Adapt standardisation practices of other industries
Environmental and socio-political	Share knowledge on potential environmental impacts Exchange expertise on the identification of stakeholders and share contacts of relevant stakeholders to engage with Raise public awareness Establish international governance structures of ocean space

Figure 41: Synergies among offshore markets



Transferring knowledge and procedures

Using expertise or technologies from other sectors is a third way of using synergies. Examples include Floating Power Plant (see Box 5), which is using proven standard mooring technologies from the oil and gas industry, and Orbital Marine Power, whose manufacturing processes are analogous to shipbuilding procedures. A shipbuilding company is also involved in Eni's new wave energy division. Another example not directly from the offshore industry is the tidal developer Minesto (see Box 2), which was built as a spin-off of an aircraft manufacturer and incorporated expertise from aviation into the new industry.

International co-operation within IRENA

In 2020, in response to a call by its global membership, IRENA created collaborative frameworks that serve as an effective platform for increased dialogue and co-ordinated action among its Members. A new Collaborative Framework on Ocean Energy / Offshore Renewables brings countries together to identify priority areas and actions and foster international collaboration to understand the role of ocean energy and offshore renewables in the energy transition, while ensuring its widespread deployment in the future.

This collaborative framework has been endorsed by several countries from IRENA's membership and is now operational. The platform for collaboration aims to advance in areas relevant to offshore renewables including technology development, research and innovation, market incentives, regulatory frameworks and sustainability. It shows IRENA's continued commitment as a leading global platform to share knowledge and support governments in pursuit of the deployment of renewable energy.

4.3 Innovative business models: Powering islands

Another pathway to accelerate the commercial deployment of ocean energy is expanding into other markets to demonstrate and build confidence around ocean energy technologies. Islands and remote coastal areas present such markets because they have smaller entry challenges than conventional markets, have ideal geographical preconditions and can benefit from the innovative business models and hybrid renewable electricity generating systems as presented in sections 3.1 and 3.2.

Resource potential

Islands set ideal preconditions for ocean energy first and foremostly because they are surrounded by water. In addition, as presented in Figure 42, all SIDS and many other islands are located in tropical regions.

Wave energy resources are constantly available in tropical regions, with theoretical annual average powers reaching up to 20 kW per metre near the coast and up to 30 kW per metre in deep waters (Felix *et al.*, 2019). Numerous developers are now working on devices that need lower wave power density, and some existing wave energy converters are being adapted to operate in tropical conditions. Wave resources that are suited for wave energy converter deployments can therefore be found in proximity to most SIDS and tropical islands. Tidal resources are constrained geographically, but tidal streams are particularly strong around insular formations as they are further enhanced by the topography of archipelagos. As seen in Figure 42, SIDS are located in regions between latitudes of 30 degrees north and 30 degrees south, thus ideally suited for OTEC. Although salinity levels are particularly high in tropical regions, depending on the island there may be a lack of large freshwater bodies entering the oceans to fully harness this potential.

Drivers

Islands have numerous unique characteristics that go beyond their geographical preconditions, and ocean energy similarly faces unique challenges. Figure 43 outlines the major characteristics of islands and ocean energy (upper section) that, under suitable grid connection conditions, can be drivers to unlock benefits for both the islands and the ocean energy market and industry. The benefits that arise can be categorised into four groups of drivers: energy costs, blue economy, decarbonisation and energy access/security, which are each presented here in more detail.

Costs

Due to the remote location of many islands and the lack of natural fossil fuel resources, there is a need to import refined petroleum products over long distances. Through transport, volatile foreign markets and a lack of alternative power plants, electricity costs are therefore often much higher on islands than elsewhere. SIDS, for example, are among the places with the highest electricity costs worldwide, ranging from USD 0.30/kWh to more than USD 1.00/kWh (IRENA, 2017a). Ocean energy currently has an LCOE between USD 0.2/kWh and USD 0.6/kWh (see section 1.1), which means it can already compete and even undercut the common electricity prices in such locations. With growing deployment and decreasing costs for ocean energy it can quickly provide added value through affordable energy to the islands. In addition, ocean energy, once deployed, has few operating costs as no fuel is required. Sudden spikes in fuel costs can thus also be avoided, and communities can become more resilient to oil price shocks.

Blue economy

Numerous blue economy sectors, as described in section 3.2.1, are particularly important on islands. About 71% of SIDS are already at risk of freshwater shortage (UNESCO-IHP and UNEP, 2016), and the freshwater supply is projected to decrease further due to changing climate patterns and increasing demand (UNESCO WWAP, 2020). In Tuvalu, for example, 14% of the population was left with no access to fresh water in 2011, when there was no rainfall for six months (Gheuens *et al.*, 2019). To avoid such scenarios and expensive freshwater imports and to allow islands to be more resilient, desalination plants are of high relevance.

Many islands, predominantly SIDS, are located in tropical regions where there is a high need for cooling and the number of air conditioning units is growing significantly. In Mauritius, for example, air conditioning units grew by over 90% in only three years, and they account for 30% to 50% of electricity consumption in buildings (Elahee, 2014). Not only the cooling of air but also refrigeration, particularly for seafood, is important, leading to higher energy demands.

Desalination and cooling can easily be coupled with ocean energy to deliver additional benefits. In addition, fishing and aquaculture are often the main pillars of

Figure 42: Map of small island developing states (SIDS)

Boundaries and names shown on this map do not imply any endorsement or acceptance by IRENA

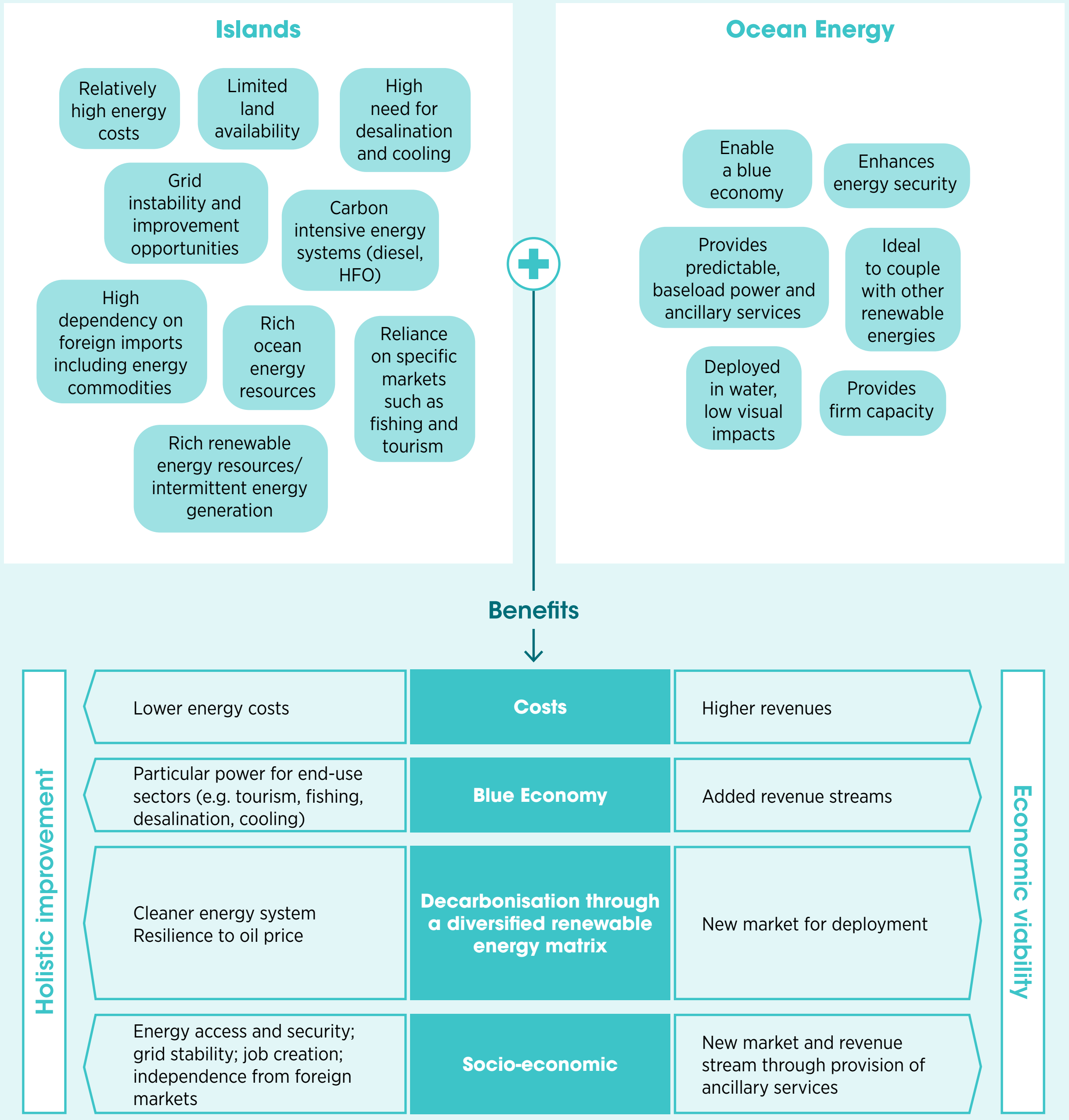
Source: *IRENA, 2018b*

local economies, and the livelihoods of large parts of the population are directly or indirectly dependent on it. Another major pillar of SIDS' economies is tourism, which can account for over 25% of the gross domestic product (GDP) (UN, 2017). Ocean energy not only can deliver the needed electricity to power such industries, but as a carbon-free energy source it could play a role in mitigating climate change, thus indirectly counteracting fish die-off related to climate change and assisting the fishing industry in a sustainable manner.

Decarbonisation through a diversified renewable energy mix

Island energy systems are in some cases 100% reliant on diesel power and/or heavy fuel oil, generating large amounts of CO$_2$ emissions (IRENA, 2018b). At the same time, SIDS are highly exposed to changing climate patterns and are environmentally and socio-economically vulnerable to disasters caused by climate change (Gheuens et al., 2019). SIDS additionally have broadly

Figure 43: Ocean energy on islands



available renewable energy resources, particularly those that support wind and solar PV (IRENA, 2017a). Both resources are ideally suited to be coupled with ocean energy to form hybrid renewable energy systems as presented in section 3.1. Ocean energy can thus play a significant role in decarbonising islands' electricity supplies. Moreover, since ocean energy offers firm capacity to the power system, it is a suitable means for increasing the uptake of variable renewable energy sources, such as solar PV and wind.

Energy access and grid stability

In addition to the technical and environmental benefits, developing countries especially have much to gain on a socio-economic level as well. Long-term energy security and a stable grid infrastructure raises the quality of life of local communities in terms of safety; access to health care, education and information; storage of food, etc. Businesses lose some of their competitive disadvantage towards international markets, and opportunities for new businesses arise. Jobs are created, and women in particular can be empowered through skills development, as renewable energy sources employ a larger share of women than conventional energy sources (IRENA, 2019b). Due to the submerged nature of many tidal and wave energy devices, they do not visibly impose landscapes, indirectly aiding the tourism industry.

Everywhere but specifically on islands, ocean energy should not be viewed as a competition to conventional renewable energy but as a reliable, predictable complementary system, and it could even be delivered together with other renewable energy as a "package deal".

Deployment

Based on IRENA findings, a considerable share of ocean energy is already deployed in and around islands, most prominently in the major ocean energy test sites in the islands of Hawaii in the US and in Orkney, Scotland. In addition, further islands in developed countries are or have been used to demonstrate wave and tidal devices. They include the Shetland Islands in Scotland, Texel in the Netherlands, Ushant in France, Roosevelt Island in New York City in the US, Goto Island in Japan and the Mediterranean islands of Crete in Greece and Pantelleria in Italy. In addition, projects have been announced in sites in the Atlantic Ocean such as the Canary Islands, Faroe Islands and Cabo Verde, in islands off the coasts of Australia, China and the Republic of Korea, and in the Indian Ocean. These projects often serve as demonstration projects to showcase ocean energy use in islands with an increasing focus to later deploy similar systems in developing countries and SIDS.

Less-developed islands have additional characteristics that make a case for ocean energy. They include their heavy reliance on fossil fuel imports, their often-recurring stability and reliability issues in the grids, and plans to integrate variable renewable energy into their electricity mixes (IRENA, 2018b). This is particularly the case in SIDS, a group of 57 islands that share geographical characteristics and have similar economic and environmental challenges. Therefore, interest is arising from such locations, and feasibility studies, resource assessments and/or cost analyses have already been conducted for some islands.

The Pacific Community, including Fiji, Kiribati, Maldives, Marshall Islands, Nauru, Palau, Tonga, Tuvalu, Samoa, etc.,

BOX 12: SAN ANTONIO, ISLAND OF DALUPIRI, NORTHERN SAMAR, PHILIPPINES

Oceantera – made up of OceanPixel (Singapore and the Philippines) and Aquatera (UK) – and the Filipino tidal stream specialist Poseidon Renewable Energy Corporation propose to deliver renewable energy to roughly 9 000 residents and businesses in Dalupiri Island (San Antonio) in the Philippines. The 963 kW diesel generation system will be replaced with a hybrid renewable system, saving roughly 32 100 litres of diesel per month. The hybrid system is expected to deliver cheaper electricity, reduce government subsidies, adapt to climate change, and increase energy and food security and disaster resilience.

Key features:

- Tidal stream
- Solar PV
- Energy storage
- Smart energy management system

and the Caribbean Community (CARICOM), including Antigua and Barbuda, Barbados, Grenada, Jamaica, Saint Lucia, Saint Vincent, and Trinidad and Tobago, have shown a particular interest, but also Atlantic Islands such as Cabo Verde and overseas territories such as Aruba, French Polynesia and New Caledonia. Larger islands such as Indonesia, Jamaica and the Philippines (see Box 12) have also started activity in the ocean energy field. These studies are conducted by a wide range of different stakeholders including local and foreign governments, energy providers and ocean energy developers. France, for instance, is interested in different ocean energy sources for some of its oversea territories, as its defence contractor is looking into OTEC in Martinique and Réunion. Another OTEC example is the Republic of Korea's state-run research centre KIOST, which is deploying an OTEC plant, funded by the Korean government, on the Pacific island of Kiribati (see Box 3).

Challenges

With the deployment of ocean energy on islands, new challenges arise. Some were not previously mentioned in section 2 as they pose challenges on islands exclusively, and others play a particularly important role on islands. Notably, these challenges do not apply to all islands to the same extent and are more relevant for SIDS. While all challenges outlined in section 2 are also present for ocean energy deployment on islands, Table 11 describes those of major importance on islands specifically.

The risks concerned with infrastructure, supply chain and resources are preconditions and need to be taken care of before beginning an island project. Most of the challenges can be mitigated by employing strategies and engaging all stakeholders, not least the communities themselves, early on. It is important to look at each island separately, to understand their needs, current economies and infrastructure and deal with the implementation case by case. A critical challenge is resource assessments; they are the foundation to any ocean energy project, but resources to conduct such assessments are often not readily available on SIDS. Several SIDS, including Belize, Fiji, Samoa and the US Virgin Islands, have conducted or are planning to conduct resource assessments with feasibility studies in their waters. The Marine and Coastal Biodiversity Management in Pacific Island Countries (MACIBO) has developed a toolkit to assist Pacific countries in the process, but struggles of adequate funding to obtain data remain. Section 4.2.3 outlines these challenges in more detail and presents pathways to overcome them.

4.4 Innovative business models: Ocean energy for coastal protection

Coastal protection could be coupled with ocean energy technologies, offering a new multi-faceted business case addressing multiple societal issues of climate mitigation (energy generation) and adaptation (improve water safety and water quality), including the development of new infrastructure.

Breakwater dams: Demonstrated integration of coastal protection and ocean energy are breakwater barriers to protect harbours from wave impact, such as the pilot projects in Mutriku in Spain and in Port of Civitavecchia in Italy. A large part of the capital expenditure of a wave energy project is offset as part of the civil cost of the breakwater barrier.

Storm surge barriers: With increasing sea-level rise, there is a growing need for smart and affordable coastal protection solutions. Coastal structures, such as dams and storm surge barriers, can be used to integrate tidal turbines and shoreline-integrated wave energy converters and provide space for solar and wind power plants. A recent study (Deltares, 2019) revealed that 461 locations worldwide are suitable for dam-integrated tidal energy, based on the fact that these areas 1) are prone to increasing risk of flooding with future sea-level rise and increasing storms, 2) have tidal range availability, and 3) have a population density with high energy needs. In 2015 a consortium led by Huisman and Tocardo installed an array of five turbines in the opening of the Eastern Scheldt Storm Surge Barrier (the Netherlands). Despite the bankruptcy, Tocardo recently re-acquired the plant and has re-commissioned it (Tocardo, 2020). The Dutch Government (Managing Authority for Waterworks) is preparing a tender to open the Brouwersdam and realise a tidal power plant in order to improve the water quality of the Grevelingen Lake and at the same time provide pumping capacity to mitigate sea-level rise.

Bridges: Dutch project developer TidalBridge is developing a floating bridge in Indonesia including a 20 MW tidal power plant. The innovative financing mechanism for the civil works (low interest rates through international donor funding) allows a relatively favourable financing for the tidal power plant.

While the creation of additional revenue streams through innovative business models can increase the value of ocean energy technologies, it is still of absolute importance that the LCOE is reduced quickly to reach cost parity with other renewable energy sources. Financial instruments that support capital and revenue are of key importance to lower the LCOE and increase ocean energy's viability (section 4.1). To attract investments of such instruments, risk reduction, which can be done through standardisation, assessment frameworks or thorough resource assessment, are crucial (see section 4.2).

Table 11: Challenges of ocean energy deployment on islands

Challenges and Barriers	
Technology	Manufacturers target relatively large devices; such high capacities may not be needed on small islands
	Little available information on local geotechnical seabed conditions
Infrastructure	Low-quality grid infrastructure (new / improved infrastructure needed)
	Dispersed market
	Lack of trained personnel
	Limited energy services and deployment and maintenance equipment
	Constraint or non-technical local supply chain
	Challenging to transport components and equipment to the remote islands
	Lack of data, knowledge and resources for resource and environmental assessments
Financial	Lack of capital for high upfront costs
	High operation costs due to remoteness
	Highly subsidised fossil fuel plants
Regulatory and Policy	Consent delay and high bureaucracy in permissions
	Lack of legal framework and policies
	Revenue support mechanisms often not available
Environmental	Little experience with seismic activity in the area
	Concerns regarding megadiversity that prevails in many tropical regions
Socio-political	Weak awareness and knowledge of technology by all involved stakeholders (governments, end users, investors, etc.)
	Lack of social acceptability and community readiness
	Potential issues with sharing oceans, particularly interference with the local fishing industry


EQUATOR
REMEMBER
BLUE WAVE

5. PATHWAYS AND TOOLS FOR REDUCING LEVELISED COST OF ELECTRICITY

5.1 Blended finance: Financial instruments for ocean energy

Although technological improvements will help to reduce costs, at first investment in research, development and demonstration needs to be available to make the necessary progress. In the recent past there have been several high-profile bankruptcies of ocean energy developers that can be attributed mostly to financial issues in the deployment phase. Major challenges relate to the high upfront costs, even for the more mature technology of tidal range. The latest and largest such installation at Sihwa Lake in the Republic of Korea cost USD 560 million, and the proposed Swansea Bay project in Wales is estimated at USD 1.7 billion. For comparison, the Tengger Desert Solar Park costs almost the same as the Korean plant but can generate more than triple the electricity (Kimani, 2020) .

Financing ocean energy technologies can be done through different mechanisms according to the technology stage. In the R&D phase, money is often acquired through capital support schemes such as grants or through special tools such as stage-gate metrics. The same funding instruments are also necessary in the consecutive stages, early testing and demonstration phase. The phase between demonstration and first commercial deployment, also known as the valley of death, is critical for innovations and start-ups. Large sums of money have been spent but no real revenue has returned at this stage, posing challenges to survivability. This is one of the stages where standardisation can play a significant role in decreasing costs.

Capital support financing is also needed, and revenue support agreements also play an important role because the LCOE of ocean energy is still higher than electricity market prices. With increased equity and loan uptakes, the LCOE increases even further due to the required dividends and interests. For all stages of maturity, minimising the perceived risks can help greatly to secure any type of financial support, which can increase a project's viability and help to attract more investment, particularly through private investors and loans.

The use of different financial instruments according to the maturity level of technologies can also be observed when looking at maturity levels of markets. Solar PV and onshore wind, for example, are largely funded by commercial debt and private equity, while less mature markets are more reliant on grants and concessional finance (IRENA and CPI, 2018). In general, however, blended finance should be utilised, since each instrument reduces the total financing, and the application of one instrument helps to attract the next one. Project finance is the best mechanism for ocean energy, and it is strongly reliant on blended finance due to the interlinkage between the issuing of loans and strong future cash flows.

A financial institution only lends money if a company has a strong credit worthiness, or certainty that a loan can be repaid. Traditionally this certainty is given through collateral (*i.e.*, if the borrower cannot repay the debt, the financial institution can seize the collateral) or through a strong balance sheet (*i.e.*, the partner is strong and can be trusted). The challenge with ocean energy is that neither of these creditworthiness types apply, as a tidal turbine or wave energy converter has little value to a lender, and the companies are mostly small-and-medium enterprises or start-ups with little previous activity to prove their creditworthiness. In project finance, however, rather than using the turbines themselves as collateral, the projected future cash flows are used to make a deal with the bank. Therefore, revenue support instruments to improve cash flows are needed to secure capital investments and to deliver an ocean energy project.

Blended finance, additionally, not only mixes several mechanisms, private and public, with different parties and different expertise to advance an innovative technology, but also secures wider philanthropic benefits that can in turn mobilise larger flows of capital. Ocean energy has the potential to play a significant role in mitigating climate change and helping to achieve a number of other SDGs. Therefore, it is highly eligible for such schemes. Scotland, for example, introduced its Energy Investment Fund following the publication of the Scottish Energy Strategy and Climate Change Plan as a tool to mitigate climate change effects.

Many such instruments already exist, and are numerous within the EU, but they need to be enhanced to better target ocean energy projects and allow a balanced profit-and-loss statement. Some tools and mechanisms that can help balance the equation – reducing costs on the investment side and increasing cash flows on the revenue side – are presented in Table 12. This section focuses mainly on measures to reduce expenses through capital support and to increase income through revenue support.

Data and funding, however, remain limited, and annual investment in new ocean energy assets (*i.e.*, in OTEC, tidal energy and wave energy) has fluctuated widely, ranging between USD 4 million and USD 445 million, with peaks above USD 100 million in 2007, 2009 and 2014 (BNEF, 2020). Since 2013 only 0.02% of annual investment in renewable energy assets has been directed towards ocean energy technologies (IRENA and CPI, 2020). Between 2003 and 2016, 63 investment commitments to ocean energy projects reached financial close. Around two-thirds of the commitments were for wave energy projects, while the remainder was almost entirely for tidal energy projects. Moreover, 75% of these projects were concentrated in six countries: Australia, China, Portugal, Spain, the UK and the US (BNEF, 2020).

Unlike with other renewable energy technologies, however, asset finance (*i.e.*, investment for the construction of new renewable energy assets) represents only a small portion of investment in marine energy. The majority of investment in the sector comes in the form of early-stage finance, including venture capital, government grants (for example, for R&D) and equity investment from engineering majors, showing that the industry is still at a very early stage of development (FS-UNEP/BNEF, 2020).

Capital support

Due to the commercialisation gap of ocean energy and the associated lack of incoming cash flows, capital support is needed in the early stages. Such capital is awarded through three main financial instruments. Equity is the real assets of a company, grants are awarded to specific projects to support a technology, and, when equity and grants are not sufficient, debt, often as loans from financial institutions, is required. By 2018, USD 1.6 billion had been allocated to ocean energy projects through capital support schemes within Europe (Ingmarsson and Hüffmeier, 2019). In a recent survey of 21 ocean energy organisations, less than half reported that they sought commercial debt, and over a third of them were rejected due to market uncertainty, lack of revenue support and early technology stage (Pirttimaa and Cagney, 2019).

As with comparable new industries, grants and private finance also make up most of the funding of ocean energy. With maturing technologies and decreasing risks, it can be expected that an increasing share of funding

Table 12: Ways to balance the profit-and-loss equation

Investments: reduce capital costs	Operations: increase income
CAPITAL SUPPORT • Grants • Equity • Loans	**REVENUE SUPPORT** • Power purchase agreements • Feed-in tariffs • Feed-in premiums • Tenders and auction-based instruments • Contracts for Difference • Quota schemes • Certificates, for example renewable obligation certificates or renewable energy certificates

will come from financial institutions in the form of debt. The instruments for financing options can be publicly or privately funded or through joint programmes. The instruments also do not necessarily have to be separated, but there are also a number of mechanisms that include grant, loans or equity. Ocean energy projects profit mainly from support mechanisms specifically designed for the technology or for innovations, but climate finance (for example, the Green Climate Fund, Global Environment Facility, Climate Investment Funds, green bonds and national clean investment funds) is another interesting and increasingly common angle to consider.

Grants

Grants are funds that do not need to be repaid, and they displace capital that would otherwise need to be acquired elsewhere; as such, they reduce financing requirements. Grants are often awarded by governments or foundations and usually aim at helping certain projects, technologies or entire industries overcome the valley of death. They are thus particularly important for reaching the deployment phase but can also play significant roles in the early stages of development. They are central for innovative technologies; however, more mature renewable energy sources, such as

Illustration by Ling Ling Federhen

solar PV or wind, also receive near-negligible shares of their financing through grants (0.5% between 2013 and 2016) (IRENA and CPI, 2018). In addition to providing funds to allow a project to move forward, grants are important tools to de-risk projects and as such catalyse investments and improve the case for loans.

In addition to intergovernmental organisations (see Box 13), national and regional governments can play a major role in providing grant opportunities for ocean energy. The UK, and Scotland and Wales in particular, have continuously provided funding opportunities for wave and tidal energy, which played a central role in the UK becoming a leader in the field. Scotland, hosting the wave and tidal test centre, EMEC, has taken significant steps to allocate funding to ocean energy developers. The Marine Renewable Commercialisation Fund of the Scottish Government was a grant scheme that awarded USD 24 million in the form of capital support to assist ocean energy in the path towards commercialisation between 2013 and 2016.

Other funds in the UK are allocated within larger funding schemes such as the Scottish Government Energy Investment Fund, which has a marine energy cluster through which it funds the Wave Energy Scotland technology programme (USD 52.8 million invested in 80 projects so far). It calls on different fields of innovation, from control system or power take-off technologies for wave energy converters to academic research. Additionally, the Saltire Tidal Energy Challenge Fund, a competition by the Scottish Government, awarded USD 13.3 million in grants and loans to tidal developers with the aim of reducing tidal energy's LCOE. Among others, Orbital was able to secure USD 4.5 million.

Other countries with high ocean energy activities also have or had such schemes in place. They include Ireland's Ocean Energy Prototype Development Fund (over USD 22 million), China's Special Funding Programme for Marine Renewable Energy (USD 196 million since 2010) and the Basque Region's aid programme that invests in the demonstration and validation of emerging marine renewable energy technologies.

Most of the regional and national funds have a similar way of operating as the European funding opportunities and issue calls for relatively specific R&D, innovation, demonstration or prototyping activities. Another way of providing grants is by holding contests and giving away funding as prizes. The US Department of Energy is particularly strong in that regard. It previously issued the Wave Energy Prize (USD 1.5 million) and is currently issuing the Waves to Water prize (USD 2.5 million), the Powering the Blue Economy: Ocean Observing Prize Series (total USD 3 million) and the Marine Energy Collegiate Competition to find ocean energy solutions to power the blue economy.

Equity

Capital investment and sponsoring typically falls under the category of equity, which is the actual ownership of assets. Unlike loans and grants, money is not just handed over to a company but is used to buy stocks and with it voting rights and shares of future returns. In more advanced stages of ocean energy projects, there are higher funding needs that can often not be met by grants alone, and equity is therefore a crucial element to project financing. Equity can come from players of all sectors, but a study among ocean energy organisations concluded that public authorities and agencies and institutional investors are the main source of equity in ocean energy (Pirttimaa and Cagney, 2019). Examples include France's Brittany region, which participated in Sabella's tidal deployment, France's Normandy region, which partnered with SIMEC Atlantic for the Raz Blanchard projects, and Wales in the UK, which supported Marine Power Systems in the development of its device (ETIP Ocean, 2019).

Securing equity without direct government involvement can be very challenging, and the absence of private or public investors has often marked the end of a company. One option to help secure investors is through collaborative investment platforms. The EU, for example, has numerous platforms to help attract private equity and improve access to capital. Its European Institute of Innovation and Technology (EIT) establishes Innovation Communities that connect businesses, research and universities and provide investments. Among the EIT's that are relevant for ocean energy is the EIT InnoEnnergy, which supports sustainable energy innovations and holds stakes in Minesto and CorPower, and the EIT Climate Knowledge and Innovation Communities, promoting innovation and knowledge to lead towards a zero-carbon economy.

Furthermore, under the EU's Horizon 2020 scheme the EU and European Development Bank built the InnovFin scheme, which offers different financing tools including equity to innovative first-of-a-kind

BOX 13: EUROPEAN GRANTS FROM HORIZON 2020 AND INTERREG V

Horizon 2020

Several local, national and European-level grant funding opportunities are available for ocean energy. The largest funding scheme is the EU's Horizon 2020 programme. This is the current European Framework Programme for Research and Technological Development, which supports research and innovation with a total budget of USD 90 billion and often also attracts large amounts of private investment money. In the time frame 2021-2027 it will be succeeded by the Horizon Europe programme with an even higher proposed budget of USD 110 billion. Within the Horizon 2020 programme many funding opportunities have been created for ocean energy, amounting to USD 210 million in total funding (ETIP Ocean, 2019).

Numerous ongoing Horizon 2020 grants support specific ocean energy project developers in reaching commercialisation through deployment support (e.g., arrays and demonstration) and R&D support in a specific technical field (e.g., control system, breaking modules, power take-off system, generator, mooring, performance). These programmes include FloTEC, CEFOW, ELEMENT, WaveBoost, TIPA, EnFAIT, PowerKite, MegaRoller, DEMOTIDE, IMAGINE and UPWAVE. They are clustered under broader projects such as SME (aimed at small and medium enterprises to foster innovation), RIA (to assist research and innovation action to show technical feasibility) and IA (to help innovation solutions in testing, demonstrating, piloting, etc.).

Besides these specific project-based programmes, the OCEANERA-NET and MARINET projects were specifically designed to allocate resources to ocean energy and offshore renewable developers more generally. OCEANERA-NET aimed at demonstrating investability in ocean energy by de-risking technical challenges, and it supported research and innovation of 13 projects with USD 2.9 million when it ended in 2016. Its successor OCEANERA-NET COFUND (2017-2021) has a budget of USD 10.8 million and has so far supported nine ocean energy projects in R&D. The MARINET2 project, the successor of MARINET, has a budget of USD 13 million and focuses on providing a platform for networking and balancing joint research and transnational access for ocean energy and offshore wind.

Interreg V

The Interreg V programme framework is another EU-funded umbrella project with USD 11.9 billion allocated to support pan-European co-operation. Interreg V complements Horizon 2020, which has a main focus on R&D, by supporting market integration. Under its name, the FORESEA/OCEANDEMO programmes have allocated funds specifically to ocean energy. The FORESEA project, which supported 30 projects with USD 12.7 million before it ended in 2019, focused on facilitating market access and commercialisation by providing access to one of the four Northwest European test sites (EMEC, Scotland; SmartBay, Ireland; SEM-REV, France and DMEC, Netherlands). Its successor OCEANDEMO (2019-2022) focuses on multi-device deployment, with a budget of USD 15.2 million.

The Interreg 2SEAS project ENCORE offers USD 11.4 million (EUR 9.8 million) to advance marine energy technologies according to International Electrotechnical Commission (IEC) standards and certification schemes (Interreg 2SEAS, 2020).

demonstration projects to catalyse private capital. The NER300 programme had a budget of USD 2.5 billion, specifically aimed at providing finance in the valley of death phase of innovative low-carbon solutions. AW-Energy and SIMEC Atlantis were able to secure funding from this scheme. Although some European platforms are in place, more regional and specifically ocean energy-based investment platforms need to be built and promoted across the globe.

Loans

The third pillar to finance capital is through debt, which is borrowed capital, typically from financial institutions. Yet, similar to equity it is challenging for ocean energy to secure loans due to perceptions around high risks and unproven markets. In addition, interest rates increase with increasing risks, which can lead to such high interest rates that project financing becomes unfeasible. Concessional or subsidised loans can partly counteract these issues by offering loans with reduced interest. The InnovFin Energy Demo Project also provides public-guaranteed loans for innovative start-ups with advantageous funding conditions (lower rates). The scheme is purposely aimed at the development stage between prototype and commercialisation, the valley of death, a stage when it is particularly difficult to secure financing elsewhere. InnovFin also provides project support and advisory services in addition to financial means, and it helps projects to gather further funding. It is important that such schemes are maintained, but there remains a need for more and complementary mechanisms.

Revenue support

The LCOE of early-stage innovative renewable energy sources such as ocean energy is often higher than wholesale prices, which means that the market alone will not allow ocean energy projects to finance operating expenses, interest from debt and dividends for equity. This creates the need for revenue support per produced unit of electricity (*i.e.*, kWh) to allow ocean energy projects to break even. In the earlier stages of other renewable energy sources such as wind and solar PV such schemes were also required, but they are slowly decreasing with the drop of electricity costs of these technologies.

Revenue support mechanisms must be established at the national level that provide support after deployment over several years. Such schemes are available but need to be further rolled out and specified to ocean energy. The support should be higher for demonstration and pre-commercial projects, and to ensure that funds are applied efficiently they can be built in such a way that support decreases over time and with a larger number of operating ocean energy projects. It is also important that pots are allocated to ocean energy specifically to avoid unfair competition against more established markets (ETIP Ocean, 2019).

Power purchase agreements

Power purchase agreements (PPAs) are long-term supply contracts negotiated between a power plant and an off-take entity that will buy the electricity (usually a utility). Among other terms the contract defines a set price per unit that the power company will pay for an agreed period of time and as such allows a power plant developer to assess future revenue streams. The project developer can therefore show its project's viability early on, and PPAs hence play a key role in attracting investors and reducing initial project costs. They also provide protection against price volatility as they have no connection to the market price and give financial confidence and security of supply. For ocean energy, where market uncertainties prevail, such a financial safety net is crucial, particularly when no feed-in tariffs are accessible.

Where PPAs are in place, the revenue support can be taken further via tax reduction schemes – for example, companies can claim the difference in the higher ocean energy PPAs in respect to regular PPAs (ETIP Ocean, 2019). Scottish Renewables has proposed financing through tax debates with an innovative PPA (IPPA) for the UK that is aimed at small ocean energy projects of up to 5 MW. Assuming a certain deployed capacity is needed for the industry to reach competitive prices, Scottish Renewables suggests that the IPPA would be applicable for roughly the first 15% of that needed capacity (Scottish Renewables, 2019). Notably, PPAs will only become an option once the technology has achieved commercialisation, as off-takers focus on the cheapest options.

Feed-in tariffs

Feed-in tariffs are long-term contracts where a fixed level of renumeration per unit (kWh) is awarded to renewable energy generators. Feed-in tariffs are often aimed at small-scale power plants such as rooftop solar, where a share of the generated electricity is used for self-consumption.

Feed-in tariffs are completely detached from market prices and therefore are perceived to be an efficient tool for risk reduction, but they are a distorting measure where markets are in place. In addition to assuring long-term purchase prices, they typically offer guaranteed grid access, which is not granted equally to all technologies. They are also often differentiated by capacity size (often not aimed at utility-scale projects), location, and technology, and sometimes even by developer (manufacturer) or project (for example, the Raz Blanchard tidal stream projects in Normandy benefited from specific project-based feed-in tariffs of USD 0.204/kWh (Magagna, 2019b)).

Due to the decreasing costs of conventional renewable energy sources, general national or regional feed-in tariffs are often not high enough to sustain ocean energy. However, some countries or regions have specific feed-in tariffs for ocean energy, including Germany (USD 0.416/kWh for small capacities lower than 50 kW to USD 0.409/kWh for larger systems above 50 MW), Italy (USD 0.354/kWh for capacities below 5 MW) and Portugal (USD 0.112/kWh for capacities of less than 250 kW) (Magagna, 2019b), as well as China (a USD 0.33/kWh temporary feed-in tariff for tidal stream projects) and the Philippines (USD 0.35/kWh), among others. Ocean energy's LCOE is, however, often still higher than the feed-in tariff, and a mix of financial instruments is therefore required to bend it to lower values.

Feed-in premium

A feed-in premium is a market-based modification of the feed-in tariff. Instead of remunerating a fixed cost per unit, the support level is dependent on the electricity market price as the premium is received on top of the market price. Due to their better compatibility with the full liberalisation of the electricity market, feed-in premiums are available as alternatives or as main support mechanisms for renewable energy in numerous European countries.

Fixed feed-in premiums represent a fixed surplus to the market price, but this can lead to under-compensation or overcompensation depending on the wholesale price, which increases the revenue risks. To avoid too high or too low costs, fixed feed-in premiums often have a predefined minimum and maximum level (cap and floor). Sliding feed-in premiums are better adjusted to the market price than fixed feed-in premiums and slightly counteract their risks. A reference tariff is predefined, and the difference between the real market price and the predefined price is paid. The feed-in premium therefore provides additional security against decreasing market electricity prices.

Feed-in premiums allow renewable energy operators to be responsive to price fluctuations in the market and to deliver electricity according to demand. Feed-in premiums therefore not only push renewable energy

BOX 14: TOP-UP FEED-IN TARIFFS

To counteract the competition against more established energy sources, top-up feed-in tariffs can be awarded in addition to regular feed-in tariffs. The Global Energy Transfer Feed-in Tariff (GET FIT) scheme has proven successful in helping East African countries deploy low-carbon energy generation. Funded by four European governments and the EU, the GET FIT scheme pays premiums to projects that have already secured local feed-in tariffs and fulfil other criteria, with a strong focus on improving the economy. Such a design respects the real costs of a project, removes barriers and allows projects to access equal finance regardless of the location.

A similar scheme could be interesting for ocean energy, as the location of deployment plays a major role (for example, numerous European developers are deploying their devices in Canada due to better availability of financial support). The scheme needs to be designed well, with a threshold project size that is not too high and a capacity cap, and it needs to cover the real costs of ocean energy. Ideally internationally funded, for example on a European level by the EU, the funds could be kept relatively low by coupling the scheme with regional support instruments to cover the funding gap (Scheijgrond, 2019).

BOX 15: OCEAN ENERGY FEED-IN TARIFF AND AUCTION IN NOVA SCOTIA, CANADA

Canada is at the forefront of promoting renewable energy with an announced USD 1.5 billion Clean Technology Fund, and USD 17 billion of planned investment in green infrastructure, which includes renewable energy, smart grids, reduction of diesel use in remote communities and electric vehicle infrastructure (ORE Catapult, 2018).

The Canadian province of Nova Scotia is a leading region in tidal energy deployment, as it hosts the Fundy Ocean Research Centre for Energy (FORCE) with four grid-connected tidal test berths. Nova Scotia implemented energy feed-in tariffs early on, with a specific rate of USD 0.503/kWh for small-scale in-stream tidal projects set in its Community Feed-in Tariff (COMFIT) scheme since 2010. The COMFIT scheme lists tidal power among other developmental and more established renewable energy sources and sets the preconditions for single tidal units to not exceed 500 kW (can be greater for arrays) (Nova Scotia DEM, 2011). So far, three tidal projects have been approved in this context between 2011 and 2012 (Nova Scotia DEM, 2019)

Canada is the only country so far that has taken feed-in tariffs further and introduced a tariff for tidal energy specifically. Canada's developmental feed-in tariff is aimed at supporting "large" arrays and sets a minimum capacity of 500 kW for in-stream tidal single device projects. The programme has approved five projects with a total of 22 MW of electricity. There are ongoing negotiations to issue new PPAs to existing feed-in tariff holders. Different feed-in tariff schemes are applicable depending on the technology level as well as the output and time frame, and are presented in Table 13. So far, all awarded projects were of the first developmental category receiving USD 0.409/kWh.

Table 13: Developmental feed-in tariff in Canada

Technology level	Output per year	Term	FiT
Developmental	≤ 16 640 MWh	15 years	0.409 USD/kWh
Developmental	> 16 640 MWh	15 years	0.401 USD/kWh
Testing	≤ 3 330 MWh	3 years	0.444 USD/kWh
Testing	> 3 330 MWh	3 years	0.351 USD/kWh
Testing	≤ 16 640 MWh	15 years	0.382 USD/kWh
Testing	> 16 640 MWh	15 years	0.297 USD/kWh

Source: *Nova Scotia DEM, n.d.*

Since OpenHydro left its berth in the FORCE site in 2019, a new call for applications was issued in late 2019 for the vacant berth D. This call is coupled with a PPA of maximum USD 0.409/kWh and is in hand with the developmental feed-in tariff as applicants need to fulfil requirements such as in-stream tidal projects and terms of maximum 15 years. In addition, there is a cap of annual renumeration: the projects cannot exceed nameplate capacities of 4 MW, and companies must have USD 3.5 million as abandonment security, an amendment to avoid a repetition of the financial issues of OpenHydro. The successful candidate is awarded a licence to install tidal devices at berth 4 and a PPA (Nova Scotia Power Advisory LLC, 2020).

technologies but also positively affect the integration of variable renewable energy.

Tenders and quota-based schemes

Tenders and quota-based instruments add a competitive element to possible renumeration mechanisms. They are frequently combined with feed-in tariffs or PPAs. Such instruments are aimed at determining tariff levels by supporting the lowest bidders. When defining the quotas, policy makers have the choice between technology-neutral and technology-specific mechanisms. To support ocean energy, technology-specific tenders and/or quotas would be needed, because these are currently not cost competitive with other renewable energy sources. (See, for example, the Bay of Fundy call described in Box 15.)

As a general trend, countries' policies are increasingly moving to tender schemes and only keep the initial feed-in tariffs for small-scale applications or use tender schemes when higher volumes are deployed than forecasted. Contracts for Difference (CfDs) are auction- or tender-based schemes where a fixed price is negotiated. If the market price falls below this threshold the electricity off-taker tops up to reach the fixed price, and if it rises above the market price the electricity generator pays back the difference to the electricity off-taker. CfDs therefore offer long-term price stabilisation and independence from future changes in the wholesale market.

The UK has a CfD programme in place to support low-carbon electricity generation. Within its scheme it has a specified pot for less established technologies including wave and tidal. Although the MeyGen project placed a bid in the second bidding round, no money was allocated to the project through the scheme, or to any other ocean energy project so far. The main issue was again that more established technologies such as offshore wind placed bids under the same category and were able to achieve lower prices (BEIS UK, 2020). There has therefore been a proposal for Innovation CfDs (ICfDs), using the existing CfD but limiting it to new innovations such as ocean energy, advanced combustion, etc. The plan aims at applying the ICfD in succession of the IPPA to support larger projects for the additional capacity until competitive prices are reached, estimated to be at a level of 800 MW (Scottish Renewables, 2019).

The Netherlands has a generic national premium tariff tender scheme called SDE++. It allocates its budget along six categories, with many sub-categories, and wave and tidal are included in the hydropower category under "new hydroelectric power stations with a drop of < 50 cm". The phase limit of the final phase of the next tender round is set at USD 0.15/kWh, which will most certainly be too low for ocean energy. The only ocean energy project that has secured subsidies from the scheme so far is the Tocardo Eastern Scheldt project (Netherlands Enterprise Agency, 2020).

Renewables obligation certificates / renewable energy certificates / green certificates

Tradable renewable energy certificates (RECs) that accredit the renewable nature of the energy source per unit can create added revenue streams. The MeyGen project secured renewable obligation certificates (ROCs) from the UK government, but the scheme has since been replaced with CfDs, making it much more difficult for ocean energy to secure revenue support funding. The Republic of Korea has a REC system in place with specific values for tidal stream and tidal barrage (different tariffs depending on embarkment). The Norwegian government also supports a green certificate market, regardless of the technology, as does Singapore (Magagna, 2019b).

Numerous policy instruments are available to support revenue streams for renewable energy, but issues remain with tariffs that are not high enough to sustain ocean energy innovations, and ocean energy cannot compete with more established renewable energy projects in bidding auctions. The instruments therefore need to be redesigned to give innovations a chance or be designed to specifically fund ocean energy projects.

Other measures to balance the profit-and-loss equation

In addition to the much-needed capital support at the early stages of ocean energy deployment, further measures associated with capital cost reductions are vital. Such measures include, and are not limited to, focused R&D, innovation and industry learning, certification (which can reduce the real and perceived risks), insurance and guarantees, economies of scale, but also innovative multi-facet business models reducing interest rates.

Similarly, in addition to revenue support, there are other measures to increase the income once the investments

BOX 16: FUNDING OF THE FIRST MULTIPLE-DEVICE TIDAL ARRAY, MEYGEN

The MeyGen project currently under deployment in the north of Scotland has received blended funding through different instruments. Before deployment it was able to secure capital support through loans (USD 28.9 million from Scottish Enterprise through its Renewable Energy Investment Fund (REIF) and The Crown Estate), grants (USD 21.9 million from the UK Government Department of Energy and Climate Change, Scottish Enterprise, Highlands and Islands) and equity (USD 33.7 million through a purposely established holding company by SIMEC Atlantis with Scottish Enterprise's REIF and Scottish Enterprise holding) (Atlantis, 2014). It furthermore received accreditation by the UK regulator and with it renewable obligation certificates.

For its second phase, when it will deploy another 4x 1.5 MW turbines in 2020, MeyGen secured USD 22.9 million worth of grants through the Horizon 2020 project DEMOTIDE to design, build and operate the MeyGen Phase 1B (European Commission, 2020b) and another USD 16.8 million through the NER300 project STROMA to complete the project phase (European Commission, 2016c).

have been secured. Such measures include but are not limited to increasing output and creating new revenue streams. Increasing the output can be achieved through increasing energy yield as well as increasing the efficiency through R&D, as well as validated power production through a certification scheme, whereas new revenue streams can be achieved through the introduction of innovative business models.

5.2 Risk assessment and mitigation

Due to the novelty and early commercialisation stage of ocean energy there are high perceived risks for stakeholders, supply chain and investors, which increase investment return rates and with it overall project costs. It is thus incredibly important to focus on risk reduction to unlock growth in the ocean energy sector.

NREL's *Marine and Hydrokinetic Technology Development Risk Management Framework* (Snowberg and Weber, 2015) discusses different processes to identify, analyse, monitor and control potential risks and plan responses and proposes a risk register. The first step is risk identification through a Risk Breakdown Structure (RBS) to determine the applicable risks for a project. The NREL framework provides a standard RBS table (see Table 18 in Appendix II), which is based mainly on the ATOM risk template (Hillson and Simon, 2007). Risk analysis can be performed by indicating the type, impact and frequency of occurrence for each identified risk. This can be displayed with a consequence/probability matrix, showing how to prioritise risks. Because of the subjective nature of this assessment, NREL indicates the need for other types of risk assessments, such as fault tree analysis, scenario analysis, cost/benefit analysis, root cause analysis, etc. Possible response strategies for negative risks are based on avoidance, transference, mitigation or acceptance.

Also, to assess the different ocean energy technologies and reduce their deployment risks, ORE Catapult with the support of EMEC has developed the Technology Assessment Process (TAP) for ocean energy. The core principles of the TAP are the consistent assessment processes and benchmarking, structural development pathway focusing on key areas of uncertainty, and clear metrics to demonstrate performance (EMEC, n.d. c; ORE Catapult, 2016). Examples of risks from literature are indicated in Table 19 in Appendix II.

Many tools are available, but challenges still exist in their access and handling. Wide access to risk mitigation instruments and the provision of financial risk mitigation facilities are crucial to mobilise investors and thus increase feasibility. This is, however, only possible if procedures are simplified, their use is incentivised, and their toolbox is widened to include instruments that are specifically aimed at ocean energy (IRENA, 2016b).

Too-high risks will inevitably imply a lack of investments and loans for a project to succeed. Therefore, project finance through a special purpose vehicle (SPV) should be executed to deliver ocean energy projects. As such, the risks are not accumulated with a technology developer but can be transferred or assigned to a contracted counterparty, ideally with stronger balance sheets. Management of risks is still an important aspect of an SPV, but by transferring them to counterparties and/or professional agents they can be retained more easily (Gatti, 2018).

Resource risks, offtake risks and payback risks are extremely relevant for energy projects and need to be considered for ocean energy as well. Resource risks – that is, assuring that the selected sites fulfil the desirable conditions – occur when fluctuations in the energy generation are present, which may lead to fluctuating revenue streams and may not bring the overall expected income. All ocean energy sources have considerably higher P-values (energy yields) than, for example, solar, making this risk relatively small for ocean energy. It can be further mitigated through thorough resource assessment.

Energy off-take risks are associated with curtailment risks and the assurance that the generated electricity will be taken off by the grid or other customers. PPAs typically include an amount of energy to be sold in addition to the price it will be sold at, thus reducing this risk. Payback risk – that is, achieving lower cash flows than anticipated and not being able to repay loans – can be mitigated by a number of instruments such as agreements to repay debt slower, cash sweep contracts or clearly defined cash-flow waterfalls.

A widely known way to mitigate risks across industries and build trust for financing institutions is through insurances and guarantee funds. Risk mitigation instruments have been extended for renewable energy in the past, particularly in Asia and Africa (IRENA and CPI, 2018), and governments have established programmes to provide guarantees for riskier perceived technologies such as geothermal (IRENA, 2017b). Commercial insurances and manufacturer guarantees are, however, not largely available for the coverage of novel technologies with many uncertainties such as ocean energy devices, and where they are available, their premiums are high and increase the costs of projects. In turn this shifts finance that then needs to be acquired elsewhere. Therefore, uncertainties need to be mitigated first (ETIP Ocean, 2019). This section provides some measures that help in de-risking the ocean energy sector and its projects.

Standards and conformity assessment

International standards provide global rules and guidelines for product safety, design, performance, and more and offer the tools to make adequate comparison between different technologies. The application of standards throughout technology development can be an effective way to mitigate technical risk and contribute towards increasing investor confidence. As such it can play a significant role in the development and deployment of renewable energy technologies (IRENA, 2013).

IEC, the International Electrotechnical Commission, develops international standards for electric and electronic products, systems and services, collectively known as electrotechnology. It does this through its Technical Committees (TCs), where IEC TC 114 *Marine energy – Wave, tidal, and other water current converters* (IEC, 2020a) is specifically for ocean energy. It consists of a group of more than 100 international experts that volunteer to develop technical specifications and standards. A summary of the technical specifications (TS), precursors to international standards, that have been published or are under development are shown inTable 14. Further publications of second editions are expected from 2020 onwards. The improvements to second editions are done as a base to move to international standards, although technical specifications can already be used for certification.

The technical specifications are based on experience from experts in the Technical Committees and the established liaisons with organisations that deliver a significant contribution to standardisation in the sector. These can be internal with other IEC Technical Committees, which have developed their own standards. IEC TC 114 has liaisons with TC 4: *Hydraulic turbines*, TC 8: *Systems aspects for electrical energy supply*, Sub Committee (SC) 8A: *Grid integration of renewable energy generation*, SC 8B: *Decentralized Electrical Energy Systems,* TC 82 *Solar Photovoltaic Energy Systems* and TC 88: *Wind energy generation systems*. The latter is an excellent foundation for marine energy converters, specifically for tidal turbines. Also, IEC TC 114 has liaisons with international organisations, including the International Organisation for Standardization, namely ISO/TC 43/SC 3: *Underwater acoustics* and ISO/TC 108/SC 5: *Condition monitoring and*

Table 14: Development of marine energy technical specifications

Reference number	Title	Publication date
IEC TS 62600 – 1 ED 2	Part 1: Vocabulary	2020 (ED. 1 2011 + 2019 Amendment)
IEC TS 62600 – 2 ED 2	Part 2: Design requirements for marine energy systems	2019
IEC TS 62600 – 3 ED 1	Part 3: Measurements of mechanical loads	2020
IEC TS 62600 – 4 ED 1	Part 4: Standard for establishing qualification of new technology	2020
IEC TS 62600 – 10 ED 2	Part 10: Assessment of mooring system for marine energy converters (MECs)	Expected in 2020 (ED. 1 2015)
IEC TS 62600 – 20 ED 1	Part 20: General guidance for design and analysis of an ocean thermal energy conversion plant	2019
IEC TS 62600 – 30 ED 1	Part 30: Electrical power quality requirements for wave, tidal, and other water current	2018
IEC TS 62600 – 40 ED 1	Part 40: Acoustic characterization of marine energy converters	2017
IEC TS 62600 – 100 ED 2	Part 100: Electricity producing wave energy converters – Power performance assessment	Expected in 2020 (ED. 1 2012)
IEC TS 62600 – 101 ED2	Part 101: Wave energy converter resource assessment and characterization	Expected in 2020 (ED. 1 2015)
IEC TS 62600 – 102 ED 1	Part 102: Wave energy converter power performance assessment at a second location using measured assessment data.	2016
IEC TS 62600 – 103 ED 1	Part 103: Guidelines for the early stage development of wave energy converters: Best practices and recommended procedures for the testing of pre-prototype scale devices	2018
IEC TS 62600 – 200 ED 2	Part 200: Electricity producing tidal energy converters – Power performance assessment	Expected on 2020 (ED. 1 2013)
IEC TS 62600 – 201 ED 2	Part 201: Tidal energy resource assessment and characterization	Expected in 2020 (ED. 1 2015)
IEC TS 62600 – 202 ED 1	Part 202: Scale testing of tidal stream energy systems	Expected in 2021
IEC TS 62600 – 300 ED 1	Part 300: Electricity producing river energy converters – Power performance assessment	2019
IEC TS 62600 – 301 ED 1	Part 301: River energy resource assessment	2019

Source: *IECa, 2020*

diagnostics of machines, the International Hydrographic Organization and International Towing Tank Conference, the International Energy Agency (IEA) and IEA Ocean Energy Systems (IEC, 2020b).

Conformity assessment, including testing and certification, provides third-party verification of compliance to these standards, it aims to give an independent statement of the safety, quality, efficiency and effectiveness of products. A global conformity assessment system to international standards can improve market engagement, limits uncertainties and risk, thereby increasing confidence in the product (IRENA, 2013). In the context of ocean energy, conformity assessment, or certification, is organised under the IEC System for Certification to Standards Relating to Equipment for Use in Renewable Energy Applications (IECRE) and is currently performed by accredited (ultimately peer-assessed) certification bodies and testing laboratories. IECRE certificates are recognised globally by means of peer assessment between the certification bodies and testing laboratories.

The IECRE was established in 2014 in collaboration between the wind energy, solar PV and marine energy sectors. Each renewable energy sector has been working to develop conformity assessment products (test reports, conformity statements, certificates, etc.) based on international, consensus-based standards, such as those developed under IEC TC 88, IEC TC 82 and IEC TC 114 respectively. The certifications can reduce barriers to market entry and perceived risk while enhancing access to finance and insurance, among other benefits. The marine energy group is currently working on both; the detailed conformity assessment products that will be offered and on the acceptance of IECRE Certification Bodies (RECBs) and IECRE Test Laboratories (RETLs) that will issue these products. It has approved the Operational Document (OD) 300-200 with guidance for the issuance of an IECRE Test Report (RETR) for the verification of compliance to IEC/TS 62600-200 (Power performance assessment of electricity producing tidal energy converters) and for a three-year transition period to allow for RETLs to join with an existing ISO/IEC 17025 accreditation.

Currently, the ocean energy sector needs to expand accreditation and peer assessment in order to increase the number of qualified certification bodies and testing laboratories across the globe. Similar to the assessment of wave energy converters, the power performance assessment of tidal energy converters provides measurement and a reporting procedure for replicability.

Efforts are being made to get certification bodies such as Lloyds Register, DNV GL and Bureau Veritas involved in supporting the adoption of the aforementioned international standards and conformity assessments (Scheijgrond, 2019). It is important to teach the community about standards and their importance because standards play a key role in reducing risks and thus help the industry to secure funding.

Stage-gate metrics

Even if financial tools are available, it is often difficult to know where to apply for funding. Due to the lesser level of maturity in comparison to other technologies, ocean energy technologies lack technical consensus, which makes it difficult to measure success among competition. There is therefore a need for consistency, which can be solved by the introduction of stage-gate metrics. Within the stage-gate process – a technique where development stages are defined and after each phase the project is re-evaluated and a decision on continuation is made – stage-gate metrics can be defined universally to measure the status at each gate.

By enhancing comparability across each ocean energy sector, stage-gate metrics can assist in decision making, guide technology development and provide a framework for assessment. Progress can be tracked, and duplication avoided, while international collaboration and information sharing is enhanced. As a financial tool, funding can be allocated to a technology by successfully passing gates. As such, the most successful innovations are funnelled, and funding is only allocated to those most likely to succeed. Risks are minimised as progress is being displayed and as more confidence in the sector is established. This not only benefits the industry as a whole but allows technology developers to track their own progress and gives funding bodies confidence in the performance of the technology.

Particularly in wave energy, where many different technologies are still being pursued, it is challenging to compare feasibilities. Therefore, Wave Energy Scotland has long been using stage-gate metrics in several categories to allocate funding. The programme is explained further in Box 17, where it is shown how technologies move through the different gates.

DTOceanPlus, an EU project with a budget of USD 9.4 million, is working with industry partners and investors to establish several tools, including assessments on: site and marine characteristics to support device and array deployment, and the suitability of a project in terms of performance, yield, costs and social acceptance. It entails a stage-gate tool that builds on the good learning from the tool by Wave Energy Scotland but will also include tidal energy. Its goal is to establish a common international framework, due to be globally available through open source in 2021. The user of the tool – that is, the technology developer – can check completed activities to move through the next gate.

The activities are assorted into ten categories: Survivability, Affordability, Energy Capture, Reliability, Acceptability, Availability, Energy Transformation, Maintainability, Installability and Energy Delivery. The tasks within the categories are specific – for example, tank testing on a certain scale (i.e., 1/25th to 1/10th scale), wave height threshold, identification of main failure modes or development of a basic O&M schedule for planned maintenance. The user submits input and sees which stage-gate they should be assessed against and which activities are outstanding to advance to the next phase.

There are 6 stages, of which phases 1 to 5 align with IEC specifications[11], and a phase 0 is added to include early-stage technologies. After running through the tool, it outputs a report including a summary of the technology status and graphical evaluations, and it suggests areas of improvements. One of the main benefits is that the reports are standardised and as such enable a clear comparison framework for investors and funders, and they provide clear views of the maturity of the sector, which can assist policy makers and regulators (ETIP, DTOceanPlus, 2020).

Resource assessment / marine spatial planning

Breakthroughs in the ocean energy field are worth little without comprehensive resource mapping[12], which is another main gap in the ocean energy sector. Resources that are needed for the different ocean energy

BOX 17: WAVE ENERGY SCOTLAND: STAGE-GATE METRICS

Wave Energy Scotland developed stage-gate metrics for wave energy converters (Table 15) in 2014, funded by the Scottish Government, and in partnerships with over 230 organisations in 13 countries, which committed GBP 39.6 million expenditure.

Table 15: Number of projects in each stage of the stage-gate process

	STAGE 1: CONCEPT DEVELOPMENT	STAGE 2: DESIGN OPTIMISATION	STAGE 3: SCALED DEMONSTRATION
Power-take offs	17	11	5
Novel wave devices	8	4	2
Structural materials and manufacturing processes	10	3	2
Control systems	13	3	2
Quick connection systems	7	Decision pending	Decision pending

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[11] IEC technical specification 62600-103:2018 Guidelines for the early stage development of wave energy converters: Best practices and recommended procedures for the testing of pre-prototype scale devices.

[12] IEC technical specification 114 has three technical specifications on resource assessment: 62600-101 (wave), 62600-201 (tidal) and 62600-301 (river).

sources not only differ globally (as seen in section 1), but local implications and higher resolutions also need consideration. To identify potential resource, a large set of data is needed, and its acquisition can be challenging and costly. Data not only have to cover the environmental resources at place (i.e., wave height, wave period, tidal velocity, sea temperature, water depth, wind speed), but also need to include environmental characteristics as well (i.e., environmental consent, bathymetry, seabed structure, extreme weather conditions, marine life).

Beyond environmental characteristics, a resource assessment should include the social setting and availability of infrastructure and policies in proximity (i.e., grid infrastructure, supply chain, revenue support scheme, distance from manufacturer and developer, cultural heritage, social acceptance, employment availability). For an ocean energy project to be successful all these aspects need to be assessed thoroughly. Frameworks in the assessment can help facilitate the process, as current methodologies vary significantly. To standardise tidal resource assessment globally, the International Tidal Energy Working Group was formed among several actors and research institutions. By sharing their results and methodologies they aim to create a standardised framework to assess tidal resources (OES, 2020).

Apart from assessing the resource for ocean energy, potential conflicts with other sectors operating in oceans need to be identified early on to avoid backlashes. This can be done in the context of marine spatial planning (MSP). MSP is an approach to manage the spatial and temporal distribution of different anthropogenic ocean practices. The process is developed to give ocean users the ability to share maritime space adequately and to make use of it in a sustainable manner, including information on area resource occupation and ecosystem characteristics. It is needed due to the growing demand and competition for resources and ocean space and the need to follow specific policies and legal requirements. An MSP typically consists of different maps indicating multiple dimensions and the determined purpose of ocean space within a country's territorial waters[13], and possibly offshore waters[14] . MSP, however, does not necessarily include zoning for ocean energy or other sectors.

Traditional uses of the ocean include transport, ports, oil and gas, marine conservation and fishing. However, as other sectors – such as offshore renewable energy, recreation and tourism, submarine grid infrastructure and pipelines, sand and gravel mining, defence, sea minerals, aquaculture, carbon sequestration, etc. – increase their activities, MSP is gaining importance not just to assess space but also to regulate industries before they take off on a large scale. By including sections for ocean energy, an MSP can provide a stepping stone for ocean energy projects, reducing risks such as permitting delays, interference of marine activities, stakeholder involvement and environmental impact. This is particularly important now as the industry is moving beyond designated test locations.

For countries and areas that are starting to investigate this topic (see Box 18), it is key to understand the best way to carry out the marine spatial planning. Sharing experience, approaches and methodologies and setting universal methodologies and requirements can help countries to assess their own MSPs, decrease risks and eliminate inconsistencies. Collaboration and data sharing of the oceans is also required by international law (UN Global Compact, 2020), but data sharing remains limited and is often incompatible.

Nevertheless, several platforms and programmes to facilitate the process have been established. Wave Energy in Southern Europe, for example, includes decision support tools for MSP for site selection, while the EU's European MSP Platform aims at supporting Member States in establishing their MSPs until 2021. Within this platform, tidal and wave energy are regarded as one of nine sectors and are given attention in a stand-alone chapter. The Decade of Ocean Science for Sustainable Development, a UN project for 2021-2030, aims to provide common frameworks to support countries' sustainable management of oceans. The project focuses on supporting high-resolution ocean mapping, with private companies, non-governmental organisations, academia and research institutes, as well as national and international authorities, collaborating in collecting and distributing data and generating knowledge (UN Global Compact, 2020).

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[13] Territorial sea: 12 nautical mile limit (Ehrler, 2014)

[14] Exclusive Economic Zone: 200-nautical mile limit (Ehrler, 2014)

The Marine Spatial Planning Programme of the Intergovernmental Oceanographic Commission of UNESCO includes a step-by-step approach defining around 40 types of human ocean use and illustrates the potential conflicts in a matrix. The European MSP platform also identifies potential competition and incompatibility with most other sectors but also takes notice of potential synergies with other offshore renewables and recognises sectors such as aquaculture as potentially compatible (European MSP Platform, 2018). It has been shown, however, that co-existence with many other sectors is not only possible but even encouraged, as it brings additional benefits. It is therefore important to establish cross-sector governmental frameworks for MSP and to re-evaluate potential conflicts.

MSP frameworks are currently being established across the globe, posing a great opportunity to integrate ocean energy as a key element. This requires special attention, as it is one of the first key enablers for ocean energy deployment on a larger scale.

BOX 18: MARINE SPATIAL PLANNING EFFORTS ACROSS THE GLOBE

While around 70 countries now have MSP systems in place (IOC, 2018), their approaches and covered sectors differ widely. Only a few include offshore renewables, and when they do the emphasis is typically on offshore wind, while ocean energy is not accounted for. Some exceptions include China, where the Mineral & Energy Zone plan includes specified sites for ocean energy; Portugal, whose test centre is included; and Scotland, where projects are reflected in the MSP, among others. Other countries have separate systems, such as Canada, which has designated Marine Renewable-Electricity Areas (MREA) (OES, 2016), and the Philippines, which has government-supported funding of a tidal integrated resource assessment and MSP tool (ERI, 2017; OES, 2017).

Developing countries and SIDS

Several developing countries and SIDS (for example, Indonesia, Malaysia, the Philippines) have already completed initial resource assessments, and others (for example, Brunei, Fiji, Myanmar, Samoa, Thailand and Vietnam) are developing technologies to conduct such research (ERI, 2017; OES, 2017). However, many still lack the resources for such processes despite expressing interest. Inadequate funding has been an issue, as well as initial permitting processes and initial data validation.

Co-operation

Local governments are crucial stakeholders in the process, while the assessments are often carried out by universities and other collaborations of developers and research institutions. In Australia, for example, a consortium between two universities, one research centre, and industry partners (tidal developers) and co-funded by the Australian Renewable Energy Agency (ARENA) is delivering a resource assessment for tidal power in Australia. Partnerships, such as the Caribbean Regional Ocean Partnership (between Puerto Rico and the US Virgin Islands) and the Marine and Coastal Biodiversity Management in Pacific Island Countries (MACIBO), have co-operated on assessing resource potential or have developed toolkits to assist SIDS in the process.

6. PROPOSED ACTION AND POLICY RECOMMENDATIONS

The main bottlenecks hindering a wider, more competitive deployment of ocean energy are related to the cost-competitiveness of these technologies, compared to other renewable power generating technologies. Throughout this report, numerous opportunities to reduce the levelised cost of electricity have been discussed, ranging from business models and financial instruments to de-risking strategies. Table 16 and this section propose seven steps of actions to be undertaken to move forward, decrease the LCOE and position ocean energy as a recognised renewable energy source on the global agenda.

Table 16: Proposed action and stakeholder identification

Proposed action	Stakeholder	Implications
Enhance the business case	Policy makers Industries Power system operators	Use ocean energy to power the blue economy and couple with other offshore sectors (e.g., ports, shipping, desalination, oil and gas, etc.)
	Power system operators Energy planners	Include ocean energy as a predictable energy source that can integrate VRE and energy storage
	Policy makers	Joint tenders with other VRE installations (e.g., wave energy and offshore wind)
	Policy makers Local municipalities	Promote application on islands, coastal communities and micro grids
	Project developers Policy makers	Quantify and consider additional benefits, avoided costs, externalities (e.g., job creation, climate change mitigation or security of energy supply, etc.)
Improve access to financial support	Policy makers Regulators Financial institutions	Create innovative financial revenue support schemes aimed particularly at ocean energy (e.g., local investments, prizes, funding based on capacity size, funding based on Technology Readiness Level)
	Policy makers	Promote blended finance which encourages private capital to invest in projects that benefit society and contribute to achieve sustainable development while also providing financial returns to investors
	Financial institutions Private investors	Invest in ocean energy technologies
	Policy makers	Improve revenue and capital support schemes across all stages of development (R&D, deployment, operation)
	Financial institutions (multilateral donors)	Increase access to finance in developing countries and SIDS

Set up and strengthen resource and site assessment	Regulators	Develop regulatory processes and frameworks for site assessment and identification
	Policy makers	Conduct effective marine spatial planning (MSP) and incorporate ocean energy on regional and national levels
		Include mapped resource potential in climate and energy strategies
	Energy planners	Use advanced modelling tools
	Data owners	Improve access and exchange to baseline data, and address need for more data
	Power system operators Developers	Include assessments of local grid capacities and requirements in site assessments
	Regulators	Provide guidance and frameworks for environmental impact assessment
Build supply chain	Private sector Coastal communities	Build upon local expertise and create supply chains (include local business)
	Established offshore industries	Adapt supply chains from related offshore industries
Boost ocean energy policy and regulatory schemes	Policy makers	Include ocean energy in long-term national and/or regional energy roadmaps and Nationally Determined Contributions (NDCs)
		Establish clear policies with national targets
		Engage and support the financial institutions
	Regulators	Remove bottlenecks in the permitting process
Minimise risks by improving reliability and efficiency of the technology	International organisations	Adoption of technical specifications and advanced development of prototype/component/type/project certifications of the International Electrotechnical Commission (i.e., power take-off system, foundation, mooring, etc.)
	Policy makers Regulators	Develop and promote the use of existing assessment frameworks to track and compare development progress, e.g., stage-gate metrics
	Utility Private sector	Develop innovative hybrid renewable energy systems to integrate and share platforms with other technologies
	Asset owner	Collect and share performance data
	Technology manufacturers Developers	Scale up manufacturing by deploying arrays
	Technology manufacturers	Use modular design that can be compatible with other renewable energy generation technologies

Develop capacity through enhanced co-operation	International organisations (e.g., IRENA)	Share best practices and lessons learned (within the ocean energy sector and with other offshore industries)
	Policy makers International organisations (e.g., IRENA)	Emphasise stakeholder partnerships and build international co-operation
	Power system operators Private sector	Collaborate with local grid operators to upgrade and adapt infrastructure to allow ocean energy connection
	Educational institutions Universities	Enhance skills in the workforce and via education programmes
	Policy makers Civil society	Consult and engage the public early on

Action 1: Enhance the business case

As described in section 3 ocean energy should not be viewed as a stand-alone energy source but rather as part of a holistic solution that can add value to other industries and communities. Ocean energy project developers should therefore aim to find markets where the business case can be enhanced. To do so, sector coupling between ocean energy and other offshore markets of the blue economy (see section 3.1) or with variable renewable energy sources can be applied (see section 3.2). Islands and other remote communities are also ideally suited to integrate an ocean energy economy (see section 3.3). Deployment of ocean energy in such environments is not only facilitated but can lead to additional revenue streams and higher cash flows, as a result decreasing LCOE. Adapting the value proposition and changing the narrative to include avoided costs and additional benefits such as climate change mitigation, job creation and grid resilience can open new markets and improve the business case.

Action 2: Improve access to financial support

As indicated in section 4.1, funding opportunities for ocean energy are already in place but are not sufficient. There is a major need to improve continuous support throughout the different stages of development. These direct incentives should be built on the principle of blended finance coming from different corners, including stronger support from the public sector, taking the opportunity to use public and private partnerships as an initial vehicle. Financial support should also include traditional capital and revenue support mechanisms (see section 4.1.1) as well as new innovative funding schemes. Such innovative schemes can include competitive prizes, tender rounds, developmental feed-in tariffs, etc. and need to be designed in a way that ocean energy has a real chance by being based on specific capacity sizes or TRLs (*i.e.*, stage-gate metrics as described in section 4.2). Furthermore, emphasis should be placed on securing funding locally as well as unlocking financing opportunities for developing countries and SIDS.

Action 3: Set up and strengthen resource and site assessment

The development of processes and frameworks for site identification, resource assessment and effective marine spatial planning is of key importance to advance ocean energy deployment, as was presented in section 4.2.3. A first step to overcome the gaps is by committing to include spatial planning and ocean mapping in national strategies and to acknowledge the need for better access to baseline data. It is also of critical importance that cross-industry and government plans allocate attention to ocean energy. Marine spatial planning should go hand in hand with social, economic and environmental impact assessments – that is, assessing the potential harm to the environment and including capacities of local grids in the analyses. Costs to conduct assessments can be reduced by using advanced modelling and simulation tools and by collaborating with other sectors and nations to share best practices, methodologies and data.

Action 4: Build supply chain

A major bottleneck in the ocean energy sector are the supply chains that have yet to be built. Section 3.2 presented examples of how synergies among different industries can be used to assist deployment, not exclusively but including views on supply chains. Offshore sectors such as oil and gas and offshore wind have overcome similar issues that ocean energy is facing today, and parts of their supply chains such as sensors, subsea cabling, mooring, practices for deployment etc. could be adapted for ocean energy applications as well. It is also important that the supply chains are built locally, and that expertise is built up in proximity of operation.

Action 5: Boost ocean energy policy and regulatory schemes

In the decarbonisation discussion, countries should plan for an offshore renewables roadmap and establish clear policies that can help in the achievement of national ocean energy targets. This includes Nationally Determined Contributions (NDCs) and National Renewable Energy Action Plans (NREAPs) and should incorporate ocean energy, such as Scotland's commitment to support the wave and tidal sector by, for example, establishing working groups and supporting R&D programmes, and Nova Scotia's provincial action plan that includes a developmental feed-in tariff and designated marine renewable electricity areas (more examples are described in section 4.2.3). Frameworks and guidance to incorporate ocean energy in such roadmaps need to be created and widely distributed. For a proper sector scale-up, countries should adopt different regulatory and tariff schemes to propel ocean energy and expand and replicate them in other locations. Permitting and consenting processes must be facilitated, and bottlenecks in these processes must be revised and diminished.

Action 6: Minimise risks by improving the reliability and efficiency of the technology

Although the technologies for tidal and wave have improved significantly in recent decades, there is still room to make the devices more reliable and efficient, helping to minimise risks and raise investors' trust. For tidal energy it is important to scale up deployment and install more arrays. This will help to bring down the LCOE and prove the technology's viability. In the wave energy sector, more prototypes need to be built and pilot plants deployed, which can contribute to reaching a convergence in technology that will lead to higher know-how and lower cost. To achieve both, international standards should be developed further, and assessment frameworks such as stage-gate metrics need to be further developed (see section 4.2). Ocean energy may also consider the production of modular devices to decrease deployment costs and consider hybridisation of devices (see section 3.1.2) to increase yield and improve the value proposition. Data, best practices and lessons learned should be shared among actors within the ocean energy sector and with different offshore sectors (see section 3.2.2) and platforms, with workshops created and encouraged.

Action 7: Develop capacity through enhanced co-operation

The small size of the ocean energy sector necessitates measures to strengthen capacity building and international technology co-operation among policy makers, industry, academia and users of ocean energy technologies. There is a growing need to increase the number of professionals with knowledge and skills in ocean energy technology development and deployment. This can be done by exchanging knowledge between offshore renewables (see section 3.2), by facilitating reskilling of the work force from the fossil fuel industry to renewables and by working closely with academia and younger generations to align curricula with sector jobs (for an example, see Box 3) by focusing on education in science, technology, engineering and mathematics (STEM). Also, partnerships need to be built to share existing information and collaborate in a more organised manner (see examples in section 3.2.2). Frontrunner countries can encourage knowledge transfer to locations where ocean energy is still in early stages of development, and such cross-water partnerships could spur emerging continental economies and islands' needs for financial resources and business development analyses.

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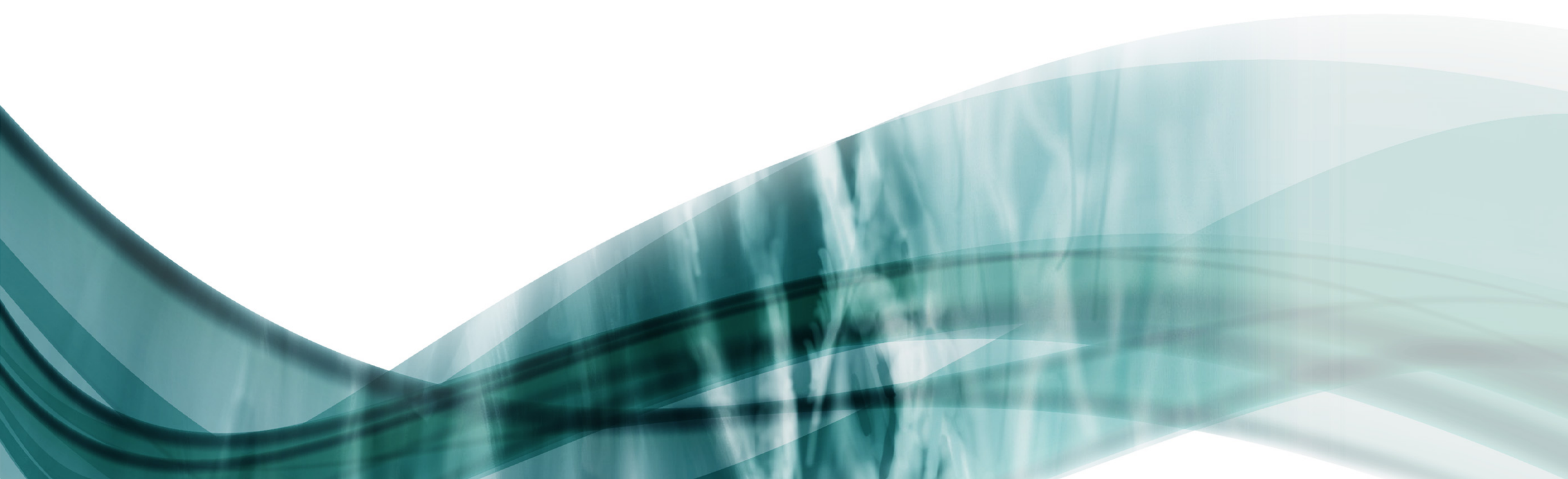

APPENDIX I

Table 17: Active ocean energy projects

Type	Power plant	Subsidiary name	Region	Country	Total capacity (MW)	Active capacity (MW)	Pipeline capacity (MW)	Owner/Developer	Status	Year online
OTEC	Imari OTEC Plant	Imari OTEC Plant	Asia-Pacific	Japan	0.03	0.03			Active	2003
OTEC	NELHA Ocean Thermal Power Plant	NELHA Ocean Thermal Power Plant	North America	United States	0.10	0.10		Makai Ocean Engineering Inc	Active	2015
OTEC	Okinawa Prefecture Ocean Thermal Energy Conversion Power Demonstration Project	Okinawa Prefecture Ocean Thermal Energy Conversion Power Demonstration Project	Asia-Pacific	Japan	0.10	0.10		GOSEA (Global Ocean reSource and Energy Association Institute)	Active	2013
Salinity	ENECO and Redstack for Salinity Gradient Plant	ENECO and Redstack for Salinity Gradient Plant	Europe	Netherlands	0.05	0.05		REDstack	Active	2014
Tidal Barrage	Annapolis Royal Tidal Power Plant	Annapolis Royal Tidal Power Plant	North America	Canada	20.00	20.00		Nova Scotia Power Inc	Active	1984
Tidal Barrage	Jiangxia Tidal Power Generation Plant	Jiangxia Tidal Power Generation Plant Phase I	Asia-Pacific	China		0.70			Active	1980
Tidal Barrage	Jiangxia Tidal Power Generation Plant	Jiangxia Tidal Power Generation Plant Phase II	Asia-Pacific	China		2.70			Active	1985
Tidal Barrage	Jiangxia Tidal Power Generation Plant	Jiangxia Tidal Power Generation Plant Phase III	Asia-Pacific	China		0.70			Active	2007

Tidal Barrage	Kislaya Guba Tidal Energy Plant	Kislaya Guba Tidal Energy Plant	Europe	Russian Federation		1.70	RusHydro, Malaya Mezenskaya PES	Active	2007
Tidal Barrage	Kislaya Guba Tidal Energy Plant	Kislaya Guba Tidal Energy Plant	Europe	Russian Federation		1.70	RusHydro, Malaya Mezenskaya PES	Active	2007
Tidal Barrage	La Rance Tidal Power Plant	La Rance Tidal Power Plant	Europe	France	240.00	240.00	Electricite de France SA	Active	1966
Tidal Barrage	Sihwa-ho Tidal Power Plant	Sihwa-ho Tidal Power Plant	Asia-Pacific	Republic of Korea	254.00	254.00	Korea Water Resources Corporation	Active	2011
Tidal Stream	Holyhead Deep Tidal Energy Project	Holyhead Deep Tidal Energy Project Phase I	Europe	United Kingdom		0.50		Active	2019
Tidal Stream	LHD Tidal Current Project	LHD Tidal Current Project Phase I b	Asia-Pacific	China		0.40	Zhejiang Zhoushan LHD New Energy Corporation Limited	Active	2016
Tidal Stream	LHD Tidal Current Project	LHD Tidal Current Project Phase I a	Asia-Pacific	China		0.60	Zhejiang Zhoushan LHD New Energy Corporation Limited	Active	2016
Tidal Stream	LHD Tidal Current Project	LHD Tidal Current Project Phase II a	Asia-Pacific	China		0.30	Zhejiang Zhoushan LHD New Energy Corporation Limited	Active	2018
Tidal Stream	LHD Tidal Current Project	LHD Tidal Current Project Phase II b	Asia-Pacific	China		0.40	Zhejiang Zhoushan LHD New Energy Corporation Limited	Active	2018
Tidal Stream	MeyGen Tidal Stream Project	MeyGen Tidal Stream Project Phase IA Unit I	Europe	United Kingdom		1.50		Active	2018
Tidal Stream	MeyGen Tidal Stream Project	MeyGen Tidal Stream Project Phase IA Unit II	Europe	United Kingdom		4.50		Active	2018
Tidal Stream	Paimpol-Brehat Tidal Farm	Paimpol-Brehat Tidal Farm	Europe	France	1.00	1.00	EDF, HydroQuest SAS, Constructions Mecaniques de Normandie (CMN)	Active	2019

Tidal Stream	Seapower GEMSTAR System	Seapower GEMSTAR System 1	Europe	Italy	0.10	0.10	ADAG and SeaPower s.c.r.l.	Active	2019
Tidal Stream	Shetland Tidal Power Plant I	Shetland Tidal Power Plant Phase IA	Europe	United Kingdom		0.10		Active	2016
Tidal Stream	Shetland Tidal Power Plant I	Shetland Tidal Power Plant Phase IB	Europe	United Kingdom		0.10		Active	2016
Tidal Stream	Shetland Tidal Power Plant I	Shetland Tidal Power Plant Phase IC	Europe	United Kingdom		0.10		Active	2017
Tidal Stream	Uldolmok Tidal Power Plant	Uldolmok Tidal Power Plant Phase I	Asia-Pacific	Republic of Korea		1.00		Active	2009
Wave	Gibraltar Wave Power Project	Gibraltar Wave Power Project Phase I	Europe	United Kingdom		0.10		Active	2016
Wave	Jaffa Port Eco Wave Project	Jaffa Port Eco Wave Project	Middle East and Africa	Israel	0.01	0.01	Eco Wave Power	Active	2015
Wave	Mutriku Wave Power Plant	Mutriku Wave Power Plant	Europe	Spain	0.30	0.30	Ente Vasco de la Energia	Active	2011
Wave	Jaffa Port Eco Wave Project	Jaffa Port Eco Wave Project	Middle East and Africa	Israel	0.01	0.01	Eco Wave Power	Active	2015
Wave	Ocean Generation Arrey Project Heraklion 2	Ocean Generation Arrey Project Heraklion 2	Europe	Greece	0.07	0.07	SINN Power	Active	2019
Wave	Ocean Generation Arrey Project Heraklion1	Ocean Generation Arrey Project Heraklion 1	Europe	Greece	0.04	0.04	SINN Power	Active	2018
Wave	Pantelleria Wave Energy Plant	Pantelleria Wave Energy Plant	Europe	Italy	0.05	0.05	Enel SpA, Wave for Energy S.r.	Active	2019
Wave	Peniche SURGE2 Wave Power Plant	Peniche Wave Power Plant 1.1	Europe	Portugal		0.35		Active	2019
Wave	WAVEGEM® at SEMREV test project	WAVEGEM® at SEMREV test project	Europe	France	0.15	0.15	GEPS Techno	Active	2019

Source: *IRENA ocean energy database*

APPENDIX II

Table 18: Risk Breakdown Structure

RBS Level 0	RBS Level 1	RBS Level 2
All sources of project risk	Technical Risk	1.1 Scope definition
		1.2 Requirements definition
		1.3 Estimates, assumptions, constraints
		1.4 Technical processes
		1.5 Technology
		1.6 Technical interfaces
		1.7 System reliability
		1.8 Performance
		1.9 Safety
		1.10 Security
		1.11 TBD
	Management Risk	2.1 Project management
		2.2 Programme/Portfolio management
		2.3 Operations management
		2.4 Organization
		2.5 Human resourcing
		2.6 Funding
		2.7 Communication
		2.8 Information
		2.9 Quality
		2.10 Reputation
		2.11 TBD
	Commercial Risk	3.1 Contractual terms and conditions
		3.2 Internal procurement
		3.3 Suppliers and vendors
		3.4 Subcontracts
		3.5 Client/customer stability
		3.6 Partnerships and joint ventures
		3.7 Levelised cost of energy (LCOE)
		3.8 TBD
	External Risk	4.1 Legislation
		4.2 Exchange rates
		4.3 Site/facilities
		4.4 Environmental/weather
		4.5 Competition
		4.6 Regulatory
		4.7 Political
		4.8 Force majeure
		4.9 External stakeholder
		4.10 TBD

Table 19: Examples of risks from literature

Risk	Phase	Root cause	RBS Level	Source
Certification/Consent process delay	Design & Certification	Legislation	4.1	Green Giraffe (2017)
Asset/component damage	Construction/ Installation/ O&M/ Decommissioning	Collisions/entanglement/ excessive environment force/ wear/corrosion rate	1.7	Martins (2014), Green Giraffe (2017), Snowberg & Weber (2015)
Interference other activities	Construction	'Sharing area'	4.9	Martins (2014), Snowberg & Weber (2015)
(Seabed) Geotechnical conditions not as expected	Construction	Lack of sufficient assessment	1.3	Green Giraffe (2017)
Personal risk to operators/ general public	Construction/ Installation/ O&M/ Decommissioning		1.9	Snowberg & Weber (2015)
Inadequate weather window	Installation/ O&M/ Decommissioning	Sea state conditions	4.4/ 4.8	Martins (2014), Green Giraffe (2017)
Short term exploitation consent	Design & Certification/ Installation	Contract	3.1	Martins (2014)
Cost overruns (e.g., fuel cost, steel price, exchange rate)	Construction/ Installation/ O&M/ Decommissioning		4.2/ 4.5	Green Giraffe (2017)
Delivery delay	Construction/ Installation		2.1/3.3	Green Giraffe (2017)
Unplanned maintenance/ Failure predictability	O&M	Power output loss, mooring failure, material failure, system malfunction, interface failure, anchor/foundation failure, breach of water integrity of compartments or equipment	1.5/1.6/ 1.7	Martins (2014), Green Giraffe (2017), Snowberg & Weber (2015)
Maintenance delay due to sourcing	O&M	Unavailability of infrastructure (crane, spare, etc.)	4.3	Martins (2014), Green Giraffe (2017)
Lower expected performance	Construction/ O&M	Poor resource assessment/ Changing resource characteristics/ Poor technology assessment	1.3/ 1.5/1.8	Martins (2014), Green Giraffe
Stability failure	O&M		1.6	Snowberg & Weber (2015)
Seismic events	Construction/ Installation/ O&M		4.4/ 4.8	Snowberg & Weber (2015)
Fires	Construction/ Installation/ O&M		4.8	Snowberg & Weber (2015)

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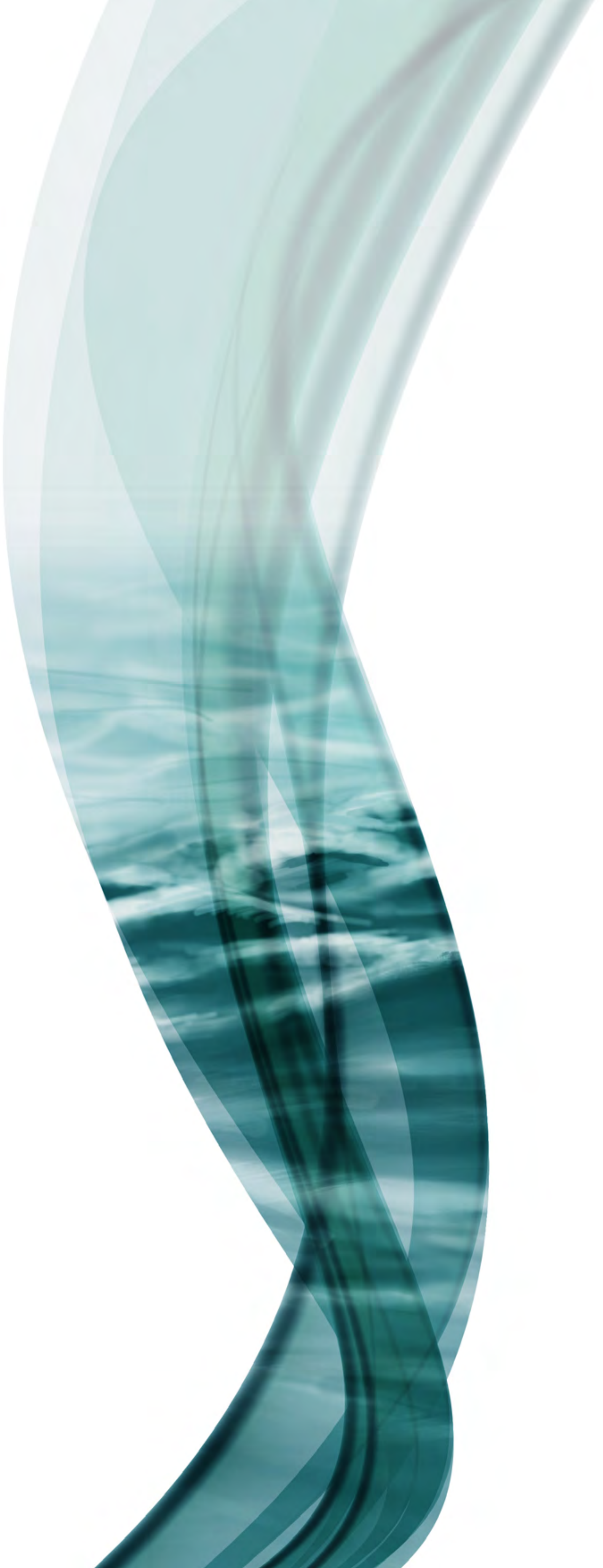

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