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Potential Markets for Ocean Energy

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EXECUTIVE SUMMARY

This report is the outcome of Task 8.1 "Analysis of Potential Markets for Ocean Energy Technology" of the DTOceanPlus project. The aim of this task is to develop a greater understanding of the potential markets for ocean energy technology deployment and exploitation. The focus includes both the present market status and future opportunities for commercialisation of both grid and non-grid applications.

Background context is provided on the global energy system, future energy scenarios, as well as challenges and opportunities for the energy transition. The current status of ocean energy sector is also summarised along with historical context.

The core of this report offers an overview of the large potential that ocean energy technologies show, wave and tidal stream in particular. Prospective market opportunities for these technologies have been identified and reviewed. Although determining the potential revenue opportunities at such an early stage in development of the wave and tidal stream technologies is rather challenging, this report provides information regarding prospective or current market sizes, potential applications, geographical locations, and future outlook of the markets.

The **largest opportunity** for ocean energy technologies is the **future market for grid power**. Future scenarios for both global and EU electricity markets are given, together with projections for ocean energy growth over the short-to-medium term and the medium-to-long term.

In addition to grid power, other potential markets for ocean energy are considered. A wide range of alternative markets have been identified, based on the US DoE 'Powering the Blue Economy' study and other resources, and these can be summarised as below.

- **Isolated power systems/ islands/ microgrids**. Ocean energy can provide energy to regions not connected to a central energy infrastructure and located close to the coast. Thereby, ocean energy can become a means for sustainable development providing access to affordable and clean energy and powering a series of basic services such as health, water supply, among others.
- **Offshore oil & gas extraction, processing, and decommissioning.** Offshore oil and gas platforms often partially meet their energy needs by burning the fuel extracted or through imports. There are a number of associated issues with this. In the case of energy imports, since platforms are normally installed in isolated locations, the fuel has to be transported with vessels or pipelines have to be installed. Additionally, with platforms having high energy availability requirements, turbines are forced to work at very low efficiencies (increasing the environmental impacts of the industry). Therefore, integrating local, clean ocean energy alternatives into the offshore O&G industry could support the reduction of its carbon intensity whilst increasing its energy security.
- **Marine aquaculture and algae**. Ocean energy can replace diesel generation in this industry and power aquaculture systems including monitoring equipment, circulation pumps, navigation lighting, and refrigeration equipment. Furthermore, ocean energy systems can be integrated into and co-developed with algal systems and meet power requirements that are similar to those from aquaculture: safety, navigation lights, maintenance equipment, refrigeration, etc.
- **Desalination**. Providing water for water utilities and isolated or small-scale distributed systems is an energy-intensive process traditionally powered by fossil fuels. Ocean energy systems are

inherently located near desalination plants and, thus, can replace fossil fuels and contribute to decarbonisation efforts.

- **Coastal resiliency and disaster recovery**. Coastal areas are among the most frequently affected regions by weather extreme events such as tsunamis and hurricanes. Additionally, these regions are at high risk due to climate change consequences such as sea-level rise. Mitigation and adaptation measures are being set in place including shore protection structures. There are already successful cases where ocean energy devices have been integrated into these structures. The power generated from ocean energy devices can meet power requirements after a coastal disaster as well.
- **Ocean observation and navigation**. Other applications that would benefit given their co-location is ocean observation and navigation. Instruments, platforms and tools used to monitor and forecast oceanographic and meteorological data and ensure safe navigation receive their power via cables to shore power, solar panels, or batteries. Having this equipment meet their own power needs through their integration into ocean energy devices can be an attractive alternative.
- **Unmanned underwater vehicles**. These vehicles, usually used for observation, surveillance, persistent monitoring and subsea inspections, are currently limited in their range and duration due to the capacity of their batteries. Ocean energy has the potential to power underwater recharge stations and supply power continuously, if paired with battery banks, thereby reducing the reliance on expensive surface vessels and extending mission duration.
- **Seawater and seabed mining**. The alternative to extract valuable minerals from seawater has attracted much attention given their demand for modern-day technologies such as wind turbines, solar panels, and electric vehicles. Ocean energy can meet some of the power needs from seawater mining including electrolysers, absorbent exposure systems, and on-site logistical needs.
- **Marine datacentres**. Computer datacentres require significant amounts of cooling, so one solution is to locate them underwater, which offers the additional opportunity to power them by nearby ocean energy sources.

These alternative applications may form a market for some technology developers. They may also act as a 'stepping-stone' to reduce costs to a level where ocean energy technologies can be cost competitive to provide grid power. Furthermore, wave and tidal stream offer an additional benefit that can be exploited for the establishment of smart local energy systems and the contribution to the development of a blue economy by enabling synergies between the potential markets identified.

Further and targeted research is required to estimate the specific total addressable market or potential revenue for the market opportunities identified and the prospective market barriers and enablers.

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ABBREVIATIONS AND ACRONYMS

2Ds	2°C Scenario (IEA future climate scenario)
AIMS	African and Indian Ocean, Mediterranean and South China Sea (region)
AUV	Autonomous Underwater Vehicles
B2Ds	Beyond 2°C Scenario (IEA future climate scenario)
CARICOM	Caribbean Community
CF	Capacity Factor
CfD	Contracts for Difference
DG-MARE	(European Commission) Directorate-General for Maritime Affairs and Fisheries
DOE	(United States) Department of Energy
EMEC	European Marine Energy Centre
FiES	Future is Electric Scenario (IEA future climate scenario)
FIT	Feed-in-Tariff
GC	Green certificates
GHG	greenhouse Gas
GT	Gas Turbine
HATT	Horizontal Axis Tidal Turbines
IEA	International Energy Agency
JRC	(European Commission) Joint Research Council
LCEO	Low Carbon Energy Observatory
LCOE	Levelised Cost of Electricity
NPS	New Policies Scenario (IEA future climate scenario)
O&G	Oil and Gas
OECD	Organisation for Economic Co-operation and Development, with 36 member countries
OES	Ocean Energy Systems
OPDS	Ocean Powered Desalination Systems
OWC	Oscillating Water Column (WEC type)
OWSC	Oscillating Wave Surge Converter (WEC type)
PA	Point Absorber (WEC type)
PPA	Power Purchase Agreement
PV	Photovoltaic
RE	Renewable energy
REC	Renewable Energy Certificates
ROV	Remotely Operated Vehicles
RPS	Renewable Portfolio Standard
RTS	Reference Technology Scenario (IEA future climate scenario)
SDS	Sustainable Development Scenario (IEA future climate scenario)
SIDS	Small Islands and Developing States
SP	Strike Price
SPD	Submerged Pressure Differential (WEC type)
TEC	Tidal Energy Converter
TPES	Total Primary Energy Supply
TRL	Technology Readiness Level
UUV	Unmanned Underwater Vehicles
WEC	Wave Energy Converter

GLOSSARY OF TERMS

Capacity factor	It is the ratio of an actual electrical output over a given period of time to the maximum possible electrical output over that period. It is defined for any electricity producing installation and may vary depending on factors such as reliability issues and maintenance, design of the installation, location, local weather conditions, etc.
Demand-side management	Energy demand management strategies for the control and modification of energy use (e.g., energy conservation, energy efficiency, and energy storage strategies). Recent technological advancements and the Internet-of-Things have enabled demand-response devices. With these, the market price of electricity is capable of influencing the end-user's level and time of electricity demand.
Electricity generation	It refers to the process of producing electricity from sources of primary energy in power stations. The actual output is reported in units of energy (e.g., kilowatt-hour) and will depend on the capacity factor (CF) of the installation. Assuming a fairly typical renewable energy generation CF of 35%, 1GW of installed capacity would generate around 3TWh/yr
Final energy	Energy carriers produced by conversion from a primary energy source. Some examples include electricity, fuel oil, and diesel.
Flexibility	The capacity of a power system to cope with the intermittency and uncertainty that variable renewable energy such as solar and wind energy introduce at different time scales without curtailment of power from these sources and reliably supplying all customer energy demand.
Installed capacity	Also known as nameplate capacity, rated capacity, or nominal capacity. It refers to the maximum output of a facility such as a power plant, a mine, or an electric generator, maintained for a reasonable amount of time and under ideal conditions. It is usually reported in units of power (e.g., watt). Actual output can be different from the installed capacity due to a number of reasons, depending on the equipment and circumstances.
Mariculture	It refers to a specialized branch of aquaculture involving the cultivation of marine organisms for food and other products.
Marine energy technologies	These types of technologies harvest energy from the oceans and include the aforementioned ocean energy technologies as well as offshore wind. The term is used interchangeably with the term "marine renewable energy technologies"
Marine renewable energy technologies	See "marine energy technologies". These terms are used interchangeably in this report.

Ocean energy technologies	Ocean energy technologies use tides, waves, and currents to produce electricity. These technologies include wave energy, tidal energy (both range and stream), salient gradient energy, and ocean thermal energy conversion.
Primary energy	Energy not subjected to any transformation or conversion processes. It is contained in raw fuels and can be classified into non-renewable and renewable. The former include oil, coal, natural uranium, among others, whilst the latter include solar, wind, tidal, geothermal energy, among others.
Total Final Consumption	Global consumption of energy by end-users such as households, industry, and agriculture. It refers solely to energy that reaches the consumer's door and does not include the energy used by the energy sector.
Total Primary Energy Supply	Sum of energy production and imports minus export and international bunkers, and plus or minus stock changes.
Uncertainty	Lack of predictability of the future electricity output of variable renewable energy.
Variability	Intermittent and fluctuating nature of solar and wind resources leading to swift changes in electricity output.

1. INTRODUCTION

1.1 SCOPE OF REPORT

Ocean energy remains a nascent energy industry. Tidal range is the only ocean energy technology that has reached market-readiness and been deployed commercially. Tidal stream technology is at a pre-commercial stage, whilst wave technology is at demonstration level. Ocean thermal energy conversion (OTEC) and salinity gradient technologies are at early stages of development. All technologies require further research and development (R&D) efforts to part-take in the highly competitive markets for grid power. The high-up front costs and the embryonic stage of some ocean energy technologies make their development a challenging task. Notwithstanding this, wave and tidal stream technologies in particular, have shown significant performance and reliability improvements lately. Coupled with significant resource potential and valuable features such as higher predictability than wind and solar, low to no land requirements, and a more uniform energy output, wave and tidal stream energy have become attractive alternatives for the global energy transition.

There has been a resurgence of interest in these ocean energy technologies given the highly ambitious climate-related targets set by different governments worldwide which has reflected in more R&D funding available from public agencies to ocean energy projects. One of these projects is DTOceanPlus, which seeks to accelerate the development of the ocean energy sector by developing and demonstrating advanced design tools for the selection, development and deployment of ocean energy systems, thereby aiding the understanding and identification of future opportunities.

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The report primarily concentrates on the technologies considered within the DTOceanPlus software, namely wave and tidal stream. Throughout the report, some sources referenced may aggregate results from the different ocean energy technologies listed in Table 1.1. These cases are highlighted, where appropriate.

TABLE 1.1. OCEAN ENERGY TECHNOLOGIES

Technology	Description	Included in this study?
Wave	Harnessing energy from the movement of waves	Yes
Tidal stream	Harnessing energy from the flow of water caused by the tides, by means of a turbine or other technology	Yes
Tidal range	Harnessing energy from the rise and fall of the tides, usually by means of a barrage or other impoundment	No
Ocean thermal (OTEC)	Harnessing energy from thermal gradients in the ocean	No
Ocean salinity	Harnessing energy from salinity gradients in the ocean	No

1.2 OUTLINE OF REPORT

This report is structured into four main technical chapters as shown in Figure 1.1:

- **The global energy system** in Section 2, summarising historical demand, current status and future challenges and opportunities for decarbonisation;
- **Ocean energy** in Section 3, outlining the current status of this energy sector while providing historical context;
- **Future market for grid power** in Section 4, covering future scenarios for global and EU electricity markets and projections for ocean energy growth; and
- **Future alternative markets** in Section 5, considering other potential markets for ocean energy.

The following subsections cover context on technology development, future energy scenarios, and then challenges and opportunities for the energy transition. This is followed by a discussion of key issues in Section 6, and conclusions in Section 7.

1. Introduction	▫ Scope & Outline
2. Global Energy System	▫ Global energy & electricity demand ▫ The future of electricity ▫ Challenges and opportunities for the energy transition ▫ Electricity prices for selected countries
3. Ocean Energy	▫ Resource: wave & tidal stream ▫ Technologies: status and development ▫ Market Status ▫ Funding support
5. Future Market for Grid Power	▫ Scenarios for the electricity market (Global & EU) ▫ Future projections for ocean energy growth
5. Future Alternative Markets	▫ Rational for alternative markets ▫ Description of key markets - Isolated power systems/ islands/ micro-grids - Offshore oil & gas extraction and processing - Marine aquaculture and algae - Desalination ▫ Summary of other markets - Coastal resiliency and disaster recovery - Ocean observation and navigation - Unmanned underwater vehicles - Seawater and seabed mining - Marine datacentres
6. Discussion **7. Conclusions**	▫ References & Annexes

FIGURE 1.1. OUTLINE OF REPORT STRUCTURE

2. THE GLOBAL ENERGY SYSTEM

2.1 GLOBAL ENERGY AND ELECTRICITY DEMAND

2.1.1 GENERAL OVERVIEW

The primary market for ocean energy is likely to be electricity, whether for grid power or use in remote and island communities. To provide background information and help in the assessment of the projections and insight provided later in the report, the current state of the electricity and energy market is described below.

In 2017, global electricity demand[1] increased to 23,696TWh [1], with European demand of approximately 3,874TWh (16% of global) [2]. Due to both additional demand in emerging markets and electrification of existing energy markets, the total electricity demand is increasing every year. Global electricity demand has increased by around 70% from 2000 to 2017, as shown in Figure 2.1, and is likely to continue to rise in the future. The future scenarios for grid power expansion are considered further in section 3.5.

The global power supply mix continues to be dominated by coal and gas, despite the growth in the contribution from renewable technologies. Low carbon technologies made up about 25% of electricity generation in 2018 [3], up from approximately 19% in 2000 [4]. It is important to highlight that there was a reduction in the share of electricity produced from nuclear following the Fukushima disaster and a promising growth in the share of wind and solar PV. There is, therefore, significant scope for further development of all types of renewable electricity generation to replace existing fossil fuel plants and meet the future electricity demand.

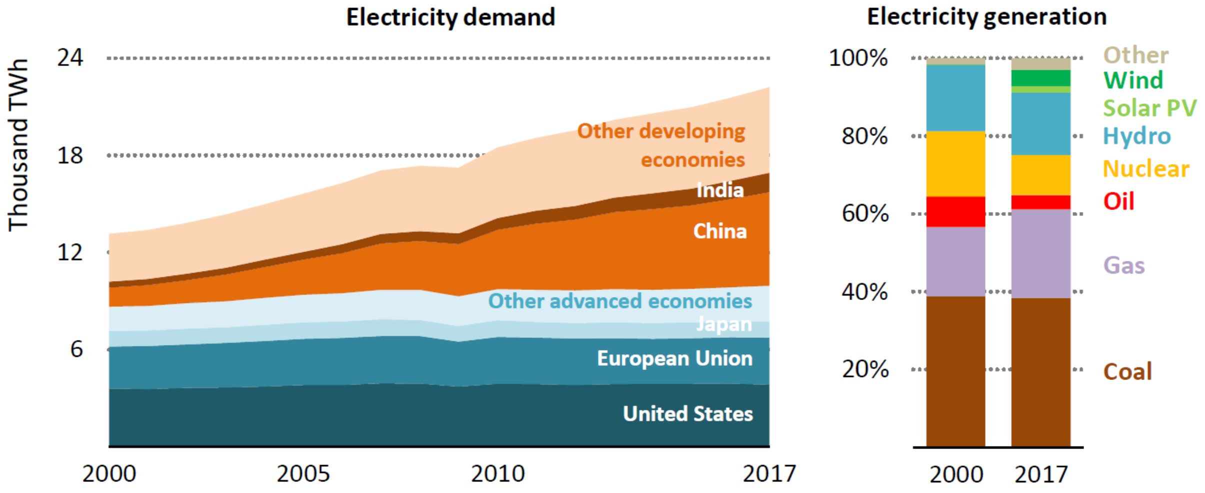

FIGURE 2.1. GLOBAL ELECTRICITY DEMAND 2000-2017 BY REGION AND GENERATION TYPE [1]

To provide wider context, the global total primary energy supply (TPES) in 2017 was approximately 14,000 million tonnes of oil equivalent (Mtoe) [2], which equates to approximately 163,000TWh.

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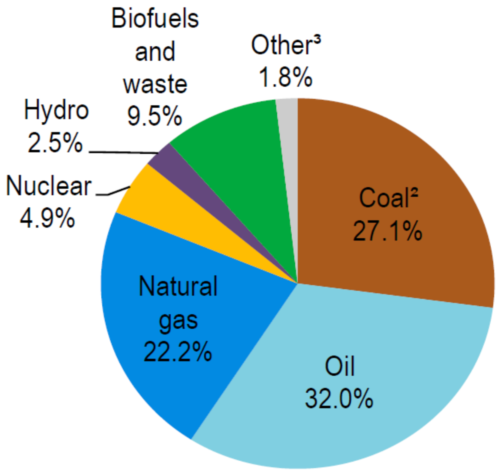
[1] Electrical energy is usually measured in kWh, MWh, GWh, or TWh, where 1 kWh is a 'unit' of electricity on, e.g., a household bill. The following conversion factors should be borne in mind throughout this report: 1TWh = 1000 GWh = 1 000 000 MWh = 1 000 000 000 kWh.

Over 85% of TPES was from non-renewable sources with traditional renewable sources (i.e., hydro and biomass) comprising around 12% and modern renewable sources (e.g., solar, wind, ocean) comprising a modest 1.8%, as shown in Figure 2.2. Europe accounted for 14.3% of the global TPES in 2017, approximately 2000 Mtoe.



Notes:

1. World TPES includes international aviation and international marine bunkers.
2. In these graphs, peat and oil shale are aggregated with coal.
3. "Other" includes geothermal, solar, wind, tide/wave/ocean, heat and other sources.

FIGURE 2.2. WORLD TOTAL PRIMARY ENERGY SUPPLY BY SOURCE [2]

2.1.2 DECARBONISATION STRATEGIES AND GOALS

Renewable energy sources have increased from a 5.1% of Europe's TPES in 1990 to 14.6% in 2017 [1]. This is the result of long-term strategic plans and ambitious policy mandates aiming to decarbonise all energy sectors through large scale electrification of the energy system and the deployment of renewable energy. From countries, through cities, to municipalities across Europe seek to further integrate renewable energy in their energy mix. According to REN21's 2019 Global Status Report [5], ambitious targets have been adopted in Europe. Some of these targets and goals are detailed in Table 2.1.This trend is being replicated in other regions of the world. Localities and regions outside Europe are also setting highly ambitious targets to further integrate renewable energy into their energy mixes in the short- and medium-term. Table 2.2 lists a selection of such locations and targets.

This global transition to low-carbon energy systems and economies requires a rapid deployment of renewable energy capacity and significant efforts on energy efficiency measures. The following section summarizes some potential energy pathways explored by the International Energy Agency and further considered in this report.

TABLE 2.1. SAMPLE OF RENEWABLE ENERGY TARGETS SET IN EUROPE [5]

Municipality/City/ Region	Target	Year
Copenhagen, Denmark	100% total energy from RE	2050
Stockholm, Sweden	100% total energy from RE 100% electricity from RE	2040 2035
Hamburg, Germany	100% total energy from RE	2050
Malmö, Sweden	100% total energy from RE	2030
Ghent, Belgium	50% of final energy from RE	2020
Amsterdam, The Netherlands	25% electricity from RE 50% electricity from RE	2025 2050
Athens, Greece Madrid, Spain Paris, France	Ban petrol- and diesel-powered cars and vans	2025
Gävle Municipality, Sweden	Fossil fuel-free transport	2030
Carinthia, Austria	100% renewable transport	2035

TABLE 2.2. SAMPLE OF RENEWABLE ENERGY TARGETS SET OUTSIDE EUROPE [5]

City/ Region	Target	Year
Berkeley, California, USA	100% total energy from RE	2050
Oxford County, Canada	100% total energy from RE	2050
Yokohama, Japan	100% total energy from RE	2050
Atlanta, Georgia, USA	100% electricity from RE	2050
Denver, Colorado, USA	100% electricity from RE	2030
Durban, South Africa	100% electricity from RE	2050
Fukusima, Japan	100% electricity from RE	2040
Kasese, Uganda	100% electricity from RE	2020
Sumba Island, Indonesia	100% electricity from RE	2025
Portland, Oregon, USA	100% total energy from RE 100% electricity from RE	2050 2035
Auckland, New Zealand	90% electricity from RE	2040

2.2 THE FUTURE OF ELECTRICITY

Much of the world's decarbonisation strategies rely on electricity generated from renewable energy sources. The substitution of fossil fuels in energy sectors such as transport and heating by renewable electricity contributes to reducing the carbon intensity of these sectors and increasing the overall efficiency of the energy systems.

The targets and objectives set throughout the world indicate that the global energy system will be mostly electrified in the future. Publications and simulations from the International Energy Agency (IEA) and the European Commission support this claim. The IEA's World Energy Outlook (WEO) [6] [7] and Energy Technology Perspectives (ETP) [8] reports explore a number of possible futures in its scenarios. With a wide range of assumptions, input parameters, and methods the WEO's Stated Policies Scenario (STEPS) – formerly known as the New Policies Scenario (NPS) –, the Future is Electric Scenario (FiES), and the Sustainable Development Scenario (SDS) all agree that electricity will play a major role in the future global energy system and that this electricity will be increasingly generated from clean energy sources, primarily wind and solar [6] [7]. Furthermore, the ETP's Reference Technology Scenario (RTS), 2 °C Scenario (2DS), and Beyond 2 °C Scenario (B2DS) draw special attention to the key role of clean electricity in the future global energy system as a source of negative emissions [8]. It is, thus, crucial to support the fast development and deployment of renewable energy technologies. The future of the global energy sector will depend largely on policy decisions and ambition, together with technological innovation. They will largely determine the future trajectory of energy-related emissions and global warming. Finally, the "EU Reference Scenario 2016" report developed by the European Commission [9] shows how energy consumption and the energy intensity of the EU economy are projected to experience a downward trend as a result of electrification as a persisting trend across the EU. Details of the assumptions and findings relevant to the purpose of this report are summarized per scenario in Annex I.

2.3 CHALLENGES AND OPPORTUNITIES FOR THE ENERGY TRANSITION

The decarbonisation and rapid transformation of the global energy system pose various difficulties. First, it entails the integration of large amounts of variable renewable energy into the power grid increasing uncertainty of supply and threatening grid stability. Furthermore, the electrification of end-use energy requires additional transmission capacity alongside enhanced systems for voltage control to bring electricity to where it will be needed. These difficulties increase the cost of the energy transition. Innovation and technological advancements are critical to accelerate this transition and increase its cost-effectiveness. Efforts and investments are required that focus on guaranteeing security of supply, adding flexibility in the energy system to avoid curtailing clean electricity production and integrating higher shares of renewable energy, and creating new capacity and transmission lines to meet the growing electricity demand.

Currently, there are a few technologies in the innovation pipeline or at the development stage as well as management strategies that could contribute to address these challenges. Figure 2.3 and Figure 2.4 illustrate some of the available alternatives to increase the power system flexibility. These include but are not limited to:

- ***Demand-side management*** [10]. The digitisation of the energy systems enables the adoption of demand-side response devices and the adaptation of consumer demand as well as sector coupling leading to improvements in energy efficiency, affordability, and security. For instance, smart thermostats enable synergies between the electricity and heating sectors; smart chargers for electric vehicles enable an interlinkage between the transport and the electricity sectors; and smart meters and load control switches for smart appliances create opportunities for energy savings. However, their most promising benefit is shifting the load between two periods and reducing peak demand.
- ***Storage*** [11]. Utility-scale batteries, pumped-hydro storage, and compressed air energy storage (CAES) are among some alternatives to avoid curtailing variable renewable energy generation. The residual load, i.e., demand minus variable renewable energy infeed, is normally supplied by dispatchable power; however, with variable renewable energy stored and being able to be fed

into the grid in times of high demand but low renewable production would advance the decarbonisation of the power sector. An additional storage alternative is electric vehicles batteries which can also be used for vehicle-to-grid applications, i.e., enabling electricity exchange between consumers and the grid when needed. Another interesting alternative, closely related to the digitisation of the energy systems, is smart charging for electric vehicles. This refers to the capability of adjusting the charging and discharging of the vehicle battery to the variations in the power mix and prices. Thereby, electric vehicles can be used as flexible loads, providing balancing services to the grids with large shares of intermittent or fluctuating renewable energy generation and reducing peak demand [12].

- ***Power-to-X solutions*** [13]. When excess electricity is generated by variable renewables, power-to-X applications (e.g., power-to-hydrogen, power-to-heat, and power-to-liquids) can "store" the otherwise curtailed renewable electricity. Furthermore, these technologies could indirectly electrify end-use sectors such as the maritime transport sector or the inland freight sector.
- ***Stronger interconnections and super-grids*** [14]. Larger network capacities such as regional markets and super-grids allow for better management and enhancement of the electric grid. These enable the balancing of demand and supply by exploiting the diversity of resources available in their area of coverage (i.e., pooling of resources) as well as higher integration of renewable energy.
- ***Mini-grids as service providers to the main grid*** [15]. Small networks can be turned into flexibility providers through the utilization of digital technologies that enable them to respond to system conditions when needed. In this sense, distributed energy resources can become back-ups for the main grid.

Another alternative to add flexibility in the energy system that is becoming increasingly important is sector coupling. Linking the heating and electricity sectors through, for example, heat pumps (also known as power-to-heat) could create significant amounts of energy storage, thereby increasing power system reliability. Moreover, cost and emissions reductions can be achieved. The potential synergies across energy sectors have given place to the concept of smart (local) energy systems [16]. These are 100% renewable energy systems efficiently utilizing excess electricity production through sector coupling.

Ocean energy can potentially contribute to tackling some of the aforementioned challenges as well. Technologies such as salinity gradient and OTEC can provide baseload clean electricity whilst wave and tidal can provide variable electricity with higher levels of predictability than, for example, wind energy [17]. Furthermore, when ocean energy is coupled with technological developments from other energy industries such as frequency converters from wind energy, the risk for power quality issues is diminished. Similarly, developments in control strategies can maximise energy absorption and enhance the efficiency of the devices, thereby improving their economy [18]. The potential synergies with other energy industries are further explored in section 5. Ultimately, renewable electricity is the future and ocean energy could be a salient player in the future global energy system.

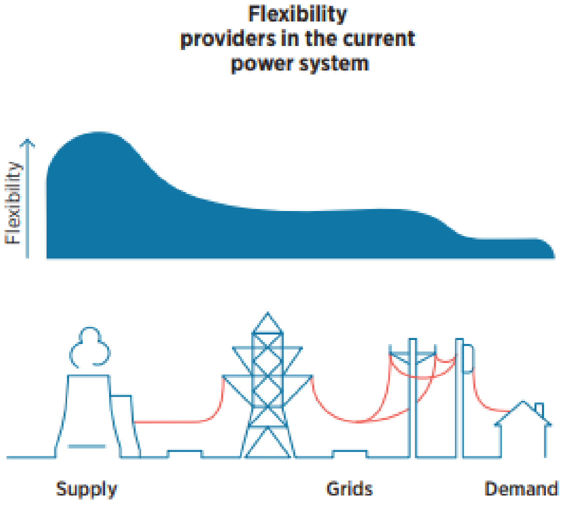


FIGURE 2.3. AVAILABLE ALTERNATIVES TO ADD FLEXIBILITY ACROSS THE POWER SECTOR [19]

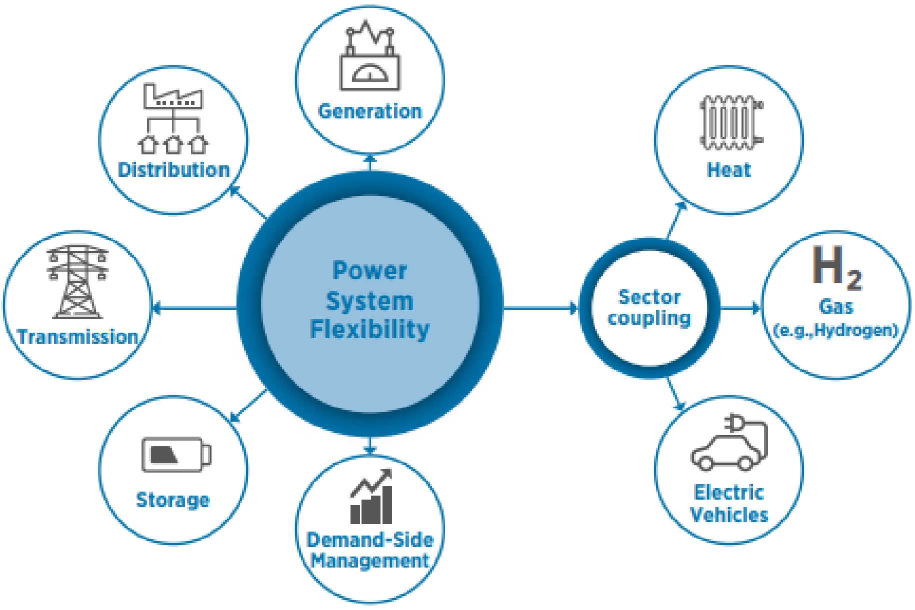


FIGURE 2.4. AVAILABLE ALTERNATIVES TO ADD FLEXIBILITY IN THE ENERGY SYSTEM [20]

2.4 ELECTRICITY PRICE FOR SELECTED COUNTRIES

Three of the main aspects challenging the energy transition and the achievement of the sustainable development goals are energy access, affordability, and sustainability. Renewable energy is seen as an important part of the solution to these three challenges. The Intergovernmental Panel on Climate

Change (IPCC) estimates that clean energy sources are fundamental to curb global warming to 1.5 °C by supplying between 70 and 85% of the electricity in 2050 [21]. Furthermore, renewable-based decentralized generation along with grid expansion are part of the strategies in place to achieve universal energy access by 2030. Finally, with the aid of push and pull mechanisms such as those that will be described in section 3.4.2, the world is seeking to guarantee market access for renewable power suppliers and establish mechanisms for achieving new lower prices for technology delivery.

The prices of electricity seen in some areas of the world are an opportunity for decentralized energy and the rise of niche renewable markets. Electricity prices vary widely across the globe. Recent data from Europe, illustrated in Figure 2.5, show the large variations among the European wholesale electricity markets where the prices range from €33/MWh in Norway to more than €66/MWh on average in Malta. These large variations are due to limitations in cross-border transmission capacities, increased production costs due to high CO_2 prices, and low output from sources such as hydro. At the end of the reference quarter, the pan-European average (approx. €39/MWh) was below the prices in Japan (approx. €77/MWh) and Australia (approx. €45/MWh); however, it was higher than the US price (approx. €30/MWh) [22].

In terms of retail prices of electricity, the smaller industrial consumers paid the highest prices in the UK (€186/MWh), Italy (€183/MWh), and Germany (€181/MWh); whilst the industrial companies with large annual consumption paid the highest prices in the UK (€142/MWh), Cyprus (€128/MWh), and Slovakia and Malta (€99/MWh each) [22]. The EU average in Q3 2019 was €124.3/MWh (excluding VAT and other recoverable taxes). Compared to its main trading partners, the EU fell only behind Brazil and paid more per unit of electricity than China, Korea, Indonesia, and the United States.

Moreover, large household consumers paid the most in Germany (€292/MWh), Belgium (€248/MWh), and Denmark and Italy (€221/MWh each); whilst small households paid the highest prices in Germany (€351/MWh), Ireland (€310/MWh) and Denmark (€290/MWh) [22]. The European average in Q3 2019 was €216/MWh [22]. Overall, it can be said that the smallest consumers tend to pay the highest prices per unit of electricity.

There is a similar trend observed in Figure 2.6, where countries such as Kenya, Jordan, Ireland, Ghana, Guatemala, Portugal, Denmark, Greece, and Pakistan consume small amounts of electricity and yet pay some of the highest prices in the world for this energy. There is a potential business opportunity for decentralized generation, and particularly for ocean energy, among some of these countries. The complete list of countries with their corresponding prices and consumption is available in Annex IV.

FIGURE 2.5. MAP OF EUROPEAN WHOLESALE BASELOAD ELECTRICITY PRICES, THIRD-QUARTER 2019 [22]

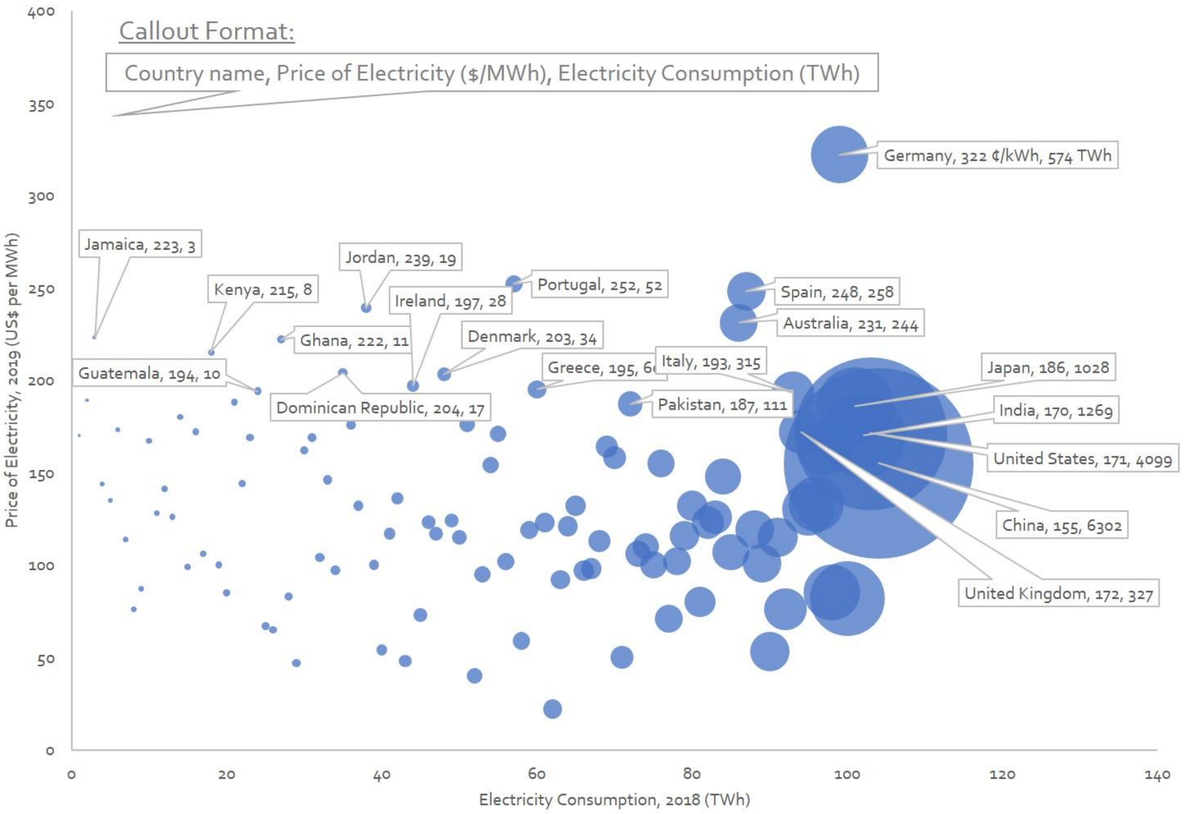


FIGURE 2.6. ELECTRICITY CONSUMPTION COMPARED TO PRICES IN SELECTED COUNTRIES. DERIVED FROM [4] AND [23]. SEE ANNEX IV FOR DETAILED DATA.

3. OCEAN ENERGY

At present, there only around 25MW of ocean energy (wave and tidal stream) deployed globally [24], which does not yet constitute an established commercial market. Although there has been historical development of ocean energy technologies over the past half century, none of these developments has reached commercialisation. This development has largely been in the form of academic studies and research with some commercial involvement, particularly in recent years.

The interest in this sector is driven in part by a large wave and tidal technical resource potential which is, although with widely varying estimates, equivalent to approx. one-third of the global electricity demand in 2017 [25]. As noted in the following section; however, much of this potential is neither technological nor economically feasible.

3.1 OCEAN ENERGY RESOURCE

This section discusses the resource potential available for wave and tidal stream energy generation. It should be noted that resources can be categorised into three nested classes of assessment, as detailed below and in Figure 3.1.

- **Theoretical resource potential:** the annual average amount of physical energy that is hypothetically available without considering constraints of any type, i.e., the total energy flux present;
- **Technical resource potential:** the portion of the theoretical resource that can be harnessed when considering a specific converter technology;
- **Practical resource potential:** the share of the technical resource available when geographical, economic, environmental, regulatory and other constraints are considered.

Headline figures often report the theoretical resource potential, even though it is not technically, let alone economically, possible to extract this energy. The technical resource potential may be an order of magnitude less than the theoretical resource potential, based on studies that show estimates for both. The practical resource potential is also site and technology specific, so there are few, if any, studies covering the resource for a whole country or the world. Figure 3.1 summarizes graphically the estimations of ocean energy resource available.

The Strategic Initiative for Ocean Energy (SI Ocean) project has identified that, across Europe, the wave and tidal energy resource is often strongest in areas where grid, port, and harbour infrastructures are weakest, creating grave uncertainty over connection possibilities in these key areas. This situation can be seen as an opportunity for off-grid solutions using these energy resources, but also a call for support from policy-makers to ensure that key milestones for commercialising the entire sector are not held up by grid-connection problems. An interesting alternative for ocean energy is coordinated offshore grid planning between wave and tidal energy projects and offshore wind projects. This might lead to cost reductions for major sub-sea connections where both resources are strong. Furthermore, the location of the ocean energy resource estimated by the SI Ocean project hints to a pan-European supply chain and, thus, return flows across the continent and not only those countries with wave and tidal resources or existing maritime infrastructure.

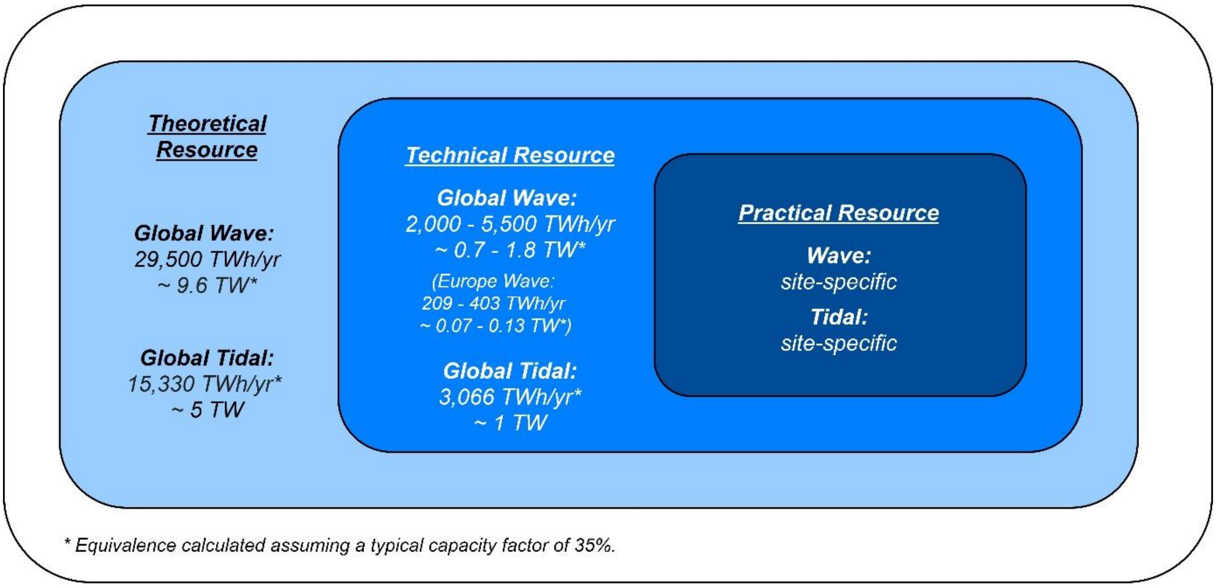


FIGURE 3.1. NESTED CLASSES OF RESOURCE [26] [27] [28] [29]

3.1.1 WAVE ENERGY

Although not feasible to harness, the global theoretical wave energy resource, depicted in Figure 3.2, has been estimated at over 29,500TWh/yr[2], with approximately 2,800TWh/yr located in Western and Northern Europe [27] [30]. Globally, the technically extractable wave energy resource has been estimated to be around 2,000 to 5,500TWh/yr [28] [31], i.e., approx. 8% to 23% of 2017's electricity demand.

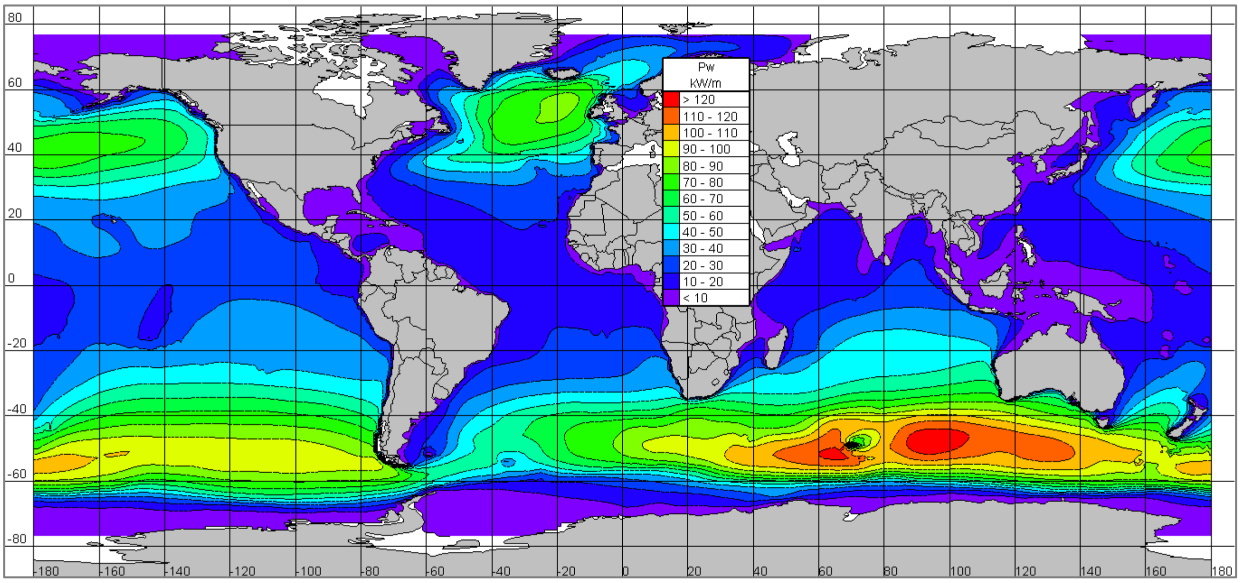


FIGURE 3.2. GLOBAL MAP OF THEORETICAL WAVE POWER RESOURCE [31]

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[2] Excluding areas where wave power is very low ($P \leq 5kW/m$) and locations which may experience ice coverage at certain times of the year.

The wave resource available have different characteristics depending on factors such as the water depth. The SI Ocean project estimated the technical wave resource in western Europe based on three deployment rounds (or scenarios). The scenarios consider different water depths and distances from the shore. The parameters considered for each round/scenario are summarized in Table 3.1 and shown in Figure 3.3. The project presents estimations of the technical wave resource ranging from 209 to 403TWh/yr and locates the best wave energy resources on the western fringes of northern Europe. The majority of this resource is located in the Atlantic arc region, off the coasts of France, the UK, and Spain, with significant resource also available in Portugal, Denmark, and Ireland, as shown in Figure 3.3[3]. Considering the SI Ocean project estimations, wave power could meet up to 34% of the current electricity demand of the six aforementioned countries.

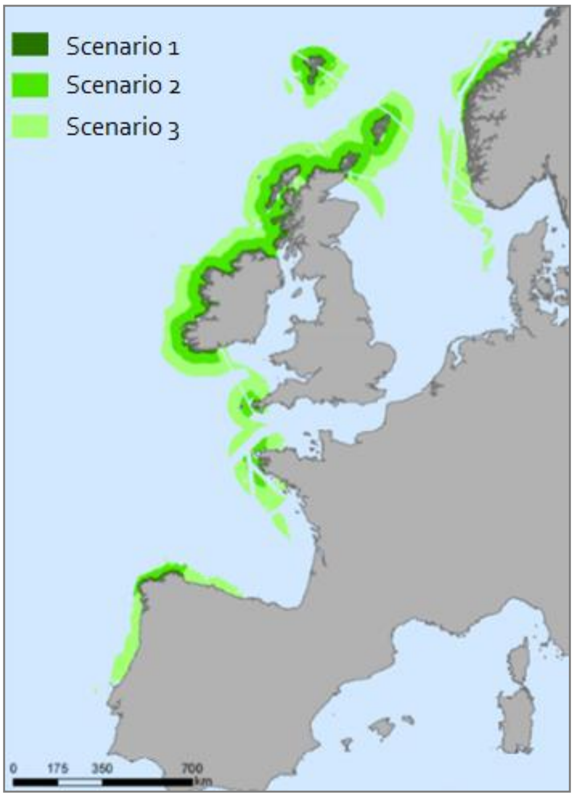

FIGURE 3.3. WAVE RESOURCE DISTRIBUTION FOR THREE SCENARIOS IN THE ATLANTIC ARC REGION [32]

TABLE 3.1. TECHNICAL WAVE RESOURCE (TWH/YR) FOR THREE SCENARIOS AND TOTAL ELECTRICITY CONSUMPTION IN 2016 FOR THE ATLANTIC ARC REGION COUNTRIES [1] [32]

	Scenario 1	Scenario 2	Scenario 3	Electricity consumption	Fraction of demand
Distance from shore	*<10km*	*<50km*	*<100km*		
Water Depth	*<100m*	*<200m*	*<300m*		
Resource	*>30kW/m*	*>30kW/m*	*>25kW/m*		
UK	99	133	145	330.4	30–44%
Ireland	75	103	125	27.6	270–450%
Denmark	0	0	13	33.7	0–39%
France	14	28	45	477.9	3–9%
Spain	21	26	50	255.7	8–20%
Portugal	0	0	25	50.3	0–50%
TOTAL	**209**	**290**	**403**	**1175.7**	**18–34%**

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[3] The maps also show significant resource off the south-western coast of Norway, although no estimations are provided.

3.1.2 TIDAL STREAM ENERGY

The theoretical energy resource due to a marine current is defined as the kinetic energy available in the free flowing water, which can be calculated as $E = ½\,\rho A U^3$ where ρ is the density of sea water, A is the cross-sectional area perpendicular to the flow, and U is the tidal current velocity. As seen by the cubic relation, the energy extractable from a flow is very sensitive to velocity U. Likewise, given that the current velocity depends on factors such as bathymetry and channel formation, the tidal stream resource is highly site specific.

For this reason, although global tidal stream estimations are available (see Annex I), these are meant as a first reconnaissance stage. Ultimately, local studies (extents of less than 25km) are required in order to account for bathymetry traits and channel formations among others, thus reducing potential uncertainties (see Table 3.2).

TABLE 3.2. TIDAL RESOURCE ASSESSMENT LEVELS [32]

Stage	Description	Power estimation uncertainty	Typical extent
Stage 1	Reconnaissance	High	Greater than 300km
Stage 2	Feasibility	Medium	20 to 50km
Stage 3	Design	Low	Less than 25km

Various high-level reconnaissance assessments are available for global tidal resource, although these typically combine both tidal range and tidal stream. For example, Charlier and Justus [33] provide an estimation of 5TW of power from ocean currents. IRENA reports that technically harvestable tidal energy resource is estimated by several sources at around 1TW [34], with tidal stream having a much larger percentage of this than tidal range. The IEA has also estimated the total worldwide theoretical tidal energy resource (including tidal range) as being 1,200TWh/year [29].

Only a small number of countries, e.g., France, Ireland, Norway, the UK, USA and some parts of the coast of China and Canada have performed resource assessment studies in detail. Other regions and countries with potential sources are the Philippines, Papua New Guinea and Argentina but studies here are lacking. A tabular summary of tidal stream resource assessment studies is presented in Annex I. It is important to highlight that the various country-specific resource assessment outcomes are not the basis of application of a common resource assessment methodology. The information presented may over or underestimate the true available resource depending upon the assumptions underlying the analysis. The reader is therefore advised to be cautious in accepting the quantitative data referenced without further analysis of the source material. These issues are highlighted by the different overall resource figures reported for the same country across a number of the referenced studies. What the data does impart is a qualitative indication of the tidal current energy potential in the countries considered.

At a European level, locations with constant current speeds above 0.5m/s across Great Britain, France, Italy, Greece, Spain, and Denmark could provide a total annual energy of 48TWh/yr [35], with most of the resource concentrated around the British Isles and the English Channel. To narrow down, the list of potential sites within Europe looked at locations with a minimum mean spring peak velocity above 2.0m/s and a maximum water depth of 200m, among others [36][4]. The areas meeting these requirements, surrounding the UK and numbered 1 to 5 in Figure 3.4, have an estimated total tidal stream technical resource of 30TWh/yr (see Table 3.3), representing more than 60% of the resource in Europe. Comparing with the total electricity consumption in the UK (330TWh/yr), Ireland (27.6TWh/yr) and France (478TWh/yr), tidal stream energy could contribute to 3.6% of the consumption within this region.

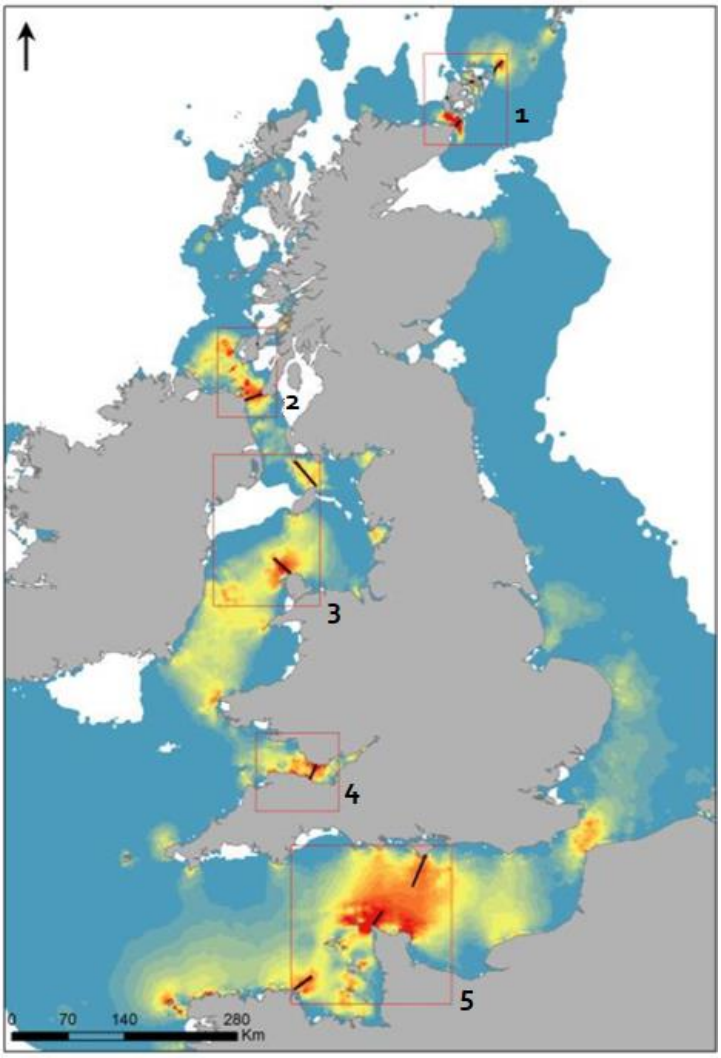

FIGURE 3.4. AREAS WITH HIGH TIDAL ENERGY RESOURCE AROUND THE UK [32]

TABLE 3.3 TIDAL STREAM TECHNICAL RESOURCE FOR REGIONS IN FIGURE 3.4 [32]

Area	Resource (TWh/yr)
Orkney Islands (1)	5.25
North Irish Sea (2)	4.81
Irish Sea (3)	4.36
Bristol Channel (4)	1.80
English Channel and France (5)	11.10
TOTAL	30.36

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[4] See report for a detailed explanation of the process and a complete view of the assumptions made during the technical resource assessment.

3.2 OCEAN ENERGY TECHNOLOGIES

Technological advancements enable the conversion of kinetic energy from the ocean currents and waves into usable electricity. A wide range of devices have been developed to seize the wave and tidal resources available. The European Marine Energy Centre (EMEC) has compiled a list of wave and tidal energy concepts developed in the last few years [37], with a total of 225 wave energy and 93 tidal stream devices. Most of them are at an early/medium stage of development, and the technologies are far from being commercially viable. In this section, we elaborate on the level of development of ocean energy technologies, particularly on wave and tidal stream converters.

In terms of device developers, the European Commission's Joint Research Centre (JRC) [38] [39] reported in 2018 the number of active companies as 43 for wave and 34 for tidal energy. In the intervening years, there has been some consolidation of companies whilst a number of companies have either entered administration or ceased development of ocean energy technology. There are new entrants into the market not listed in the JRC study, such as CorPower Ocean AB and Mocean Energy, and there are also many other alternative concepts being studied at an academic level in institutions around the world.

Within the DTOceanPlus consortium alone, there is significant ongoing progress towards commercialisation of the sector. At the moment of writing this report, some of the work from the consortium partners include:

- Corpower Ocean successfully completed half-scale prototype tests of their C3 device at the EMEC Scapa Flow site in 2018 as part of the WES Stage 3 PTO call, following extensive dry testing. They are now working towards the development of a full-scale C4 device.
- IDOM Oceantec tested their low power (30kW) MARMOK-A-5 device at the Biscay Marine Energy Platform (BiMEP) in Spain as part of the H2020 OPERA project. They are now working on the design and manufacture of a high power (300kW) pre-commercial device.
- Nova Innovation is upscaling their three-turbine array (3×100kW) in Bluemill Sound, Shetland, UK to six turbines as part of the H2020 ENFAIT project.
- Orbital Marine Power is currently working on the design an improved 2MW O2 turbine, following successful testing of the SR2000 at EMEC, exporting a total of 3GWh to the grid in its initial 12-month test period.
- Sabella is continuing to develop their 1MW rated D10 turbine and are looking at potential island opportunities (e.g. Ushant Island, Phares project).
- WES are funding Mocean Energy and AWS Ocean Energy to build and deploy half scale prototypes at EMEC in 2020 as part of the Stage 3 Novel Wave Energy Converter call. They are also funding several PTO and Control projects to develop components, plus landscaping studies to identify potential future areas for development.

Also worthy of note is SIMEC Atlantis Energy, having deployed four 1.5MW turbines in 2016 as part of the MeyGen Phase 1a project, with a potential to expand this to 398MW over several phases [40]. This project has already exported over 17GWh of electricity to the UK grid. SIMEC Atlantis Energy has also released plans to develop projects at Raz Blanchard, Alderney, and other locations worldwide including China, Indonesia, India, and Canada [41].

Technology readiness levels (TRLs) are a widely used method for tracking the technological and commercial maturity of technologies, originally developed by NASA in the 1970s. The European Commission has defined nine TRLs for the H2020 programme:

1. Basic principles observed
2. Technology concept formulated
3. Experimental proof of concept
4. Technology validated in lab
5. Technology validated in relevant environment
6. Technology demonstrated in relevant environment
7. System prototype demonstration in operational environment
8. System complete and qualified
9. Actual system proven in operational environment

Applying this TRL scale to ocean energy technologies, the Ocean Energy Europe Forum Roadmap [42] presented the phases and criteria detailed in Figure 3.5. These tie up with the five stages set out in IEC standard 62600-103 “Guidelines for the early stage development of wave energy converters”. Development of wave energy is mostly focused on the R&D, prototype, and demonstration activities at present. Tidal stream is slightly more advanced, with some pre-commercial stage projects. For an established market, particularly for grid power, these technologies need to be at TRL9 with industrial roll-out of commercial farms and mass-production of components and devices. The alternative markets discussed in Section 5 may also provide opportunities for demonstration and pre-commercial projects as part of this development process.

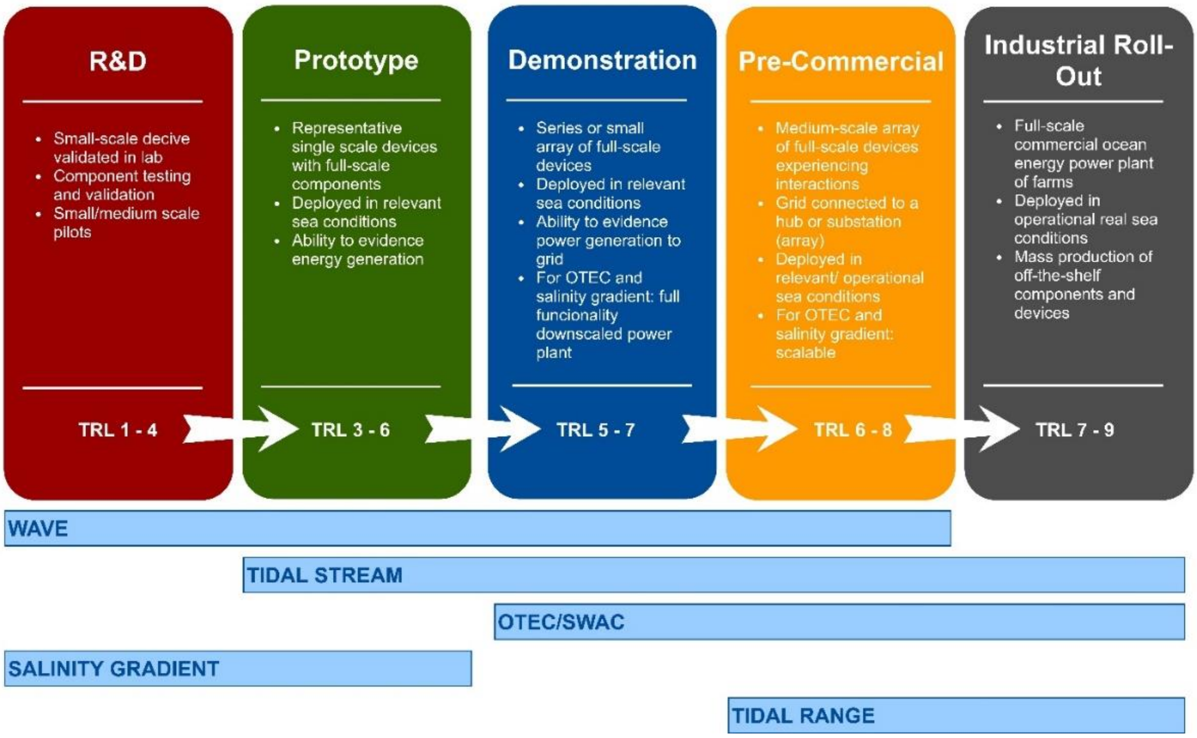


FIGURE 3.5. PHASES OF TECHNOLOGY READINESS LEVELS FOR OCEAN ENERGY TECHNOLOGIES. ADAPTED FROM [42] AND [38]

3.2.1 WAVE ENERGY TECHNOLOGIES

As noted above, EMEC identified 243 wave energy converter concepts up to September 2019 [37]. The distribution of these WEC types is detailed in Figure 3.6. The large variety of WEC designs developed to date hinders a consensus within the wave energy sector. Point absorbers are the most common type of devices developed. This type of devices has reached a TRL of 7. Oscillating water column (OWC) devices have reached the highest TRL among all WECs, i.e. TRL 8. There are far fewer concepts developed for OWC devices than for point absorber and attenuator devices. Due to this variance and disparities in the WEC designs, there is no particular type of WEC design or type comfortably leading the industry.

The vast majority of the WEC developers are located in the European Union as can be seen in Figure 3.7, primarily in the United Kingdom, Italy, and Denmark. In the rest of the world (ROW), outside of the EU, the majority of the companies are based in the United States and Australia.

Most developers work on point absorber devices. Companies such as SINN Power in Germany, Wedge in Spain, Seabased in Sweden, Albatern in UK, and Ocean Technologies in USA have developed point absorber devices that have reached a TRL of 7. However, there are other developers working on other WEC designs that have made progress in the way to commercialisation. For example, companies that have developed devices reaching a TRL of 7 include: Wello in Finland with a rotating mass device, Wave Dragon in Denmark with an overtopping device, Ocean Energy Ltd in Ireland with an oscillating water column device, and Resolute Marine Energy in USA with an oscillating wave surge converter [38].

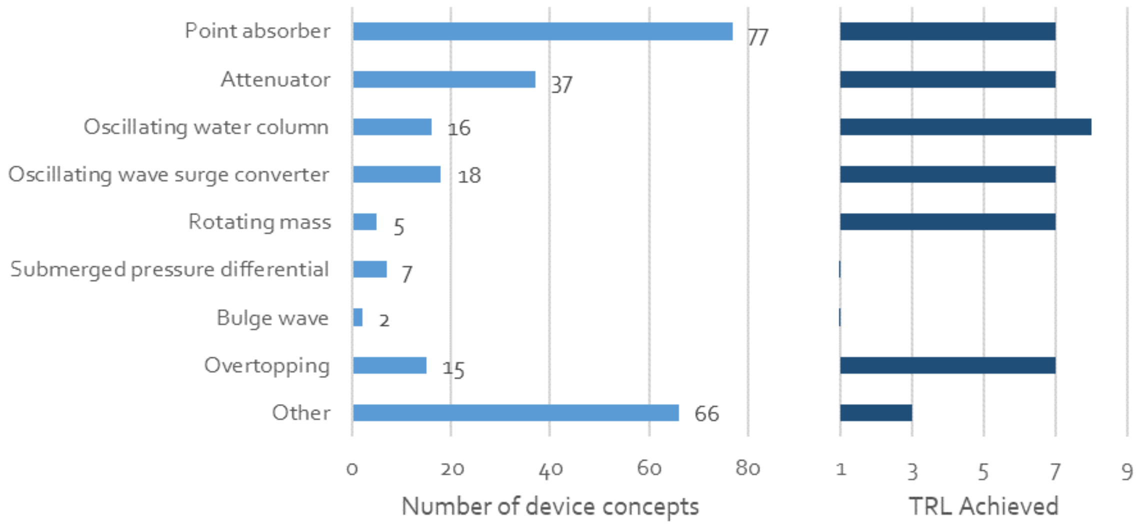
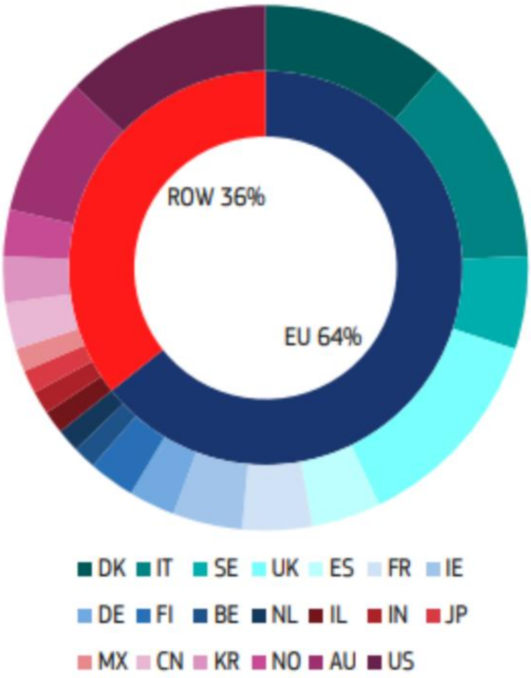


FIGURE 3.6 NUMBER OF WAVE ENERGY CONCEPTS DEVELOPED AND TRL ACHIEVED BY TYPE. DATA FROM [37] [38]



DK: Denmark,
IT: Italy,
SE: Sweden,
UK: United Kingdom,
ES: Spain,
FR: France,
IE: Ireland,
DE: Germany,
FI: Finland,
BE: Belgium,
NL: The Netherlands,
IL: Israel,
IN: India,
JP: Japan,
MX: Mexico,
CN: China,
KR: Korea,
NO: Norway,
AU: Australia,
US: United States,
EU: European Union,
ROW: Rest of World.

FIGURE 3.7. DISTRIBUTION OF WAVE ENERGY DEVELOPERS BY COUNTRY [39]

3.2.2 TIDAL STREAM ENERGY TECHNOLOGIES

As with WEC types, EMEC also considered the number and type of tidal stream energy convertor concepts. A summary is shown in Figure 3.8. Unlike WECs, there is a convergence towards horizontal axis turbines, which make up about half of all TEC concepts. These devices have reached a TRL of 8 and, currently, some technologies are attempting to complete the TRL path. However, enclosed tip turbines and tidal kit devices have also made considerable progress, reaching TRLs of 7 and 6 respectively.

Figure 3.9 provides an overview of the global distribution of tidal stream energy companies by countries. Around two-thirds of all developers are placed in the EU, with most of them found in the United Kingdom, the Netherlands, and France. In the rest of the world (ROW), the majority of the companies are based in Canada, the United States, and China.

Most of the leading companies in the sector are located in Europe and developing horizontal axis turbines. Some of these companies that have reached TRLs of 8 include: Andritz Hydro Hammerfest in Austria, and Orbital, SIMEC Atlantis, and Nova Innovation in UK. However, other developers are working on other TEC devices that have reached TRLs above 6. These companies include EEL GEN Energy in France working on an oscillating hydrofoil concept, Design Pro in Ireland developing a vertical axis turbine, Minesto in Sweden working on a tidal kite device, and Elemental Energy Technologies in Australia working on enclosed tip devices [38].

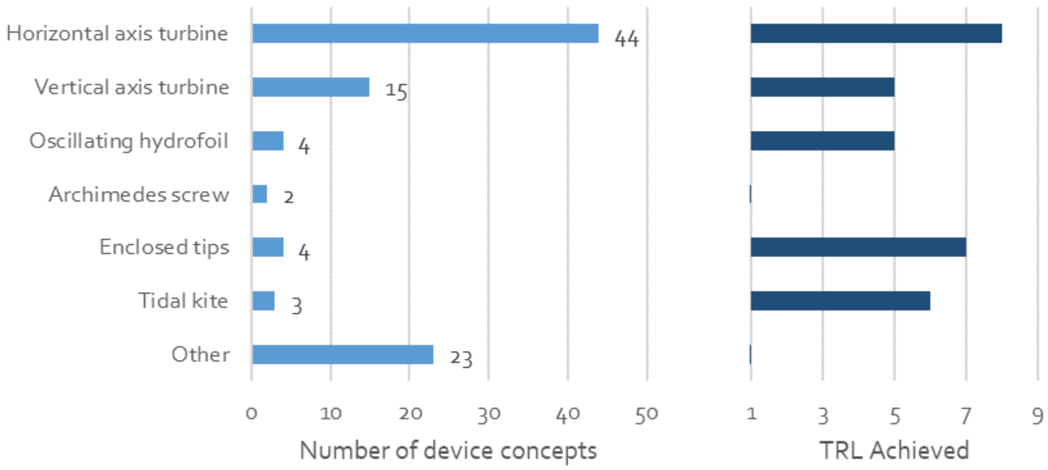


FIGURE 3.8. NUMBER OF TIDAL STREAM CONCEPTS DEVELOPED AND TRL ACHIEVED BY TYPE. DATA FROM [37] [38]

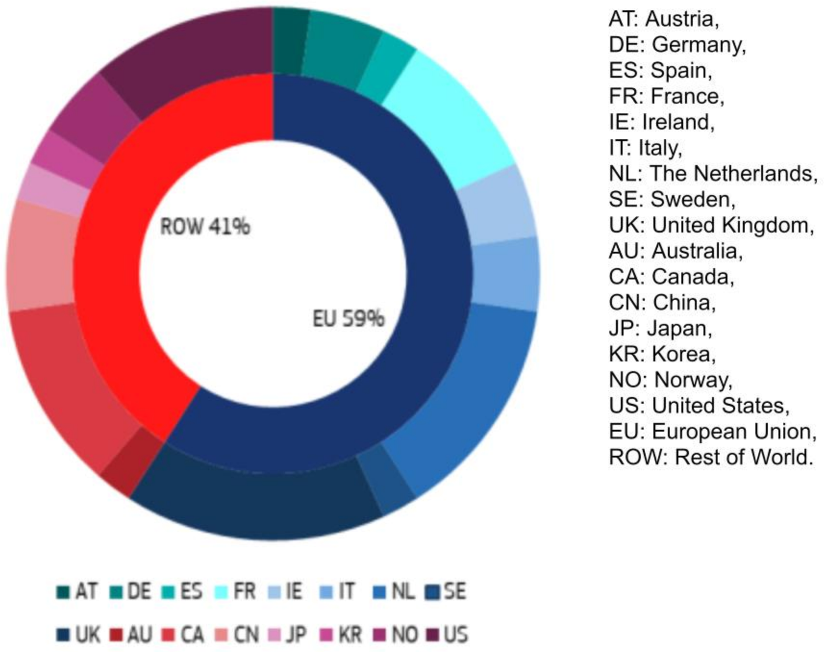


FIGURE 3.9. DISTRIBUTION OF TIDAL STREAM ENERGY DEVELOPERS BY COUNTRY [39]

3.3 OCEAN ENERGY MARKET

3.3.1 CUMULATIVE CAPACITY DEPLOYED

Most ocean energy projects are at demonstration or pre-commercial scale at the moment and located in the European Union. There are some projects taking place in Canada, South Korea, and China.

Table 3.4 and Table 3.5 offer a sample of wave and tidal devices that have been deployed since 2010. It should be noted that these were deployed primarily for testing purposes and, therefore, are not all operational at the moment [38] [43].

The installed capacity deployed for both wave and tidal stream energy in the world between 2010 and 2018 are shown in Figure 3.10 and Figure 3.11. Europe has been notably leading the tidal stream capacity installation; yet, the rest of the world is considerably investing in wave energy.

TABLE 3.4. SELECTED RECENT WAVE ENERGY DEPLOYMENTS

Company	Project /Location	Capacity	Year	Status
40South Energy	Marina Di Pisa, Italy	50kW	2018	Operational
Albatern	Isle of Muck, UK	22kW	2014	Operational
Corpower	EMEC, UK	25kW	2018	Testing completed
Eco Wave Power	Gibraltar, Spain	500kW	2016	Operational
Fred Olsen	WETS, Hawaii, US	50kW	2016, 2018*	Testing completed
IDOM Oceantec	BiMEP testing	30kW	2016	Testing completed
OceanEnergy	WETS, Hawaii, US	1MW	Dec 2019	Deployed
Seabased	Sotenäs, Sweden	3MW	2015	Operational
Wavegen	Mutriku breakwater, Spain	300kW	2011	Operational
Wello Oy	3 Penguin prototypes, EMEC, UK	1MW	2012, 2017, 2020**	Testing completed/ Being prepared for deployment

* First deployment took place in the US Navy test site in Hawaii between 2016 and 2017. The second deployment began in 2018 and was completed in January 2019.

** The first Penguin device was deployed at the Billia Croo wave test site in summer 2012. The second Penguin was installed in March 2017. The last Penguin WEC arrived in Orkney in July 2019 and is being readied for deployment.

TABLE 3.5. SELECTED RECENT TIDAL ENERGY DEPLOYMENTS

Company	Project /Location	Capacity	Year	Status
DCNS Energies/ OpenHydro	Île-de-Bréhat, France	2×1MW	2017	Testing completed
LHD Tidal Current Demo	Zhejiang Province, China	3x500kW	2016	Operational
Magallanes	2nd Gen. ATIR, EMEC, UK	2MW	2019	Operational
Minesto DeepGreen	Minesto, Holyhead deep	500kW	2018	Operational
Nova Innovation	Bluemull Sound, Shetland, UK	3×100kW	2016	Operational
Orbital Marine Power	EMEC, Orkney, UK	1×2MW	2016	Testing completed
Sabella	Sabella D10 Demonstrator, Ushant, France	2MW	2018	Operational
Schottel Hydro	SIT 250 Demonstrator, Singapore	62kW	2017	Operational
SIMEC Atlantis	MeyGen Phase 1a array, Sound of Mey, UK	4×1.5MW	2018	Operational
Sustainable Marine Energy	PLAT-I, Fundy, Canada	280kW	2018	Operational
Tocardo	Eastern Scheldt, the Netherlands	5×250kW	2015	Operational

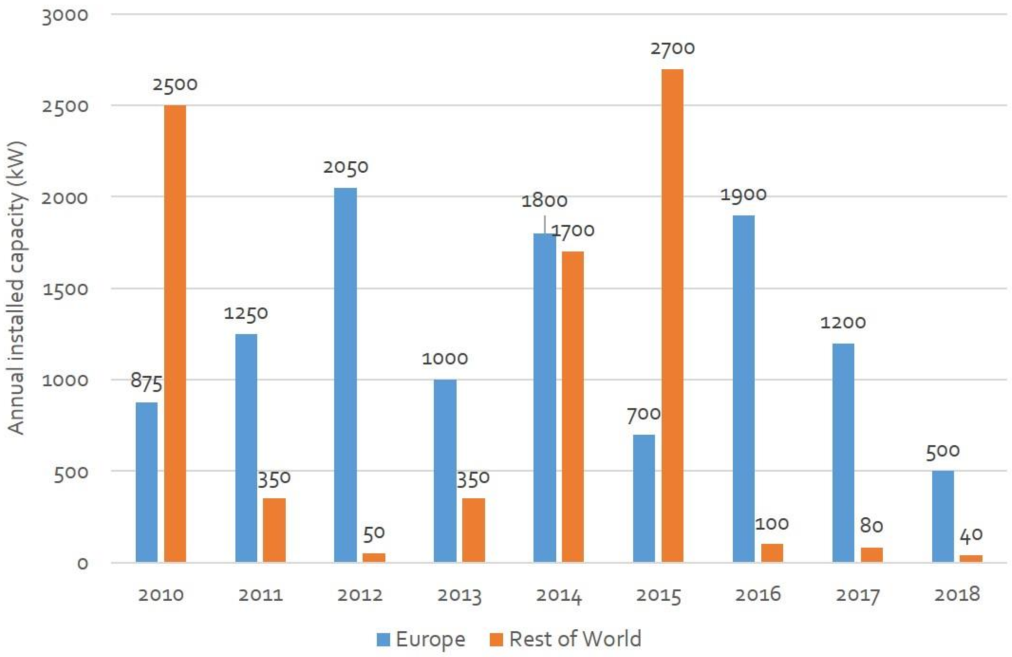


FIGURE 3.10. GLOBAL INSTALLED WAVE ENERGY CAPACITY DEVELOPMENT BETWEEN 2010 AND 2018 [44]

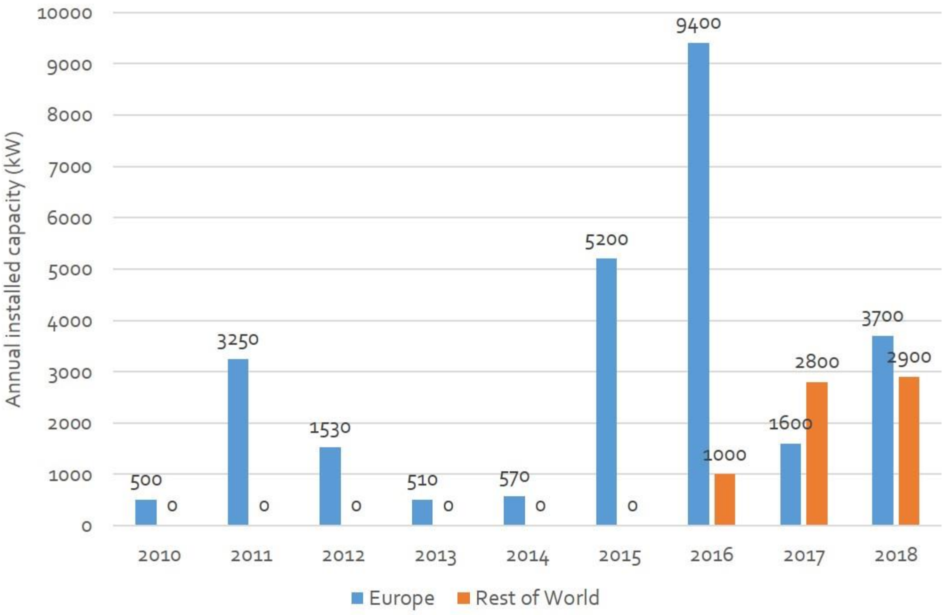


FIGURE 3.11. GLOBAL INSTALLED TIDAL STREAM ENERGY CAPACITY DEVELOPMENT BETWEEN 2010 AND 2018 [44]

3.3.2 CUMULATIVE ENERGY PRODUCED

Given the significant growth in installations of both tidal and wave energy in the recent years, electricity generation has increased as well. Between 2002 and 2018, the tidal stream energy sector produced 33.7GWh of electricity. With a less mature industry, wave energy delivered 1.8GWh of electricity between 2008 and 2015. The progress can be seen in Figure 3.12 below, with provisional figures for 2019.

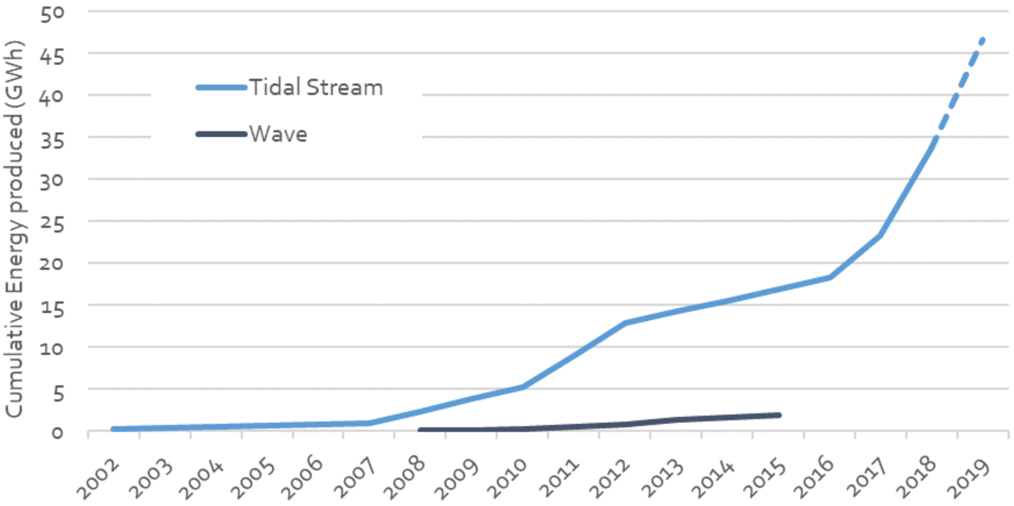


FIGURE 3.12. WAVE AND TIDAL STREAM CUMULATIVE ENERGY PRODUCED. DERIVED FROM [39] [44] [45]

3.4 FUNDING FOR RESEARCH, DEVELOPMENT AND DEMONSTRATION

Between 1974 and 2018, the IEA countries had a cumulative budget of $2.5bn (~€2.3 bn) available for research, development and demonstration (RD&D) of ocean energy[5] projects. In 2018 alone, ocean energy was accredited a RD&D budget of $88m (~€79.7m), accounting for 2.6% of the total renewables RD&D budget that year [46]. In contrast, solar and wind energy were allocated a combined budget of $1.4bn (~€1.3bn) in 2018, i.e., 41% of the total renewables RD&D budget in 2018 [46]. See Figure 3.13 for further detail.

The UK ocean energy industry, a world leader, estimates an approx. investment of £508m (~€603m) of private capital in technology development to 2017 [47]. Additionally, more than £300m (~€356m) of public support have been directed to ocean energy, beyond technology development and including academia and test centres [47].

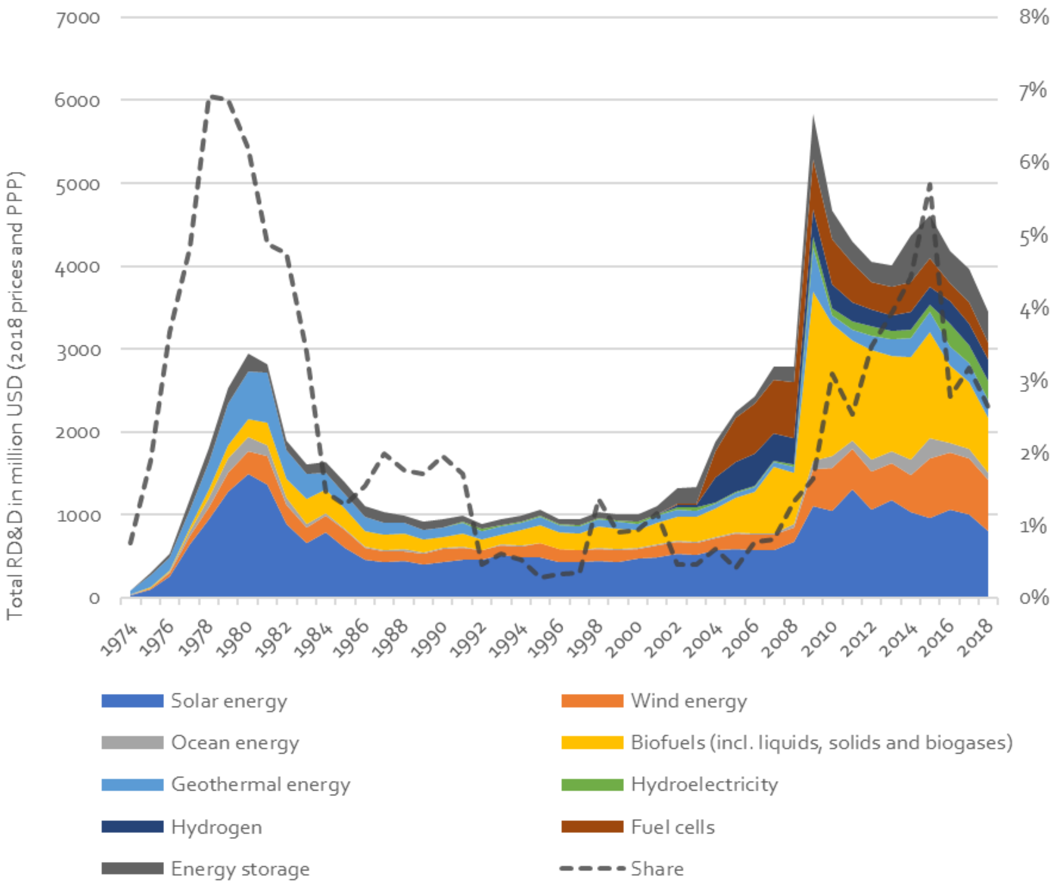


FIGURE 3.13. GLOBAL PUBLIC RENEWABLE ENERGY RD&D BUDGET IN MILLION USD -2018 PRICES AND PUBLIC-PRIVATE PARTNERSHIPS (PPP) - BETWEEN 1974 AND 2018 [46]

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[5] Includes tidal stream and range, wave, ocean thermal energy conversion and salinity gradient.

3.4.1 EARLY-STAGE DEMONSTRATION PROJECT FUNDING

One of the crucial factors to guarantee the successful development of ocean energy technologies is the availability of funding. Funding may come from a different range of public and private sources, yet some technologies will be more attractive to certain types of investors.

Figure 3.14 shows the breakdown of investment sources for renewable technologies in Europe in 2017 as reported by FS (Frankfurt School)-UNEP Centre/BNEF [48] and Figure 3.15 presents the share of public and private funding supporting ocean energy per development phase as outlined by the Ocean Energy Forum [42]. As of 2016, ocean energy is mostly funded by public support initially and, as it transitions from research and development (R&D) towards prototype and demonstration stages, private investors are attracted. This is a result of the high risk of failure of a technology during the initial development stages in combination with the high investment costs associated at this early stage. As technology development advances, the risk of failure decreases, and other type of investors gain interest. In contrast, wind energy, a mature and market competitive sector, is mostly funded by asset finance.

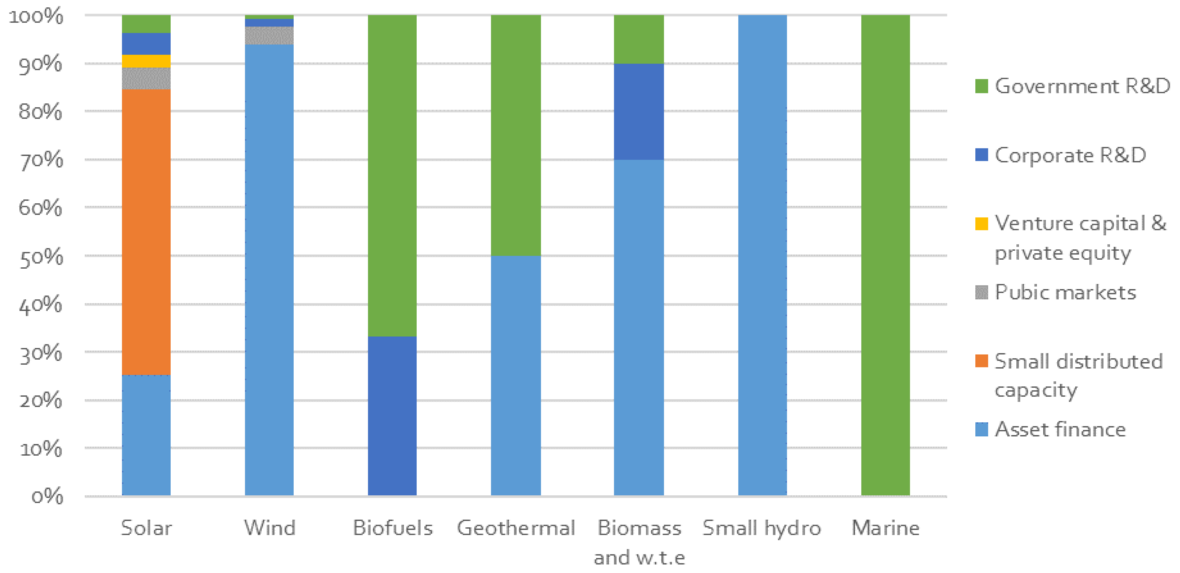


FIGURE 3.14. DISTRIBUTION OF INVESTMENT SOURCES FOR RENEWABLE TECHNOLOGIES IN EUROPE IN 2017 [48]

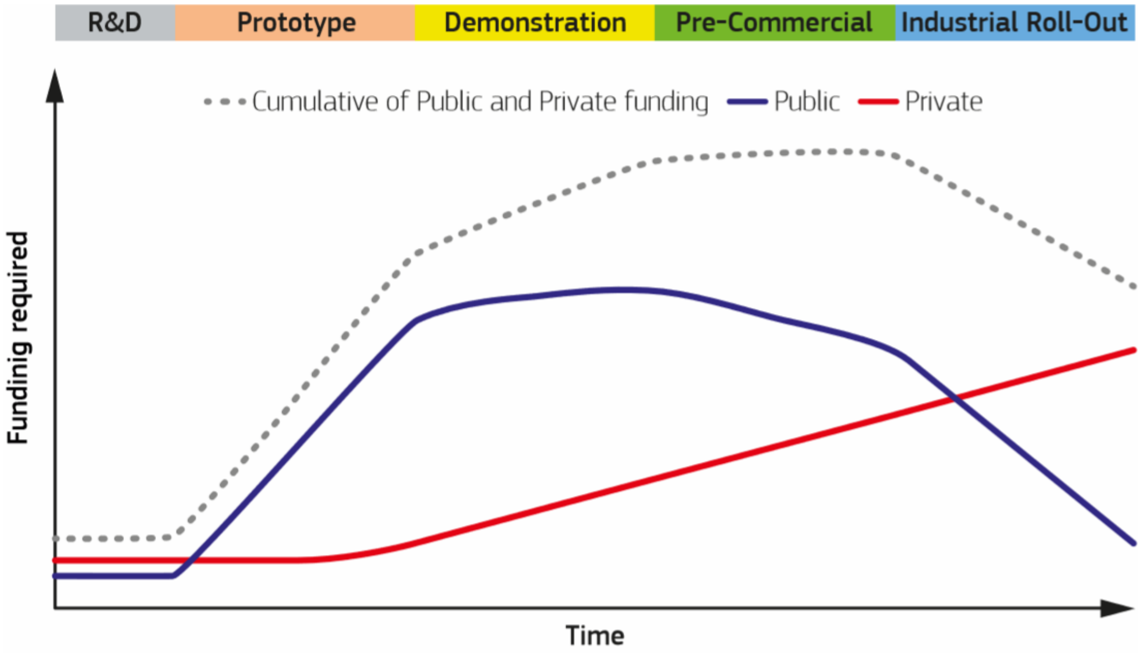


FIGURE 3.15. INDICATIVE SHARE OF OCEAN ENERGY FUNDING SOURCE AS A FUNCTION OF THE DEVELOPMENT PHASE [42]

3.4.2 COMMERCIAL-STAGE FUNDING MECHANISMS

Unless high-risk tolerance investors can be attracted, public support will remain the main source of funding for ocean energy. Public funding and support for renewable energy production and technology development is granted through a variety of push and pull mechanisms, briefly described here:

- **Feed-in-Tariffs** (FiTs): long-term agreement (typically, 15 to 25 years) offered to all types of renewable energy producers and based in proportion to the resources and capital expended to produce the energy.
- **Contracts for Difference** (CfD): a strike price (SP) for electricity is negotiated between government and the renewable electricity generator. The SP concerns the supply of electricity for a fixed period of time into the future. If the market price is below the SP, the government will pay the generator the difference and vice versa. The CfD, therefore, guarantees a price for the electricity into the future.
- **Green certificates** (GCs): green certificates, also called renewable energy certificates (RECs), are issued to renewable electricity generators once they feed a certain amount of clean electricity into the grid (normally, 1MWh). Power suppliers can then trade their RECs on the open market as a commodity.
- **Quota obligations or Renewable Portfolio Standard** (RPS): entities subjected to a RPS have the obligation to provide, purchase, or consume a minimum amount of power generated from renewables.

- **Renewable energy auctions**: calls issued by the government for renewable energy producers to procure a certain capacity or generation. Producers then submit a bid with a price per unit of electricity, and the successful bidder is then offered a power purchase agreement (PPA).
- **Tax credit**: renewable energy providers receive a deduction on their tax bills according to the amount of electricity they produced.

Push and pull mechanisms adopted vary from country to country. Furthermore, around the world, most countries have pull mechanisms for particular RE technologies such as wind and solar energy and very few ones offer support particularly targeted to ocean energy [5]. Table 3.6 describes a few pull mechanisms adopted by countries around the world that are applicable to ocean energy technologies and that may contribute to the development of an ocean energy market.

As detailed in Table 3.7, FiTs are the most popular policy mechanism among OES countries. Eight members (Canada, France, Germany, Ireland, Italy, Japan, Monaco, and Netherlands) have adopted this mechanism. Nevertheless, it is also important to highlight that, of the 29 countries listed, six (Australia, India, New Zealand, Portugal, Singapore, and South Africa) have not adopted any market incentive strategy.

Ocean energy projects are usually too capital-intensive for venture capitals and too risky for private equity. The resources available are limited. Private investment in the sector is usually self-financed. Thus, there are several push mechanisms at the national level to support prototypes and demonstration projects. In this sense, public funding is used to leverage private capital. An interesting example is Ireland's Ocean Energy Prototype Development Funding Programme [49]. This programme is divided into two mechanisms:

- The **Research, Development and Demonstration Fund**
- The **Ocean Energy Prototype Development Fund**

The programme contributes to cover costs incurred during a project timeframe related to staff, materials, equipment, travel and dissemination, and external consultants. The support offered by the programme ranges from a base contribution of 25% of approved eligible costs related to experimental development to a full support for fundamental research and varies depending on the research category, type of company, and collaboration or publication of project results.

Other countries such as France, Portugal, and the UK have implemented push mechanisms aiming to contribute to bridge the gap from demonstration projects to commercialisation [39]. The recently published Low Carbon Energy Observatory (LCEO) Ocean Energy Technology Market Report 2018 [50] offers a more detailed list of push mechanisms implemented by EU and non-EU countries. Ultimately, both pull and push mechanisms are fundamental for the sector to reach a level of maturity that allows it to compete on the market with other renewable energy technologies.

TABLE 3.6. SAMPLE OF PULL MECHANISMS ADOPTED BY COUNTRIES AND APPLICABLE TO OCEAN ENERGY [5] [51]

Country/ Region	Pull mechanism applicable to ocean energy
United Kingdom	Accredited RE plants with a capacity of up to 5MW sell their electricity to the grid at fixed rates that are updated annually by the Gas and Electricity Markets Authority (Ofgem). All technologies used in the generation of electricity from RE sources are eligible. The tariff for non-solar PV power is £53.8/MWh (~€63.9/MWh) exported [52].
Denmark	The operators of RE plants usually receive a variable bonus paid on top of the market price. There is, nevertheless, a statutory maximum per unit of power and energy source that should not be exceeded by the sum of the market price and the bonus. Technologies such as wind energy, biogas, biomass, solar energy, wave and tidal energy as well as hydro-electric power stations not exceeding 10MW are eligible. Wave power plants commissioned between 2018 and 2020, the installed capacity must be less than 1MW to be eligible for the subsidy. Plants with an installed capacity of up to 6kW may receive a maximum subsidy (bonus plus market price) of 130 DKK (approx. €17.4) per MWh, applicable for 10 years after the grid connection. Plants with an installed capacity of more than 6kW may receive a maximum subsidy (bonus plus market price) of 600 DKK/MWh (~€80/MWh), applicable for the first 10 years of operation, and 400 DKK/MWh (~€53.5/MWh), applicable for a further 10 years.
Netherlands	RE Generators that use the electricity they consume may be exempt from the tax levied on electricity consumption (i.e., Energy tax). Plants generating electricity from waves and tidal flows are eligible for an exemption from the Environmental Protection Tax. This tax has several bands depending on the level of consumption and ranging from $0.6/MWh (~€0.5/MWh) to $116/MWh (~€105/MWh).
Norway	The Electricity Certificates Act obliges electricity suppliers and certain electricity consumers to prove that a certain quota of the electricity supplied by them was generated from RE sources. Tradable certificates allocated to RE producers serve as evidence of compliance. Ocean energy is fully eligible. The quotas range from 0.137MWh of electricity in 2017 through 0.183MWh in 2025 to 0.008MWh in 2035.
Thailand	The Renewable and Alternative Energy Development Plant (AEDP 2012 – 2021) establishes a renewable power target of 2MW of installed wave and tidal energy capacity by 2021 [53]. This seeks to speed up the study to capably identify the sources and technology types to be applied for energy from Thailand sea, particularly in the Sarasin Bridge area in Phuket and the surrounding areas of Koh Sa Mui – Pa Ngan and Koh Tan.
France	The country established an ocean power target of 380MW installed capacity by 2020 [54].

TABLE 3.7. NATIONAL STRATEGIES FOR OCEAN ENERGY DEVELOPMENT AND PUSH AND PULL MECHANISMS ESTABLISHED IN OES COUNTRIES [24] [50]

	National strategy				Market incentives					
	Capacity targets	National strategy	Technology roadmap	Marine Spatial Plan	Feed-in-Tariffs	Contracts for Difference	Green certificates	Quota obligations	Auctions	Tax credit
Argentina										
Australia										
Belgium		X	X	X			X			
Brazil										
Canada	X	X	X	X	X				X	
Chile										
China	X	X		X			X			
Denmark			X	X	X					
France	X			X	X				X	
Germany		X		X	X				X	
India										
Indonesia	X									
Ireland	X	X	X	UD	UD				?	
Italy	X	UD			X					
Japan(1)		X	X		X					
Korea(2)	X	X	X					X		
Mexico	X		X				X			
Monaco(1)				X	X					
Netherlands				X	X					X
New Zealand				X						
Norway				X				X		
Portugal	X	X	X	X	X					
Singapore										
South Africa				X						
Spain	X	X							X	
Sweden		X		UD			X			
UK	X	X	X	X		X				
Uruguay										
USA		X		X				X	X	

UD: Under development. (1) Information from 2017. (2) Republic of Korea.

3.4.3 POLICY RECOMMENDATIONS FOR WAVE ENERGY DEVELOPMENT

Some policy recommendations to help improve the effectiveness of the future support for wave energy innovation and help accelerate the technology's journey towards commercialisation have been laid out on the report "Examining the effectiveness of support for UK wave energy innovation since 2000" [55]. Although the recommendations are presented within the UK framework, some of them are applicable for the development of the global wave energy market:

- Continue providing access to EU innovation funding such as Horizon2020;
- Share and synthesise lessons from past and present wave energy innovation programmes;
- Key policy decisions should be made against the backdrop that wave energy has not enjoyed the same level or consistency of RD&D support in comparison to more mature renewables such as wind and solar energy;
- Establish policies and support mechanisms to mitigate the investment risks associated to emerging technologies and attract private investors;
- Avoid competition for subsidies with established low-carbon energy technologies;
- Avoid the need for the private sector to match the funding to support wave energy RD&D;
- Support wave energy niche market formation by facilitating deployment of full-scale demonstration wave energy converters in "real-world" niche markets; and
- Enable easy access to wave energy test facilities.

3.5 RANKING COUNTRIES BY ATTRACTIVENESS FOR OCEAN ENERGY DEVELOPMENT

It is possible to develop an index to assess how attractive a country is for the deployment of ocean energy based on measures such as the revenue support available for these energy technologies in the country in question, the wave and tidal resource available, and the local facilities and supply chain. It is important to note that these rankings are subjective, and some factors may change over time (e.g. revenue support). It is therefore recommended that the analysis is repeated, which would facilitate understanding of the sector development. Despite the subjectivity, attractiveness ranking exercises can prompt useful discussion, provided they are not seen as absolute and unchanging.

A study by the University of Edinburgh created an International Marine Energy Attractiveness Index [56] investigating 21 countries using 14 metrics across three themes: resource, policy & finance, and industry & infrastructure. Countries were assigned a qualitative score for each metric based on Scottish Development International country reports, wider IEA literature and interviews, and consultation with marine energy industry experts.

De Andres et al. [57] reviewed six countries in detail, using 16 common indicators that could vary over time, plus fixed resource indicators (four wave and five tidal) with no potential for change. The countries selected had significant interest in ocean energy: the United States, the United Kingdom, France, Canada, Spain, and Chile. The results of this study indicated that the UK was the most attractive country for both wave and tidal energy. The support mechanisms as well as the country's test facilities make it appealing for developers, researchers, and investors interested in ocean energy. On the opposite end, Chile and Spain, despite their high levels of resource offer very modest or no financial and regulatory support. The index score serves as a call for action in the case of these two countries. For tidal energy, the UK holds a legacy advantage, having started earlier to support tidal energy; however, it is limited by poor grid connection availability in areas of high resource, being thus awarded a lower attractiveness score than for wave energy. It is important to highlight that the margin between the scores awarded to France, Canada, and the UK are very small in the case of tidal energy. This underpins the higher level of development and maturity achieved in the tidal energy sector compared to the wave energy sector. Once again, Chile and Spain received the lowest attractiveness scores due to the lack of support mechanisms in place and infrastructure available.

Ultimately, the attractiveness index methodology could be applied to other countries showing interest in these technologies recently, including Japan, South Korea, China, Singapore, Australia, New Zealand, and also some of the countries mentioned in section 2.4 paying high electricity prices while having low energy consumption. Such an index could facilitate the assessment and comparison of different geographical locations for ocean energy development and deployment. It might serve, as well, as a tool for governments to focus on certain areas that could help their countries improve the attractiveness level for developers, researchers, and investors interested in ocean energy. Furthermore, policy-makers could attract support by presenting the effect of different policies and regulations on the attractiveness index or attract supporters to integrate ocean energy in their energy plans, thereby contributing to achieving their decarbonisation or development goals.

4. FUTURE MARKET FOR GRID POWER

4.1 FUTURE SCENARIOS FOR THE ELECTRICITY MARKET

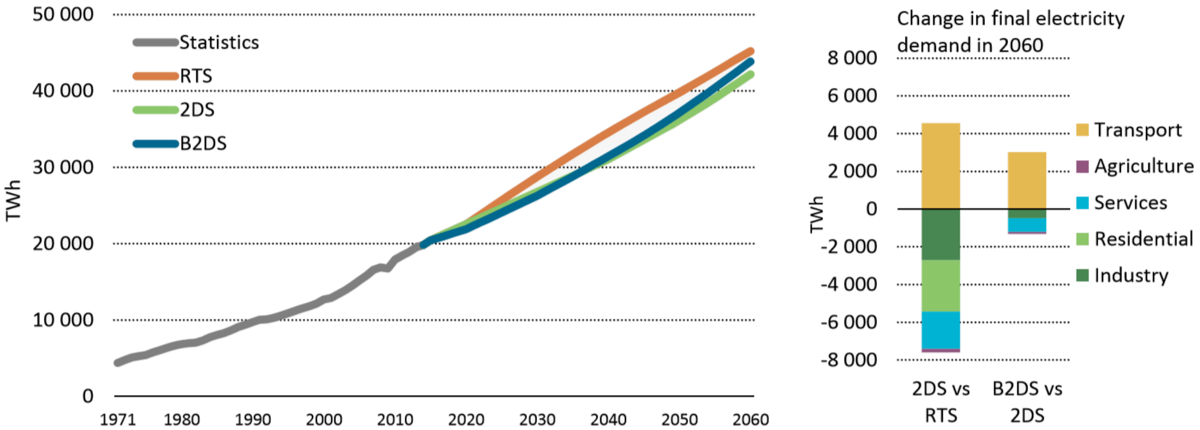
Electricity is poised to be the energy carrier of the future, aiding both in the decarbonisation and the improvement of the efficiency of the future global energy system. Renewable energy has found in this pathway a key role to play. This section elaborates on the development of the power market in the coming years.

4.1.1 GLOBAL ELECTRICITY MARKET PROJECTIONS

As described in section 2.2, the IEA has made projections for the global electricity market considering a range of future scenarios. By 2060, the global electricity needs are expected to almost double, reaching between 40,000TWh/yr and 45,000TWh/yr, with only slight differences[6] between the three scenarios considered in the ETP study, as shown in Figure 4.1. The proportion of electricity used by various sectors varies between the scenarios developed depending on the underlying assumptions.

Electricity is expected to account for approx. 23 – 31% of the total final consumption in 2040 and be generated mostly by low-carbon technologies as depicted in Figure 4.2 below.

The use of electricity in the transport and heating sectors is the main source of growth in demand in most of the scenarios. Coupled with the predominance of low-carbon and intermittent renewable energy sources expected in the coming years, this situation opens further business opportunities for the flexibility and balance alternatives discussed in section 2.3. Hydrogen, utility-scale battery storage, smart grids, and heat-pumps may become important parts of the future energy system.



RTS = Reference Technology Scenario, 2Ds = the 2°C scenario, B2Ds = the beyond 2°C scenario.

FIGURE 4.1. EVOLUTION OF THE GLOBAL ELECTRICITY DEMAND 1971–2060 FOR THE ETP SCENARIOS [8]

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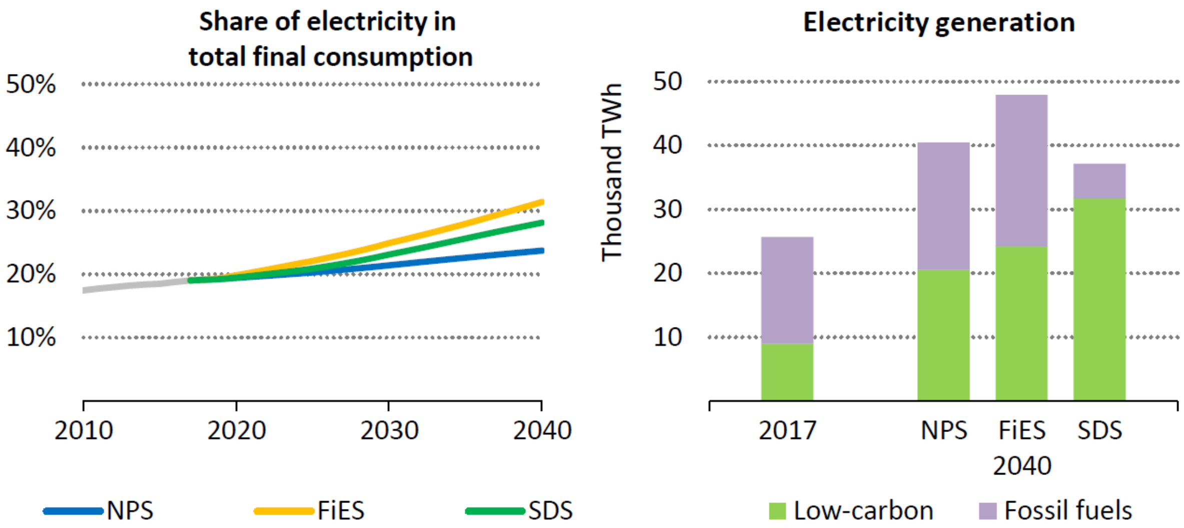
[6] 45,011 TWh/yr in the RTS, 41,860 TWh/yr in the 2DS, and 43,661 TWh/yr in the B2DS



NPS = New Policies Scenario, FiES = Future is Electric Scenario, SDS = Sustainable Development Scenario. Fossil fuels category excludes electricity generation from plants using carbon capture, utilisation and storage.

FIGURE 4.2. SHARE OF ELECTRICITY IN TOTAL FINAL CONSUMPTION AND SHARE OF LOW-CARBON ELECTRICITY GENERATION IN 2040 FOR THE ETP SCENARIOS [8]

4.1.2 EU ELECTRICITY MARKET PROJECTIONS

Focusing on the European Union, the "EU Reference Scenario 2016" report developed by the European Commission supports the electrification projections presented by the IEA. The EU Reference Scenario 2016 projected that the services sector will increase its contribution to the gross value added (GVA) from 75% in 2015 to 78% in 2050, whilst energy intensive industries are projected to remain at a similar contribution to the GVA at 2% (3% in 2015) [9].

Overall energy consumption in the EU is estimated to have peaked in 2006, and is expected to experience a slight reduction over the coming year up to 2050 as shown in Figure 4.3.

However, electricity is projected to make up an increasing proportion of final energy consumption, growing from 21% in 2010 to 28% in 2050. This is due to higher demand for air conditioning, the introduction of electric heat pumps, an increase of electric appliances in the residential and the tertiary sectors (e.g., IT, leisure, and communication appliances), further electrification of rail, and long-term penetration of electric vehicles.

The progress of electricity demand in the EU can be observed in Figure 4.4 below. It increased approx. 10% since the millennium, rising to 3,250TWh in 2015 from 3,000TWh in 2000, with a slight reduction following the global economic crisis around 2008. Demand is projected to continue to grow over the next decades, exceeding 4,000TWh in 2050.

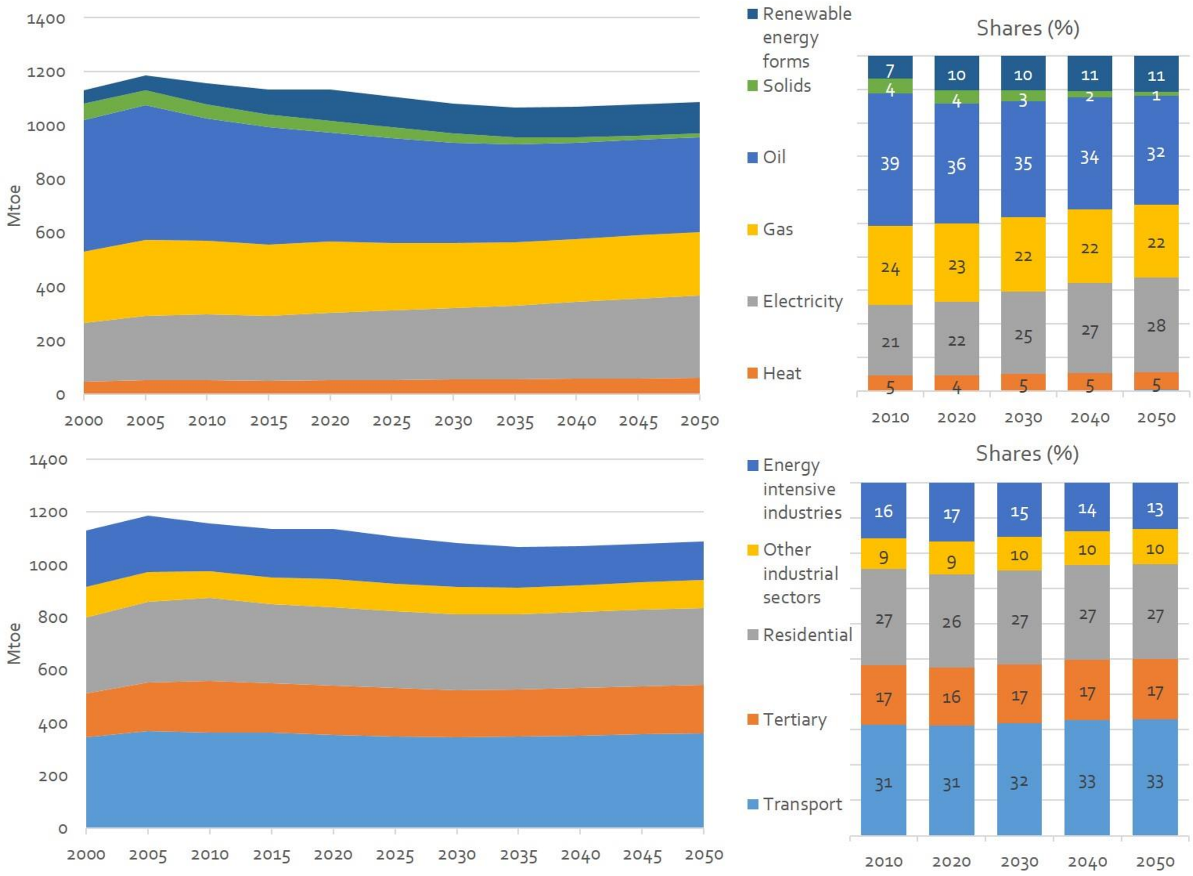


FIGURE 4.3 FINAL EU ENERGY CONSUMPTION BY FUEL AND BY SECTOR [9]

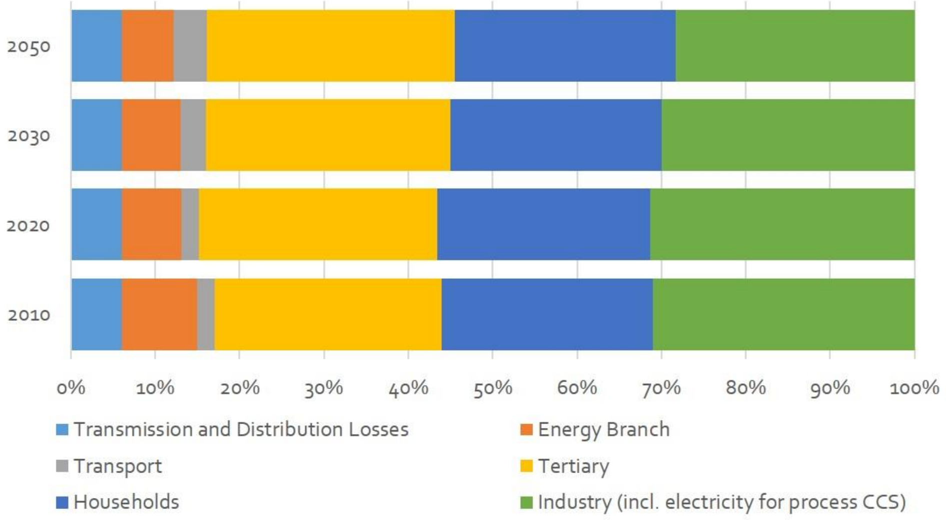


FIGURE 4.4. TRENDS IN EU ELECTRICITY DEMAND BY SECTOR [9]

4.2 FUTURE PROJECTIONS FOR OCEAN ENERGY

Considering the significant role that electricity is expected to play in the future global energy system, it is important to review how is ocean energy expected to progress and what kind of contribution could it have to the electrification trend seen in the projections described over the previous sections. For this, future deployment of ocean energy can be split into two-time horizons, based on the available projections:

- Short-to-medium term (to 2030)
- Medium-to-long term (to 2050).

Beyond 2050, there is significant uncertainty; however, there is certainly still scope for increased future deployment beyond the medium-to-long-term projections based on the potential resource detailed in Section 3.1.

4.2.1 SHORT-TO-MEDIUM TERM

Projections for short to medium term (up to 2030) deployment of ocean energy have been compiled by DG-MARE's "Market Study on Ocean Energy" [58]. The future rates were generated based on historic deployments, planned projects that had been announced, and simulations of new projects based on TRL, typical duration, and forecast growth (see the report for full methodology). From this, three scenarios were developed:

- *Optimistic*: This scenario assumes that all projects are deployed as scheduled.
- *Medium*: In this scenario all projects are deployed, yet some are delayed given the status of the project at the time the report was written.
- *Pessimistic*: This scenario assumes that all projects are delayed as in the previous scenario and some are cancelled. The cancellation of some projects is randomised; however, a threshold is established based on the status of the project, the TRL, and the technology.

The projected cumulative installed capacity per scenario is shown in Figure 4.5 overlain with the current installed capacity retrieved from OEE [59]. It can be seen that the current situation seems to be in line with the simulated pathway corresponding to the medium scenario.

In the pessimistic scenario, a maximum of 705MW of tidal stream energy and 70MW of wave energy are foreseen by 2030 [58]. On the contrary, under the optimistic scenario, a maximum of 2,388MW of tidal stream capacity and 494MW of wave energy capacity are expected by 2030 [58].

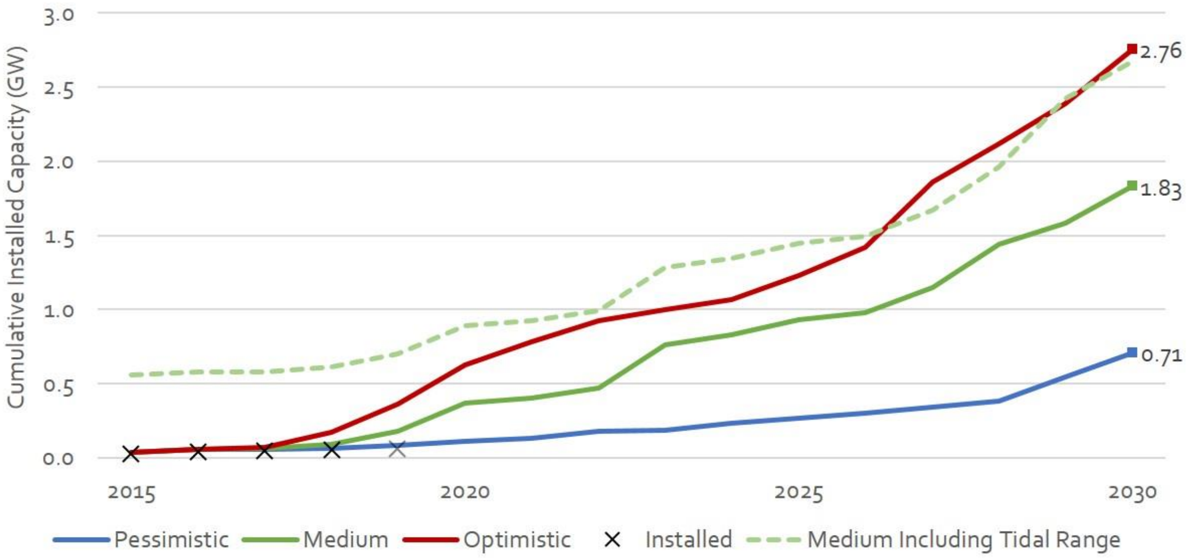


FIGURE 4.5. WAVE AND TIDAL STREAM CUMULATIVE CAPACITY DEPLOYED PREDICTIONS (SIMULATED) AND INSTALLED. ADAPTED FROM [58] [59].
NOTE 2019 INSTALLED CAPACITY IS BASED ON SELECTED DEPLOYMENTS LISTED IN Table 3.4.

4.2.2 MEDIUM-TO-LONG TERM

The 2012 IEA Energy Technology Perspectives report includes projections for ocean energy deployed capacity out to 2050 for four different emissions scenarios, as shown in Figure 4.6. Note that this study includes tidal range, which forms a significant component, particularly in the earlier period as almost all current deployment capacity corresponds to two large tidal barrages [34], as shown in Table 4.1.

TABLE 4.1. SIGNIFICANT TIDAL RANGE SCHEMES WORLDWIDE

Tidal Range Scheme	Start Date	Capacity (MW)	Nominal Annual Generation (GWh/yr)
Sihwa Lake, South Korea	2012	254	552
La Rance, France	1966	240	540
Annapolis Tidal Power Plant, Canada	1984	20	30
Total	-	*1014*	*1122*

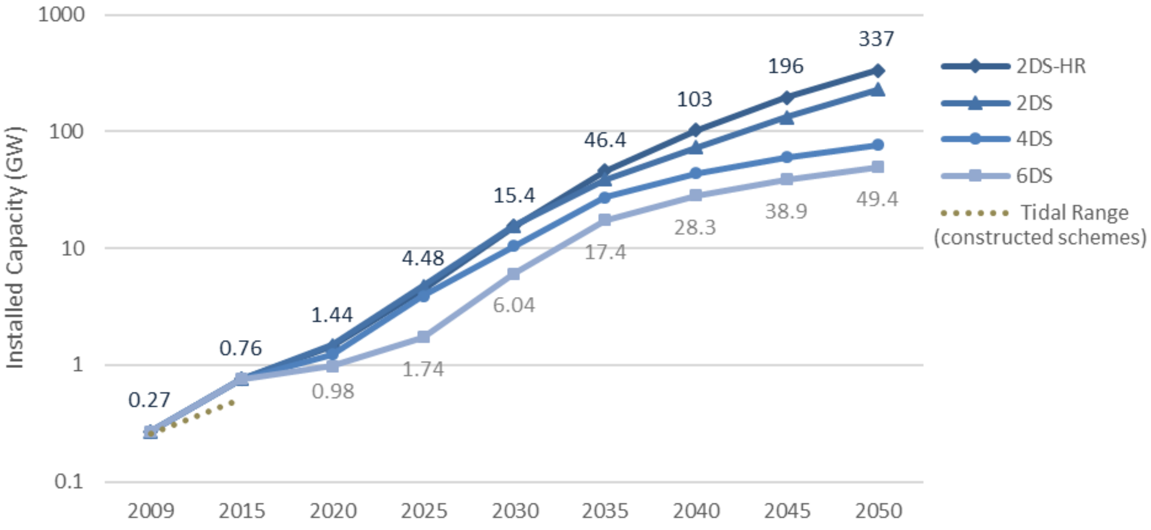


FIGURE 4.6. 2012 PREDICTIONS OF OCEAN ENERGY CAPACITY DEPLOYED TO 2050 FOR FOUR EMISSIONS SCENARIOS [60]. NOTE LOGARITHMIC SCALE AND THESE FIGURES INCLUDE TIDAL RANGE.

More recently, the IEA's SDS results show that global progress is not on track to meet the ocean power generation target, as shown in Figure 4.7. A much higher annual growth rate of 24% through 2030 is required along with policies promoting R&D, further cost reductions, and large-scale development [61]. Given the limited availability of sites for additional tidal range deployments worldwide, wave and tidal stream technologies will be fundamental to meet the ocean power generation target. Moreover, wave and tidal stream projects offer the advantage that construction and installation times are less extensive than those for tidal range projects (see, for example, Bombora's 2M wave park in Lanzarote, Spain [62] vs the Swansea Bay Tidal Lagoon [63]).

The European Commission has recently published a market outlook for wave and tidal energy based on simulations ran with the JRC-EU-TIMES model [50]. Three global scenarios are examined:

- Baseline: a basic uptake of renewable energy sources takes place.
- Diversified: higher decarbonisation is sought through the implementation of technologies such as nuclear energy and carbon capture and storage (CCUS) in the global energy system.
- Pro-RES: there is a higher uptake of renewable energy sources and lower technology costs.

To better understand the potential progress of ocean energy technologies, a so-called "SET Plan technology learning scenario" was included in the report. The SET scenario assumes that technology innovations will allow the energy sector to reach the targets of the SET Plan. This plan has set levelised cost of electricity (LCOE) targets for ocean energy technologies as described in Table 4.2.

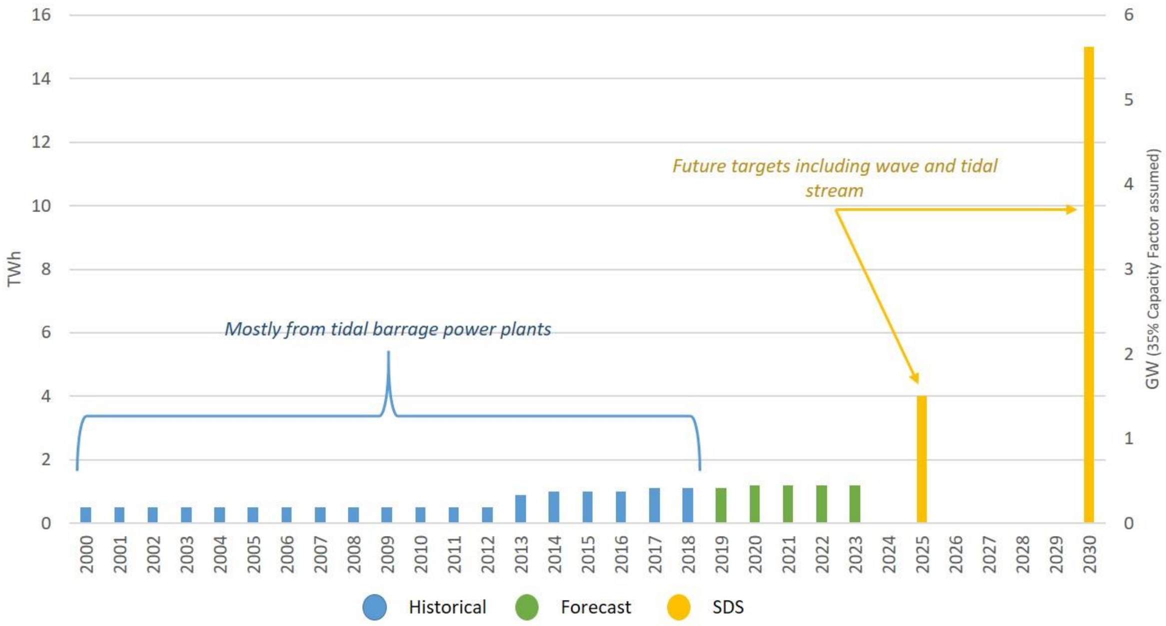


FIGURE 4.7. 2017 OCEAN ENERGY GENERATION, FORECAST AND 2025/2030 TARGETS [61]. NOTE THESE FIGURES INCLUDE TIDAL RANGE.

TABLE 4.2. LCOE TARGETS FOR WAVE AND TIDAL ENERGY TECHNOLOGIES LAID OUT IN THE SET PLAN [50]

Technology	Year	Target (€/MWh)
Tidal energy	2025	150
	2030	100
Wave energy	2025	200
	2030	150
	2035	100

The results of the simulations are presented in Figure 4.8. Tidal energy is expected to reach approx. 29GW by 2050 under the Pro-RES scenario. The SET Plan aims to introduce tidal energy into the energy system in 2030 and the cumulative installed capacity is expected to peak in 2040 at approx. 30GW. Under the SET Plan scenario, there is a decrease in the cumulative installed capacity of tidal energy between 2040 and 2050; however, this decrease does not affect power generation. Furthermore, under all scenarios the UK is the first country to integrate tidal energy into its energy system. Under the Pro-RES and SET Plan scenarios, both France and Ireland become key market players as well; although France's tidal uptake depends on the renewal of nuclear energy capacities.

The results are not as promising for wave energy under the Pro-RES scenario where a cumulative installed capacity of 0.04GW could be reached by 2050. The targets laid out in the SET Plan are shown to be fundamental for wave energy technology in particular. Under this scenario, the cumulative wave capacity by 2050 is 30.9GW. Furthermore, under this scenario, Spain takes the lead in wave energy deployment within the EU. Portugal, Poland, and Italy are expected to make important contributions as well.

It is important to highlight that Ireland is expected to be the country where ocean energy plays the most significant role within the EU. Ocean energy technologies are expected to make up approx. one-quarter of Ireland's electricity mix in 2050 under the SET Plan and Diversified scenarios and approx. 22% under the Pro-RES scenario.

Overall, ocean energy is seen as a contributor to decarbonisation efforts. Countries with significant resource potential and with enabling and supporting regulatory frameworks or support mechanisms in place are expected to be attractive markets for ocean energy development. However, further cost-reductions and push and pull mechanisms could strengthen the progress and create additional growth opportunities for these technologies.

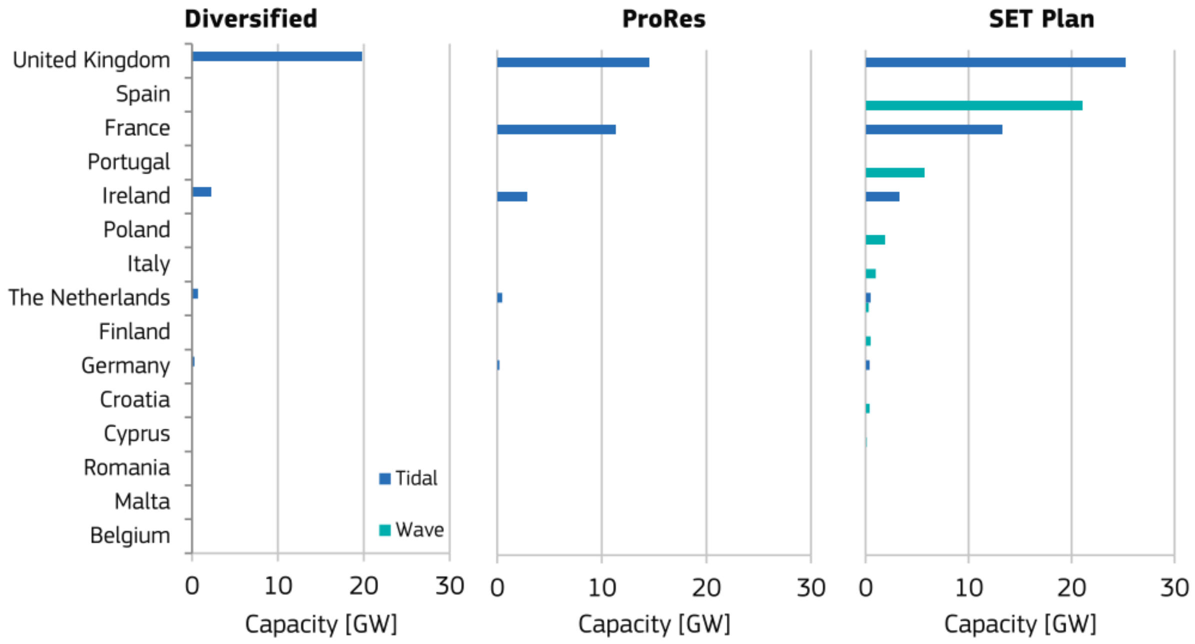


FIGURE 4.8. CUMULATIVE INSTALLED CAPACITY OF WAVE AND TIDAL ENERGY BY 2050 PER JRC-EU-TIMES SCENARIOS [50]

5. FUTURE ALTERNATIVE MARKETS

5.1 RATIONAL OF CONSIDERING ALTERNATIVE MARKETS

Integration of wave and tidal stream technologies into the grid-connected power market is challenging. Aside from the technical barriers yet to be overcome, if WECs and TECs are to be part of the grid energy mix they will either need to be cost-competitive with similar energy technologies such as offshore wind or provide additional benefits in comparison with their competitors to make them more attractive alternatives. However, at the moment, it is not clear whether wave and tidal stream technologies can meet either of these requirements, causing investors to question whether to continue funding the sector or not.

Alternatively, beyond the grid, non-utility markets could represent a unique opportunity for wave and tidal stream development. Given their nature, non-utility markets tend to have a narrower span of power-generating options, with sometimes only one source to rely on and paying a higher-than-usual cost for its energy [64]. This creates a less-competitive market environment, where wave and tidal stream could technologically and economically thrive, adopting an important role within these smaller markets.

Furthermore, the blue economy, i.e., *"the sustainable use of ocean resources for economic growth, improved livelihoods and jobs, and ocean ecosystem health"* [65], is an important opportunity for sustainable ocean energy technologies such as wave and tidal stream to play a vital role in social and economic development [66]. Non-utility markets in Small Islands Developing States (SIDS) and coastal Least-Developed Countries (LDCs) offer suitable conditions for the deployment of wave and tidal stream technologies and could be an attractive alternative to provide a source of clean, renewable energy to these nations [64] [67]. However, the idea has also been explored by developed nations such as Australia [68].

Moreover, lately, non-utility markets for wave and tidal stream have been gathering much attention. Multi-million-Euro projects in Europe – such as those described in Table 5.1 – as well as other regions of the world are exploring the synergies arising from combining wave and tidal stream with applications such as desalination [69] [70], offshore aquaculture [71], hydrogen production [72], or even coastal defence [73]. Academic and industrial research is looking into hybrid systems that combine wave and wind energy resources along the coasts of South America, Europe, and the USA, see for example [74] [75] [76] [77] [78] [79].

There are several potential business opportunities for ocean energy in these non-utility markets; however, key questions about non-utility markets for wave and tidal stream energy remain unanswered. What's their actual economic-value? Where are these markets located? Are these merely a stepping-stone for the ocean energy industry, as traditionally regarded, or the only realistic future market given the still immature state of development after years of research and economic effort? This section elaborates on some of the opportunities and potential markets identified for wave and tidal stream energy. Although determining the potential revenue opportunities at such an early stage in development of the wave and tidal stream technologies is rather challenging, this section provides information regarding prospective or current market sizes, potential applications, geographical locations, and future outlook of the markets.

TABLE 5.1 EUROPEAN PROJECTS STUDYING OCEAN ENERGY TECHNOLOGIES FOR THE BLUE ECONOMY

Project name	Description and objectives	Funding source
Blue Growth Farm [80]	This project will design an innovative automated, modular and environmentally-friendly offshore multi-purpose floating platform for open sea farm installations. These include a central protected pool to host an automated aquaculture system, capable of producing high quality fish, as well as a large storage and deck areas to host a commercial 10 MW wind turbine and a number of WECs. The Blue Growth Farm seeks to reduce costs of implementation and increase economic viability of multi-use platforms for the European maritime industry, secure acceptance of these new developments by local communities and society, and improve the professional skills and competences of those working within the blue economy.	EU Horizon 2020
Marine Investment for the Blue Economy (MARIBE) [81]	MARIBE aims to identify opportunities for Blue Growth sectors to cooperate with other sector via multi-use of space or in multi-use platforms and assist in the development of the most promising project combinations. The project seeks to provide information on the socio-economic context and the key technical and non-technical challenges facing these projects based in part on lifecycle learning. MARIBE forms part of the long-term Blue Growth strategy to support sustainable growth in the marine and maritime sectors as a whole.	EU Horizon 2020
MERMAID [82]	MERMAID will develop concepts for the next generation of offshore platforms which can be used for multiple purposes and under different physical conditions (from deep water to shallow and inner waters). The project does not envisage building new platforms, but will theoretically examine new concepts, such as combining structures for energy extraction, aquaculture and platform related transport. MERMAID aims to identify best practices to develop a project on multi-use platforms and best strategies for installation, maintenance and operation of a multi-purpose offshore platform. Finally, MERMAID will determine the economic and environmental feasibility of multi-use platforms.	EC Seventh Framework Programme for Research and Development
TROPOS [83]	The main objectives of the Tropos Project is to develop a modular floating platform, adapted to deep waters and determine the optimal locations for these platforms in Mediterranean, subtropical and tropical regions, in particular on the EU Outer-Most Regions (OMRs), composed by the Azores, the Canary Islands, Guadeloupe, Guiana, Madeira, Martinique and Reunion. The floating platform system integrates a wide range of possible sectors: ocean renewable energy and food (aquaculture), maritime transport and the leisure sector, and oceanic observation activities. The project assesses the economic feasibility and viability of the platform as well.	EC Seventh Framework Programme for Research and Development

Project name	Description and objectives	Funding source
H2OCEAN [84]	H2OCEAN (Development of a Wind-Wave Power Open-Sea Platform Equipped for Hydrogen Generation with Support for Multiple Users of Energy) aims at developing an economically and environmentally sustainable multi-use open-sea platform on which wind and wave power will be harvested. Part of the generated energy will be used for multiple applications on-site, including the conversion of energy into hydrogen that can be stored and shipped to shore, and a multi-trophic aquaculture farm.	EC Seventh Framework Programme for Research and Development
Multiple Use of Space for Island Clean Autonomy (MUSICA) [85]	MUSICA will design and build a pilot multi-use offshore platform in European waters capable of providing 70% of the electricity and all fresh water to a small island community via renewable sources including wind, wave, and PV solar and desalination. Aquaculture operations will also be carried out around the platform. MUSICA is targeting small islands with populations of up to 2,000 inhabitants in the first instance as these communities currently pay disproportionately high costs for electricity and water from outside sources - often with poor or intermittent supply. The project will also include the preparation of 'roadmap' plans for larger island groups including Malta, Gran Canaria and Chios.	EU Horizon 2020
Multi-Use in European Seas (MUSES) [86]	MUSES explores the opportunities for Multi-Use in European Seas, including the scope for innovation and blue growth potential. The project presents practical solutions on how to overcome existing barriers and minimize risks associated with Multi-Use development. Finally, MUSES provides an understanding of environmental, spatial, economic and societal benefits of co-location and highlights inappropriate regulatory, operational, environmental, health and safety, societal, and legal aspects.	EU Horizon 2020

5.2 POTENTIAL APPLICATIONS/MARKETS IDENTIFIED

A range of potential applications and markets have been identified for ocean energy based on the report "Powering the Blue Economy" [87] and other studies. These are summarised in Table 5.2. For the top four markets, a more detailed analysis is presented in sections 5.3 to 5.6. A summary of the other alternative markets is provided in section 5.7.

It is important to note that some of the potential applications identified may overlap. For example, marine aquaculture may be located in isolated communities, or costal disaster recovery could require desalination to provide much needed water. This is an additional benefit that can be exploited for the establishment of smart local energy systems and the contribution to the development of a blue economy.

TABLE 5.2. BRIEF DESCRIPTION OF ALTERNATIVE MARKETS IDENTIFIED

Section	Market	Description
5.3	**Isolated power systems/ islands/ microgrids**	Ocean energy can provide energy to regions not connected to a central energy infrastructure and located close to the coast. Thereby, ocean energy can become a means for sustainable development providing access to affordable and clean energy and powering a series of basic services such as health, water supply, among others.
5.4	**Offshore oil & gas extraction, processing, and decommissioning**	Offshore oil and gas platforms often partially meet their energy needs by burning the fuel extracted or through imports. There are a number of associated issues with this. In the case of energy imports, since platforms are normally installed in isolated locations, the fuel has to be transported with vessels or pipelines have to be installed. Additionally, with platforms having high energy availability requirements, turbines are forced to work at very low efficiencies (increasing the environmental impacts of the industry). Therefore, integrating local, clean ocean energy alternatives into the offshore O&G industry could support the reduction of its carbon intensity whilst increasing its energy security.
5.5	**Marine aquaculture and algae**	Ocean energy can replace diesel generation and power aquaculture systems including monitoring equipment, circulation pumps, navigation lighting, and refrigeration equipment. Furthermore, ocean energy systems can be integrated into and co-developed with algal systems and meet power requirements that are similar to those from aquaculture: safety, navigation lights, maintenance equipment, refrigeration, etc.
5.6	**Desalination**	Providing water for water utilities and isolated or small-scale distributed systems is an energy-intensive process traditionally powered by fossil fuels. Ocean energy systems are inherently located near desalination plants and, thus, can replace fossil fuels and contribute to decarbonisation efforts.
5.7.1	**Coastal resiliency and disaster recovery**	Coastal areas are among the most frequently affected regions by weather extreme events such as tsunamis and hurricanes. Additionally, these regions are at high risk due to climate change consequences such as sea-level rise. Mitigation and adaptation measures are being set in place including shore protection structures. There are already successful cases where ocean energy devices have been integrated into these structures. The power generated from ocean energy devices can meet power requirements after a coastal disaster as well.
5.7.2	**Ocean observation and navigation**	Other applications that would benefit given their co-location is ocean observation and navigation. Instruments, platforms and tools used to monitor and forecast oceanographic and meteorological data and ensure safe navigation receive their power via cables to shore power, solar panels, or batteries. Having these equipment meet their own power needs through their integration into ocean energy devices can be an attractive alternative.

Section	Market	Description
5.7.3	**Unmanned underwater vehicles**	These vehicles, usually used for observation, surveillance, persistent monitoring and subsea inspections, are currently limited in their range and duration due to the capacity of their batteries. Ocean energy has the potential to power underwater recharge stations and supply power continuously, if paired with battery banks, thereby reducing the reliance on expensive surface vessels and extend mission duration.
5.7.4	**Deep sea and seawater mining**	The alternative to extract valuable minerals from seawater has attracted much attention given their demand for modern-day technologies such as wind turbines, solar panels, and electric vehicles. Ocean energy can meet some of the power needs from seawater mining including electrolysers, adsorbent exposure systems, and on-site logistical needs.
5.7.5	**Marine datacentres**	Computer datacentres require significant amounts of cooling, so one solution is to locate them underwater, which offers the additional opportunity to power them by nearby ocean energy sources.

5.3 ISOLATED POWER SYSTEMS/ ISLANDS/ MICROGRIDS

Remote coastal communities are regions not connected to a central energy infrastructure, either a national electricity grid or natural gas pipeline, and located close to the coast. As a result, remote communities rely mostly on imported liquid fuels, unless they can identify and exploit local energy resources. Where energy requirements are met through imported fossil fuels, remote communities will tend to exhibit low energy security, be vulnerable to price fluctuation, and face high energy costs. In addition, where the present energy infrastructure is weak, the quality of the energy supply will be low [88].

The term "remote coastal communities" encompasses a broad range of regions throughout the world, with varied social, economic and technological backgrounds. Thus, the policy and technological measures required to improve access to affordable and clean energy may vary depending on, e.g., whether the region is a developed or a developing remote coastal community[7]. However, these regions will share similar approaches given their nature.

Determining the size of the electricity market in remote coastal areas is a difficult task at the moment. Within this market, nevertheless, there are segments and applications that have been identified and that, given their size, are more manageable and allow for a more detailed discussion.

An important market segment, and mostly the focus of the following sections, are Small Island Developing States (SIDS). SIDS are an example of remote coastal communities. SIDS are a set of 58 island state countries spread across the globe which share common sustainable development challenges [89]. Besides the energy concerns mentioned above arising from their remoteness, SIDS

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[7] The terms "developed economy" or "developed countries", here used interchangeably, refer to those nations classified as "High-income economies" by the World Bank [224]. The term "developing countries" refers to those nations classified as "Middle-income (Upper and Lower) economies" or "Low-income economies" by the World Bank [Ibid].

are especially vulnerable to food insecurity, overexploitation of fisheries, freshwater scarcity, natural disasters (e.g. hurricanes and earthquakes), limited land capacity and land degradation, and climate change effects such as sea-level rise and coastal erosion [90] [91].

Beyond providing local, clean energy to SIDS, ocean energy technologies have a unique opportunity with respect to other renewable energies in these regions. WECs and TECs could supply power to marine aquaculture farms and desalination plants, thus, securing the supply of sustainable food and freshwater. At the same time, pressure on fisheries could be reduced and the natural shore protection offered by healthy coral reefs enhanced [92]. WECs could also be integrated into new coastal protection structures to mitigate the effects of sea-level rise and coastal erosion [93].

SIDS are a short-term market opportunity for ocean energy with a total annual electricity consumption over 166TWh (see Annex III). SIDS represent just a fraction of the whole remote coastal communities' market. However, it is difficult to assess this much larger market given its extension and heterogeneity, and no global figures can be provided at this moment. Studies will ultimately have to be conducted on a case by case basis. In this regard, the attractiveness index described in section 3.5 may be useful to locate prospective sites for deployment of wave and tidal stream projects.

Closely related to the islands and remote coastal communities is eco-tourism, another potential market segment that might be attractive for the development of ocean energy technologies such as wave and tidal stream [94] [95]. A branch that has been gaining popularity in the last few years is luxury and remote tourism, which has been increasingly using the distributed nature of renewable energy to meet its energy needs. Ocean energy has become an interesting complement to luxury and remote tourism located near the shore. Recently, this type of energy has also inspired luxury architectural projects such as hotels and beach houses that harness ocean energy and are entirely energy-independent (e.g., the Harmonic Turbine Tidal Hotel in the South of China or the Hydroelectric Tidal House in Cape Town [96]). Although a much smaller market segment within remote coastal communities, these opportunities contribute to raise awareness and increase public acceptance of ocean energy technologies and are thus valuable. The energy requirements are, nevertheless, specific to each project and thus cannot be quantified currently.

Finally, there is a potential opportunity with defence and national security bodies around the world and their military bases, which may be a less price-sensitive market. Particularly, the U.S. Navy has been studying the integration of ocean energy to its remote facilities and autonomous surveillance and sensing activities [97] [98]. The Royal Australian Navy has also planned to harness the energy available from the waves offshore from Perth in Western Australia for the country's largest naval base in Garden Island [99]. Military bases usually have microgrids from 200kW to 5MW [87]. The integration of ocean energy technologies to these microgrids can mitigate the reliance on diesel fuel. Other alternative markets, such as ocean observation and autonomous underwater vehicles discussed in sections 5.7.2 and 5.7.3, could also have military applications.

5.3.1 FUTURE OF THE MARKET

By definition, remote coastal communities are regions not connected to a central energy infrastructure, with low access to affordable, reliable and modern energy services. Amongst these, SIDS have, on average, the lowest energy access. For instance, Papua New Guinea and Solomon Island in the Pacific SIDS have rates as low as 10% and 14%, respectively, the lowest amongst all

SIDS [100]. These are comparable to access rates from sub-Saharan countries, despite Solomon Island and Vanuatu having higher income levels [101].

In line with the United Nations Sustainable Development Goal 7: Affordable and Clean Energy[8], SIDS have implemented some of the most ambitious renewable energy targets at present. As noted by Dornan and Shah [102], the majority of modern countries with renewable energy targets aim to generate between 10% and 40% of electricity using renewable energies, whereas more than half of SIDS have targets higher than 40%. Some islands such as the Cook Islands and Fiji are aiming at 100% renewable energy penetration into the electric system by 2020 and 2030, respectively. Table 2 shows the renewable energy targets for all SIDS, separated by region: Pacific, Caribbean, and African and Indian Ocean, Mediterranean and South China Sea (AIMS).

In the 36 SIDS partners of the International Renewable Energy Agency (IRENA) LightHouse Initiative (LHI)[9], 660MW of renewable energy have been installed since 2014, and 2GW of additional capacity are planned by 2030 (see Figure 5.1). Although most of the renewable energy installed capacity is from solar (>400MW) and wind (100MW), the 2018 IRENA SIDS LHI report [91] mentioned geothermal and ocean energy within their priority working areas. Considering the limited land capacity and the risks of land loss due to sea-level rising that most SIDS face, ocean energies present a good opportunity for these states, which in spite of the progress noted still meet 90% of their power needs through fossils fuels.

TABLE 5.3. RENEWABLE ENERGY TARGETS FOR SIDS [102].

Country	Target	Target date	Notes
		Pacific	
Cook Islands	100%	2020	
Fiji	100%	2030	100% of electricity by 2030, 23% of final energy by 2030
Kiribati	45% urban, 60% rural	2025	Targets as listed in national development plans
Marshall Islands	20%	2020	
Micronesia, Federated States of	10% urban, 50% rural	2020	30% of primary energy supply by 2020
Nauru	50%[a]	2020	
Niue	100%	2020	
Papua New Guinea	50%[a]	2030	GHG emission reduction
Palau	20%[a]	2020	
Samoa	20%[a]	2030	
Solomon Islands	50%	2015	
Timor Leste	50%	2020	
Tonga	50%	2015	

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[8] The 2030 United Nations Agenda for Sustainable Development contains a list of 17 objectives known as Sustainable Development Goals (SDGs) which aim to spread peace, eradicate poverty and improve environmental conditions by 2030. SDG 7 "Affordable and Clean Energy" is concerned with providing universal access to affordable, reliable and modern energy services, such as electricity, and makes special mention to developing countries and small island states [225].

[9] Pacific: Cook Islands, Micronesia (Federated States of), Fiji, Kiribati, Marshall Islands, Nauru, New Caledonia, Niue, Palau, Papua New Guinea, Samoa, Solomon Islands, Tonga, Tuvalu, Vanuatu. Caribbean: Antigua and Barbuda, Aruba, Bahamas, Barbados, Belize, British Virgin Islands, Cuba, Dominican Republic, Grenada, Guyana, Montserrat, Saint Lucia, Saint Vincent and the Grenadines, Trinidad and Tobago, Turks and Caicos. AIMS: Cabo Verde, Comoros, Republic of Maldives, Mauritius, São Tomé and Príncipe, Seychelles.

Country	Target	Target date	Notes
Tuvalu	100%	2020	
Vanuatu	65%	2020	23% by 2014, 40% by 2015, 65% by 2020
Caribbean			
CARICOM[b]	47%	2027	8% baseline in 2012, 20% by 2017, 28% by 2022 and 47% by 2027
Antigua and Barbuda	15%	2030	5% by 2015, 10% by 2020, 15% by 2030
Bahamas	30%	2030	15% by 2020, 30% by 2030
Barbados	29%	2029	29% of electricity by 2029, 20% of primary energy by 2016
Belize	50%	No date	
Cuba	24%	2030	
Dominica	100%	No date	
Dominican Republic	20%	2016	Targets are for distributed power only
Grenada	20%[a]	2020	
Guyana	90%	No date	
Haiti	50%	2020	
Jamaica	30%	2020	
St Kitts and Nevis	20%	2015	
St Lucia	35%	2020	15% by 2015, 35% by 2020
St Vincent and the Grenadines	60%	2020	30% by 2015, 60% by 2020
Trinidad and Tobago	100MW	No date	5% of peak demand by 2020, 100MW of wind power (no date)
AIMS (African and Indian Ocean, Mediterranean and South China Sea)			
Bahrain	5%	2030	
Cape Verde	100%	2020	
Guinea-Bissau	2%	2015	
Maldives	16%	2017	
Mauritius	35%	2025	
Seychelles	15%	2030	5% by 2020, 15% by 2030
Singapore	5%	2020	

[a] Target refers to primary energy supply.

[b] These targets are for electricity generation across the entire Caribbean Community, which includes Antigua and Barbuda, Bahamas, Barbados, Belize, Dominica, Grenada, Guyana, Haiti, Jamaica, Montserrat (a British overseas territory in the Leeward Islands), Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, Suriname, and Trinidad and Tobago. Regional targets were agreed by national leaders from these countries.

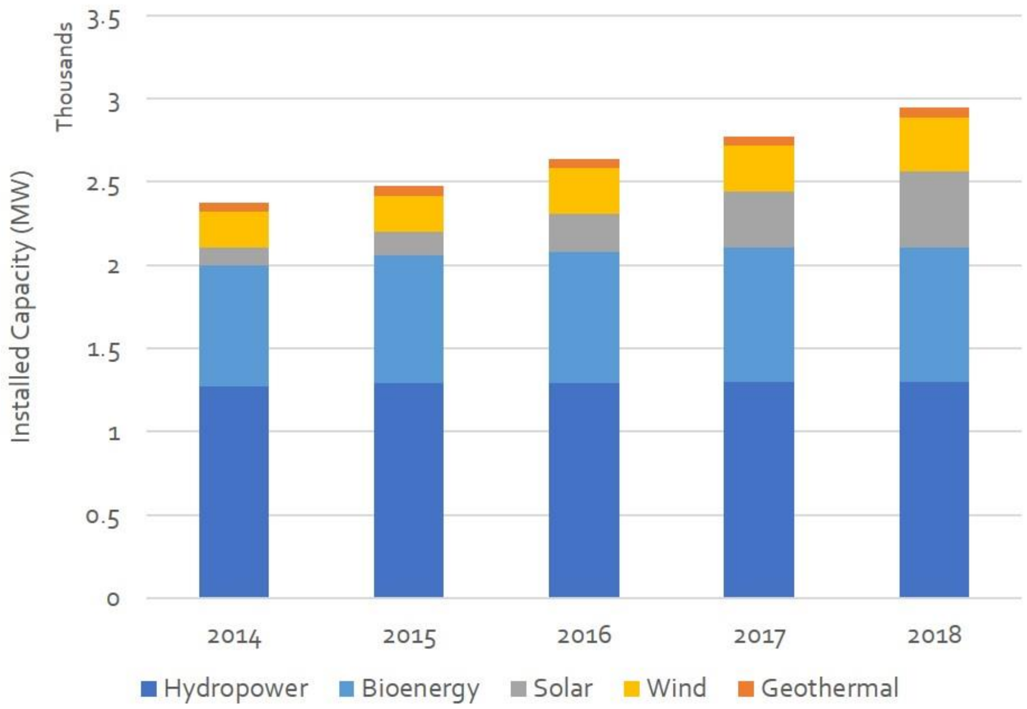

FIGURE 5.1. TOTAL RENEWABLE ENERGY INSTALLED CAPACITY IN THE SIDS LIGHTHOUSE INITIATIVE PARTNERS [91]

5.3.2 GEOGRAPHICAL LOCATION(S)

Remote coastal communities are spread worldwide and include developed and developing economies. As a result, the environmental, financial, technical, socio-economic, and institutional considerations will be different in each case. To reduce the range of technical considerations, the IEA classified remote areas into the following six categories [88]:

1. Remote areas with long winters,
2. Remote areas with temperate winters,
3. Small remote areas with warm winters,
4. Large remote areas with warm winters,
5. Research stations and National Parks, and
6. Remote areas in developing countries.

For each category, the IEA compiled a set of main characteristics to provide a more standardized approach to the study of remote areas. These are described in Table 5.4 where a list of example remote coastal communities is provided as well.

Most SIDS exhibit a warm tropical climate given their location close to the Equator (see Figure 5.2), i.e., SIDS would fall into categories four and five in Table 5.4. This makes them especially vulnerable to tropical storms, such as hurricanes [91].

TABLE 5.4. CLASSIFICATION OF REMOTE AREAS [88]

Main characteristics	Example Remote coastal areas
Category 1: Remote areas with long winters Communities may have a seasonally limited access to fuels due to icy conditions that make them inaccessible during winter periods – therefore, reliable storage of fuels is a priority. Heating is the main driver of energy demand, which leads to increased energy needs in winter months. Local transportation needs are for short local trips and fishing. Public transport options are often limited. The main renewable resource is wind, although solar may provide useful energy during summer months. Hydro and geothermal may be available at specific sites.	▫ Ramea Island (CAN), ▫ Old Crow (CAN), ▫ Norwegian islands (NOR), ▫ Remote Alaskan communities (US), ▫ Kodiak Island (US).
Category 2: Remote areas with temperate climates Temperate remote areas will have less harsh winter conditions than areas with long winters. Heating is a main requirement during winter months, although electricity needs may still be higher in summer months, in particular places with a large tourism industry. The main resources available are wind and solar, although hydro and geothermal may be available in some locations.	▫ Isle of Eigg (UK), ▫ Japanese outer islands (JAP), ▫ Graciosa Island (PT), ▫ Stuart Island (CAN), ▫ Faroe Islands (DK), ▫ Utsira Island (NOR), ▫ Fair Isle (UK).
Category 3: Small remote areas with warm climates Most of these areas are represented areas highly vulnerable to floods, hurricanes, and other climate related disasters. Energy needs are mainly for end-use electricity, with limited demands for cooling. Heating needs are primarily for household water heating. Local energy needs differ significantly due to varying tourists' demands, who will demand significantly more energy per capita. Transport needs are mostly sea and air transportation for tourists. The main resource available is solar, while wind, biomass, and hydro availability are more site-specific.	▫ Sint Maarten (NL), ▫ Saint Martin (FRA), ▫ Niue (NZ), ▫ Tokelau (NZ), ▫ Pitcairn Island (UK), ▫ Peter Island (BVI), ▫ Floreana, Galápagos (EC), ▫ Gomera (ES), ▫ Aogashima Island (JP).
Category 4: Large remote areas with warm climates Similar to small remote areas with warm climates, these large remote areas are vulnerable to extreme weather conditions. Energy needs are also driven by tourism; however, there are likely more commercial activities and larger industrial demands. Solar is a main resource with large potential for heating water and meeting electricity demand. The systems will have strong potential for wind and, if available, geothermal development. Biomass and hydro resources should be considered if local resources are available.	▫ Anguilla (UK), ▫ American Samoa (US), ▫ San Andres Island (COL), ▫ Cook Islands (NZ), ▫ Montserrat (UK), ▫ El Hierro (ES), ▫ Miyakojima Island (JP), ▫ Guadeloupe (FRA), ▫ Martinique (FRA), ▫ Reunion Island (FRA).

Main characteristics	Example Remote coastal areas
Category 5: Remote research stations Climatic conditions differ considerably since research station locations are worldwide, from arctic to tropical areas. Energy needs are heavily tied to the residential demands of the researchers. Research equipment needs may also drive demand for electricity. Transportation needs are limited – mostly for supply deliveries with limited local transport needs. Resource availability will depend heavily on the site location. Smaller research stations are stronger candidate for higher penetrations of renewables than larger stations.	▫ Resolute Station (CAN), ▫ Island of Osmussaare (Estonia), ▫ Zackenberg Research Station, Greenland (DK), ▫ Rothera, British Antarctic Survey (UK), ▫ Ross Island (Antarctica).
Category 6: Remote areas in developing countries Environmental conditions vary widely across the different locations of developing country worldwide. Energy needs are often unmet, and there is a higher reliance on traditional energy methods (for example, cow dung and wood for cooking or candles and kerosene for lighting). Many developing countries will have no or limited existing access to electricity in remote areas. Energy demand will be significantly lower than in the other categories described in this table; however, there is a higher potential for load growth. Solar is often an abundant and viable energy source. If available, hydro will be one of the most inexpensive solutions, and there may be some potential for wind and biomass technologies. There is still debate on appropriate development pathways for these areas, although approaches that are community-initiated and inclusive have proven most successful.	▫ Many regions of Africa (Kenya, Tanzania, Namibia, etc.), ▫ Morocco, ▫ Western China, ▫ Myanmar, ▫ Sri Lanka, ▫ Certain parts of Central America.

Based on UN-OHRLLS, 2015.

FIGURE 5.2. LOCATION OF SMALL ISLAND DEVELOPING STATES (SIDS) [91]

5.3.3 POWER REQUIREMENTS

Power options for remote coastal communities will inevitably depend on local circumstances, such as distance to a central energy infrastructure and available energy resources. For those closely located to a central grid, the most cost-effective solution may be to extend the existent grid, whereas mini-grids and off-grids may be the only viable way to get energy access in those that are farther from the grid or in inaccessible locations [103].

In addition, the energy requirements of each community will also depend on their degree of economic development. According to the World Bank [104], energy consumption per capita in 2015 was approx. 53MWh for high income countries and 15.5MWh for low- & middle-income countries[10]. Focusing on SIDS, for instance, Timor-Leste and Guinea-Bissau had the two lowest energy use per capita with 0.67MWh and 0.78MWh respectively, and Singapore and Trinidad and Tobago the two highest with 59.6MWh and 167MWh, respectively [104]. Consequently, their electricity consumption will also vary substantially (see Annex III). Overall, SIDS have an annual electricity consumption over 166TWh/year.

Beyond SIDS, Blechinger et al. [105] mapped around 1,800 small islands worldwide comprising populations between 1,000 and 100,000 inhabitants (see Figure 5.3). With a total population of 20 million inhabitants, Blechinger et al. determined that these islands have a total installed diesel generation capacity of 15GW. This represents another potential market for ocean energy.

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[10] Originally provided as 4,605 kg of oil equivalent (koe) per capita in high income countries and 1,332 koe per capita in low- and middle-income countries in [104]. Similarly, the same source provided energy use per capita values of 57.3koe, 67.3koe, 5121koe, and 14,446koe for Timor-Leste, Guinea-Bissau, Singapore, and Trinidad and Tobago respectively. The units have been converted in-text for consistency throughout the report.

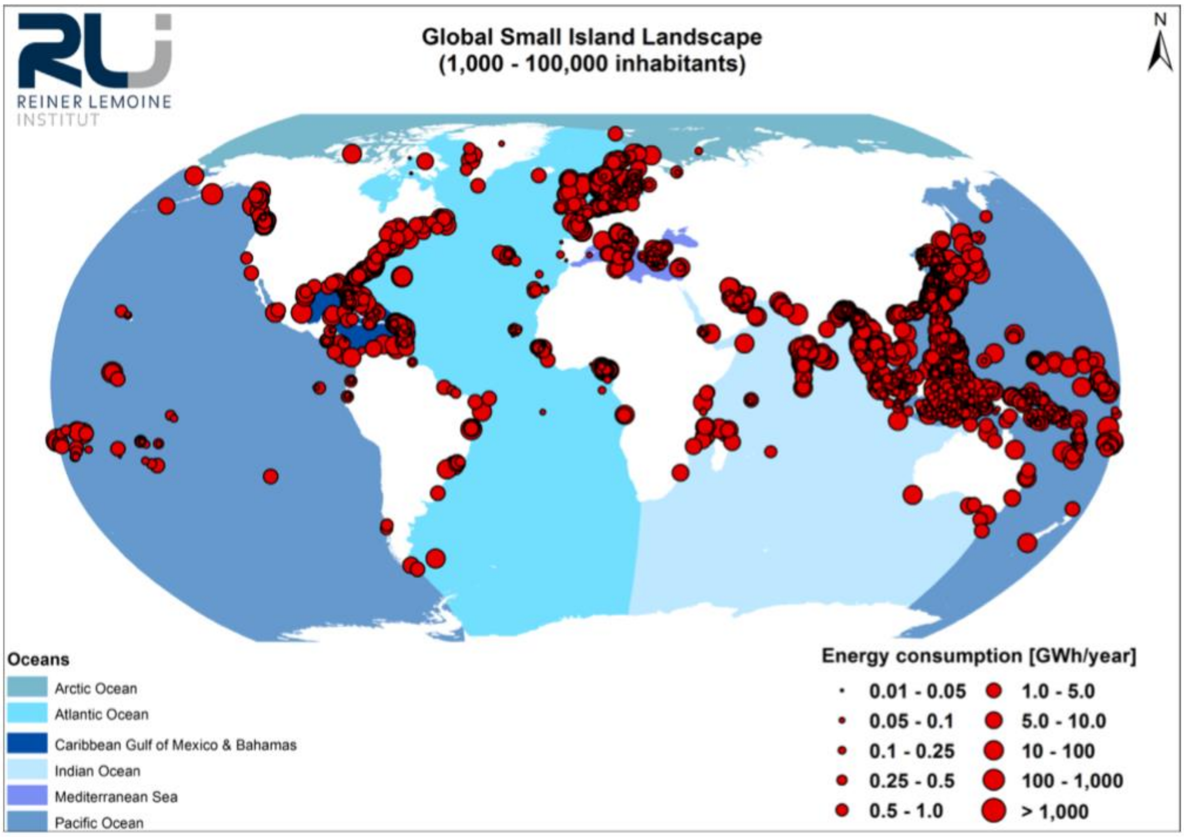

FIGURE 5.3. ENERGY CONSUMPTION OF SMALL ISLANDS [105].

5.3.4 OPPORTUNITY FOR OCEAN ENERGY

The cost of energy in many remote coastal communities is often higher than in mainland, and it can constitute a significant financial burden undermining the country's gross domestic product (GDP). For example, in the Pacific SIDS of Palau, a presidential republic in free association with the US where 99.7% of its electricity is generated using oil imports, the electricity rates in 2015 ($280/MWh ~€254/MWh) more than doubled that of the average US residential rate ($130/MWh ~€118/MWh) [106]. For Palau, this implied that oil imports accounted for almost 28% of the state's GDP (Figure 5.4).

Traditionally, these costs have been either shared or borne by central governments. For example, in 2006, the Canadian government spent around €3,000 per capita to supply fossil-fuel based energy services to the inhabitants of Nunavut (North of Canada) [88]. However, considering that these subsidies have been supporting the dependency of regions to fuel imports, there is an economic motivation for the governments to re-draw the regions' energy systems and start exploiting local cost-effective energy sources.

In SIDS, renewable energies have gained special attention given their potential to address several present issues that these communities face (e.g., access to affordable, reliable and modern energy services) and provide additional benefits, such as job creation and reduction of greenhouse gas emissions [88]. Ocean energies could contribute to their renewable energy mix, and at the same time handle primary issues in SIDS such as food security (when integrated into marine aquaculture farms) or coastal protection (when integrated into e.g., breakwaters) [93] [107] [108].

SIDS have set some of the most ambitious renewable energy targets in the world, with cases such as the Cook Islands or Fiji aiming for 100% integration of renewables into their electricity system by 2020 and 2030, respectively [102]. This provides the necessary policy framework for ocean energies to thrive in these regions; however, their suitability and attractiveness will have to be assessed site-specifically. Aquatera and Caelulum [109] provided a more general attractiveness score for wave energy development in SIDS using the wave resource and the electricity consumption per capita as indicators (see Figure 5.5). Islands with high wave resource and high electricity consumption per capita present a good opportunity (e.g., Bermuda, New Caledonia) for ocean energy development; however, islands with high wave resource and low electricity consumption per capita (e.g., Mauritius, Fiji, and Cabo Verde) are more promising, as they have a greater potential for growth.

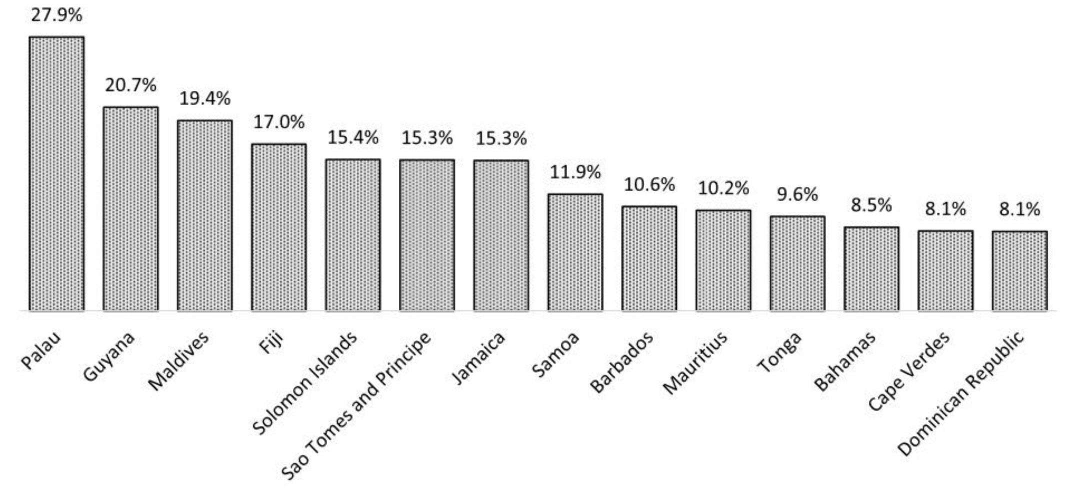

FIGURE 5.4. PERCENTAGE SHARE OF GDP ON OIL IMPORTS FOR SELECTED SIDS (2013) [110].

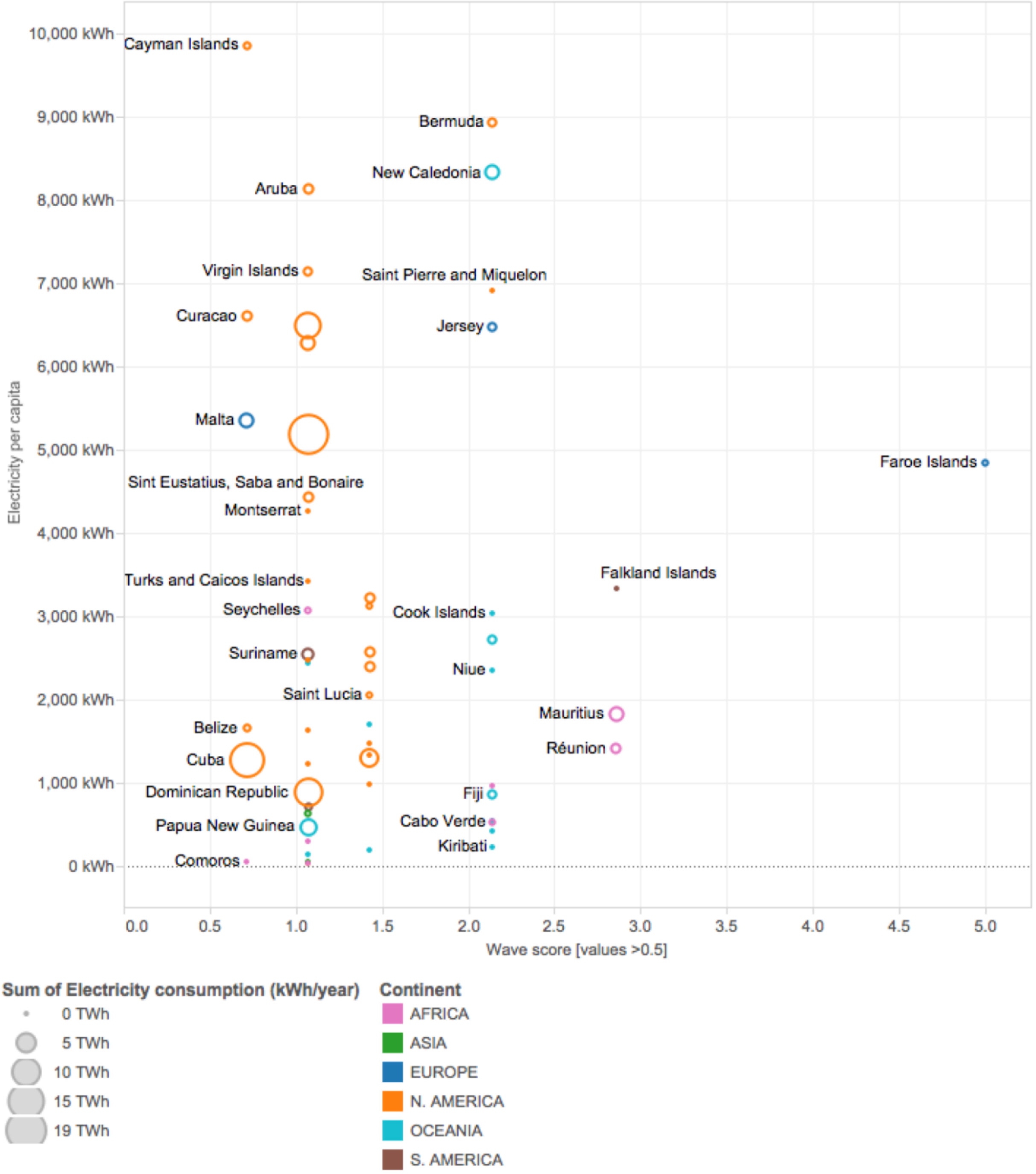

FIGURE 5.5. COMPARISON OF WAVE ENERGY RESOURCE AND ELECTRICITY CONSUMPTION PER CAPITA IN SIDS AND OTHER RELEVANT ISLANDS [109].

5.4 OFFSHORE OIL & GAS EXTRACTION AND PROCESSING

The oil and gas (O&G) market is one of the biggest energy markets globally, involving every country in the world for production and/or consumption. Offshore O&G is a significant part of this market, accounting for more than a quarter of the global O&G production in 2016 [111].

Given their co-location, ocean energies (particularly wave), could assist in the electrical requirements of offshore O&G platforms, both during day-to-day production activities and also during the decommissioning phase. There is also a public relations benefit to be exploited by O&G companies using renewable electricity to reduce their emissions, even if modestly.

There are already several companies looking at this market, thereby highlighting its relevance. Ocean Power Technologies (OPT) has developed a point absorber buoy – the PB3 PowerBuoy – which provides power to observing equipment. In August 2019, OPT deployed its device at the Huntington Oil Field, property of Premier Oil, in the UK central area of the North Sea. There, OPT's WEC is supporting communications and remote monitoring services for Premier Oil, and expects to remain in place for at least 9 months, which will serve to demonstrate PB3 capabilities [112]. Additionally, Mocean Energy has developed and continues testing the Seabed WEC and has joined an initiative gathering start-up firms looking to enter the O&G industry. Mocean Energy is seeking to create partnerships to enable a sustainable and low-carbon energy future for the O&G industry [113]. Finally, Floating Power Plant S/A (FPP) has partnered with Lundin Norway AS, APL Norway AS, Semco Maritime, CEFRONT and Aalborg University for the project "De-carbonisation of Oil & Gas Production – by cost effective Floating Renewable Technologies". This project seeks to introduce FPP's hybrid technology (floating offshore wind and wave platform) to the O&G market and develop additional concepts for exploitation and production as well as intermittent and baseload power supply both in new field developments and expansions or late-life upgrades [114].

5.4.1 FUTURE OF THE MARKET

Despite concerns over emissions, projections are for the O&G market to grow or at least remain significant over the next decades, although the exact trajectory will depend on future policies and emissions scenarios.

Forecasts for offshore oil and natural gas production for 2030 and 2040 are provided in Figure 5.6 and Figure 5.7 of the IEA World Energy Outlook Series Offshore Energy Outlook [111]. These projections are based on the IEA's NPS and SDS, introduced in section 2.2. Looking at the production of offshore oil in both scenarios, it can be seen that offshore oil production slightly increases from 28 million barrels per day (mb/day) in 2025 to 29 mb/day by 2040 in the NPS, but it decreases consistently from over 25mb/day in 2025 to 20mb/day by 2040 in the SDS. In the SDS, the decrease is a result of support for more energy efficiency practices and an increase on the number of electric vehicles, amongst others. For both NPS and SDS, however, the total share of offshore oil with respect to the total oil production decreases to below 30%.

Natural gas overtakes coal and oil in the mid-2020's and mid-2030's, respectively, as the main fuel in the energy mix as per Table 1.1. of the IEA World Energy Outlook 2018 [6]. For offshore natural gas, both NPS and SDS suggest that gas production is also to experience significant growth in the next 20 years. In the NPS, the increase is the highest, with gas production growing 140% to beyond 1,700 billion cubic metre per day (bcm/day) by 2040. In the SDS, gas grows 113% to 1,380bcm/day. The role of natural gas differs between regions for the NPS and the SDS. In the SDS, natural gas production is higher in China and India than in the NPS, where it helps displace coal from the energy mix. However, in the SDS, in Europe and other more developed countries, natural gas production remains stable throughout the 2030 to 2040 as renewables overtake, taking a supporting role to the mix. This analysis by geographic region is discussed further in the IEA World Energy Outlook Series Offshore Energy Outlook [111]. In the two scenarios, the total share of offshore gas with respect to the total gas production increases to 33%.

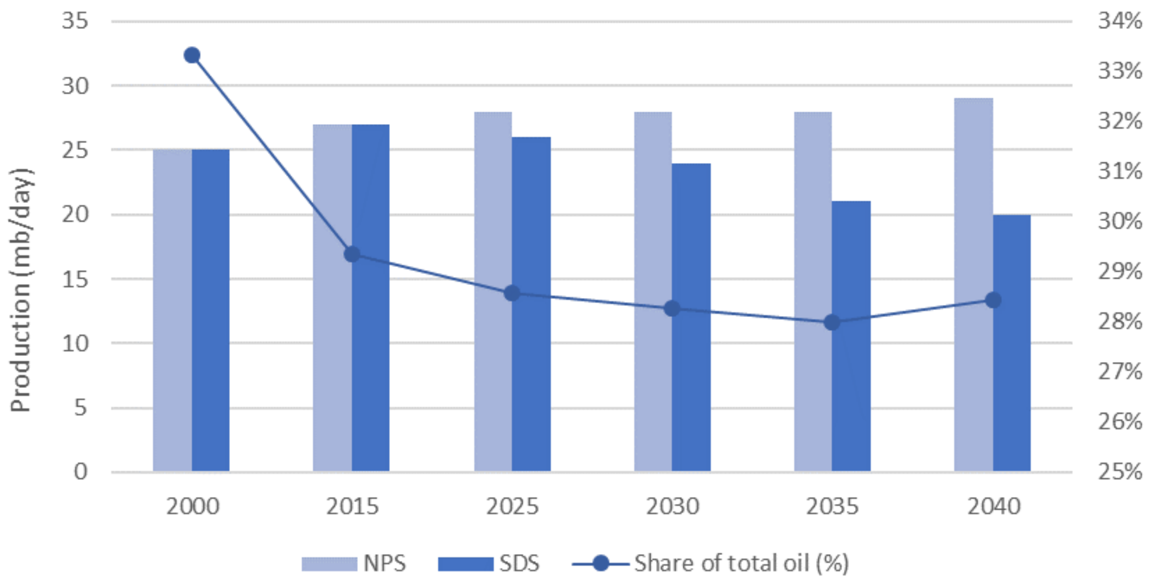

FIGURE 5.6. OFFSHORE OIL PRODUCTION IN THE NEW POLICIES (NPS) AND SUSTAINABLE DEVELOPMENT (SDS) SCENARIO [111]

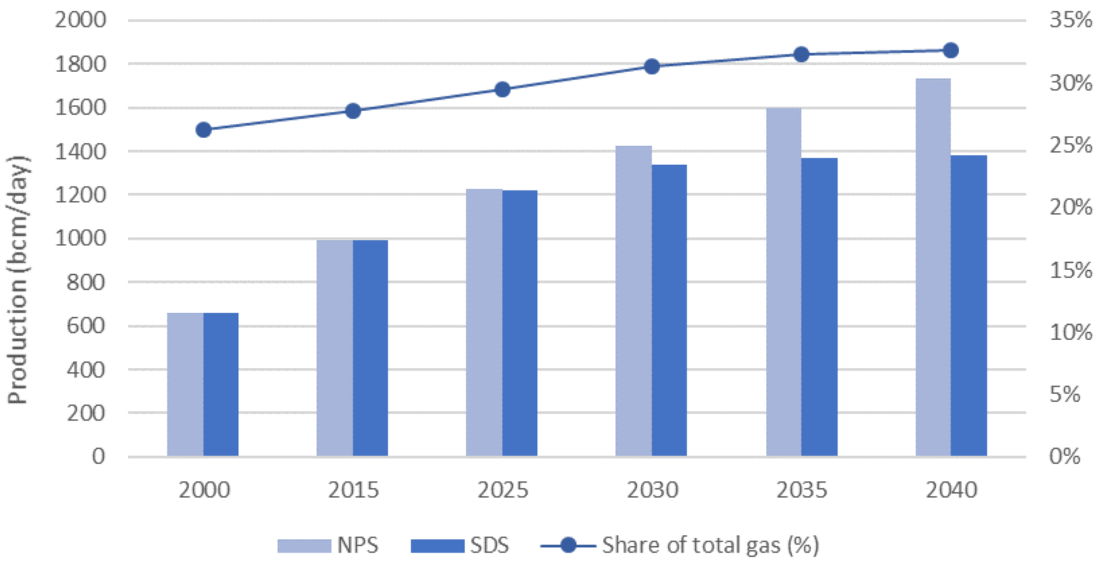

FIGURE 5.7. OFFSHORE GAS PRODUCTION IN THE NEW POLICIES (NPS) AND SUSTAINABLE DEVELOPMENT (SDS) SCENARIO [111]

5.4.2 GEOGRAPHICAL LOCATION(S)

Offshore O&G production activities take place all over the world, with over 9,000 platforms globally in the areas shown in Figure 5.8 [109]. Top producers are located in the Middle East, North Sea, Brazil, the Gulf of Mexico, and the Caspian Sea [111].

FIGURE 5.8. GLOBAL LOCATIONS OF OFFSHORE OIL AND GAS PLATFORMS [109]

In Europe, most of the offshore O&G production is located in the North Sea. Operational and non-operational, and decommissioned O&G platforms in this region are shown in Figure 5.9. This map also depicts offshore wind farms, exposing the opportunity that this sector may also be able to power offshore O&G and, thus, be a potential competitor for ocean energy.

Of the locations shown in Figure 5.8 and Figure 5.9, the areas where ocean energy resources are high represent good opportunities for offshore renewable installations which would require further consideration. In Europe, the North Sea has the highest potential for this integration.

5.4.3 POWER REQUIREMENTS

Offshore O&G platforms consist of many energy consuming facilities including drilling, accommodation, processing, exports, and injection as shown in Table 5.5. Their power consumption may vary from tens to several hundreds of MW, depending on the field conditions (e.g. temperature and pressure) and properties (e.g. oil, gas, and water and carbon dioxide contents), among others [115]. Typically, offshore O&G production may require between 5% and 15% of the total energy they generate [109].

Offshore O&G platforms are typically powered by Open Cycle Gas Turbines (GTs). Due to the high availability requirements of power offshore, the GTs are designed to account for redundancy, which implies running more units than needed to meet the power requirements. This results in poor operating efficiencies (typically 25-30%) and relatively high emissions – typically twice those of onshore Combined Cycle Gas Turbines [115]. According to the UK Oil and Gas Authority, the power demand from oil and gas platforms located in the UK continental shelf is over 2GW per annum, which represents around 5% of UK power demand [116].

Those offshore O&G applications seeking to decarbonise and with high power requirements are more likely to decide to integrate offshore wind energy. However, wave and tidal stream energy can aid the decarbonisation efforts. Renewable energy has to be economically competitive with GTs.

TABLE 5.5. INDICATIVE ESTIMATION OF THE ENERGY CONSUMPTION PER PHASE OF PRODUCTION OF OIL AND GAS BASED ON THE GLOBAL PRODUCTION IN 2013 [109]. DATA FROM [117]

Global fuel production in 2013	Energy consumed per phase of production		Total
Crude oil: 72,842,000 b/d = 4,3480,569 million m^3/y = 47,900TWh	Extraction	1,204TWh	5,307TWh (11% of the energy contained in the oil produced globally)
	Refining	3,620TWh	
	Pipeline transport	483TWh	
Natural gas: 3,480,569 million m^3/y = 38,300TWh	Extraction	946TWh	1,584TWh (4.1% of the energy contained in the natural gas produced globally)
	Liquefaction - regasification	259TWh	
	Pipeline transport	379TWh	
Total energy from fuel: 86,200TWh	Energy need for total fuel production	6,891TWh	6,891TWh (8% of the production)

Numerical values used: 1 barrel of oil = 0.163659 m^3; 1 m^3 of oil represents 11,000kWh; 1 m^3 of gas represents 11kWh.

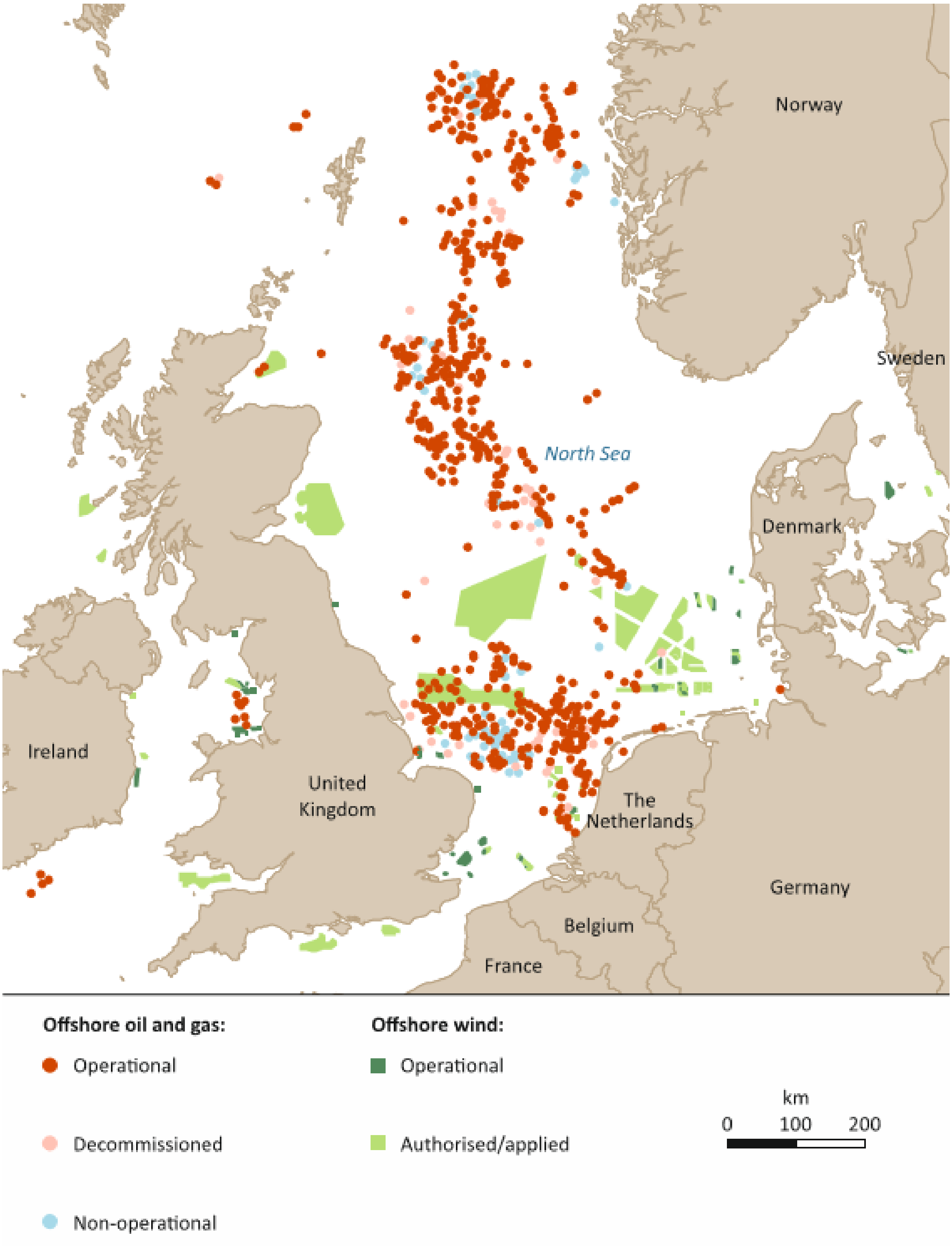

FIGURE 5.9. OFFSHORE OIL AND GAS PLATFORMS, AND OFFSHORE WIND INSTALLATIONS IN THE NORTH SEA [118] [119]

5.4.4 OPPORTUNITY FOR OCEAN ENERGY

In spite of more energy efficient extraction techniques, power requirements and environmental impacts in offshore O&G platforms are expected to increase in the upcoming years. This will be caused by greater onsite energy needs to separate and transport O&G to the shore, and to inject gas and/or water into the reservoirs to increase oil recovery [120].

However, as offshore fields are ageing, the rate of oil production together with the production rate of gas declines. At some point, the gas separated from the oil will not be sufficient to supply the GTs [121]. Therefore, alternatives to GTs will be required.

One possibility is to upgrade GTs to run with diesel fuel; however, this solution may compromise the economic viability of the field, as investments will be needed to upgrade the GTs, and the more expensive price of diesel fuel supplied to offshore facilities. In addition, this would not be aligned with global efforts to decarbonize the energy system, in which O&G production plays a major role. In Norway, it was estimated that GTs were responsible of 82% of the CO_2 emissions from the petroleum activities in the Norwegian Continental Shelf [122], and in the UK offshore O&G platforms represent around 10% of total power plant emissions [116].

Due to their co-location with offshore O&G platforms, wave energy may be a good alternative to power these stations. In open seas, wave energy density is higher than nearshore; however, given the high availability requirements of O&G platforms, wave energy must be considered in combination with other power sources.

5.5 MARINE AQUACULTURE AND ALGAE

Marine aquaculture, also called mariculture, is the farming of aquatic animals and plants at sea or in coastal regions. This is mainly for human consumption, with additional markets for animal feed, human health, food processing, cosmetics, soil additives and fertilizers, and biomass (this last one currently under research). In 2016, 47% of the global fish consumed was farmed, and from that 36% came from mariculture production [123][11]. That same year, over 99% of the world's production of aquatic plants took place in marine waters (coasts and at sea), with an estimated sale value of $11bn (~€9.96bn) [124].

Farmed aquatic animals, or simply food fish, include finfish, shellfish, and crustaceans. Farmed aquatic plants or algae comprise macroalgae (seaweed), microalgae, and cyanobacteria. The analysis below focuses on finfish and seaweed production as these are two of the main products in the mariculture and algae markets. Finfish represented 68% of total food fish produced and 57% of the total first-sale value generated in 2016, and seaweed currently dominates the aquatic plant market with over 99% of the global algae production [123].

Traditionally, aquaculture farms have relied on diesel and kerosene generation to power their operations [87]. However, given the growing interest in moving coastal farming offshore [125], a shift to local, sustainable ocean energy resources could potentially benefit both aquaculture and the ocean renewables sector.

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[11] See Tables 4 and 6 [123]

5.5.1 FUTURE OF THE MARKET

The world human population is increasing, projected to reach around 8.5 billion by 2030 [126], and with it the demand for seafood. Total fish production has increased from almost 100 million tonnes in 1990 to 170.9 million tonnes in 2016. This growth has come mainly from aquaculture. With most wild-fish stocks exploited or overexploited [127], caught fish has not experienced significant growth for the last 30 years and it is projected to remain similar to 2030, with around 1% growth as shown in Figure 5.10.

Since the late 1970's, aquaculture contribution to seafood supply has been increasing, with an annual growth of 5.7% between 2003 and 2016. At present, aquaculture contributes to around 47% of the total fish weight produced, projected to rise to 54% (109 million tonnes) by 2030 [123]. From this, marine aquaculture represents 17% of the total fish production (captured and farmed), with potential to increase further.

Global aquaculture production of algae has grown from 13.5 million tonnes in 1995 to over 30 million tonnes in 2016 [123]. Over 99% of it included seaweeds, with almost two thirds of the stock destined to culinary use, and the rest for the cosmetic and food processing industry. The latter has been the major contributor of the industry growth, with e.g. Indonesia almost trebling its output to over 11 million tonnes from 2010 to 2016.

Attracted by the possibility of larger production levels, reduced space competition with other land users, and more cost-effective systems, the mariculture sector seems to be shifting towards developing their activities further offshore [128] [129] [130].

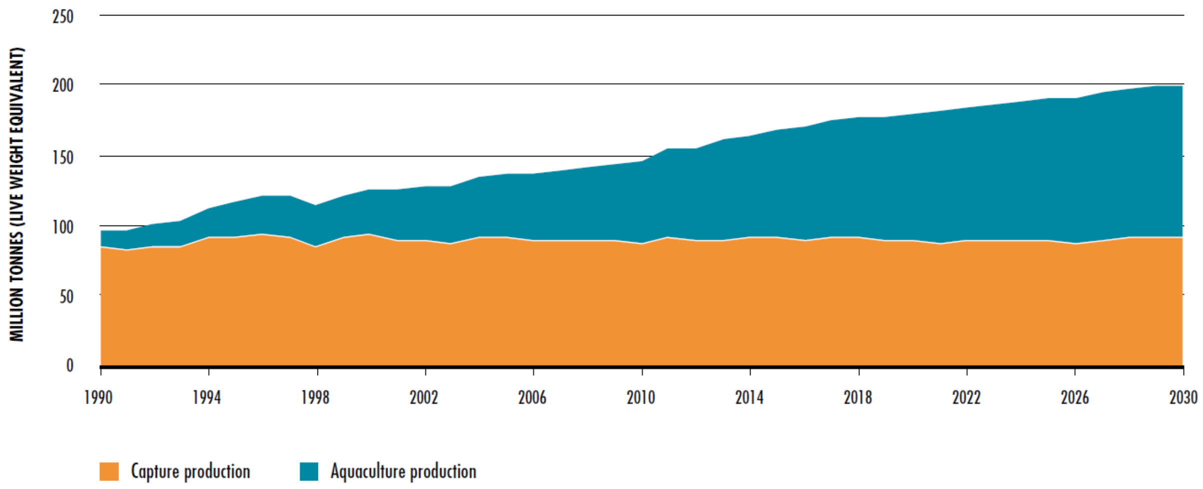
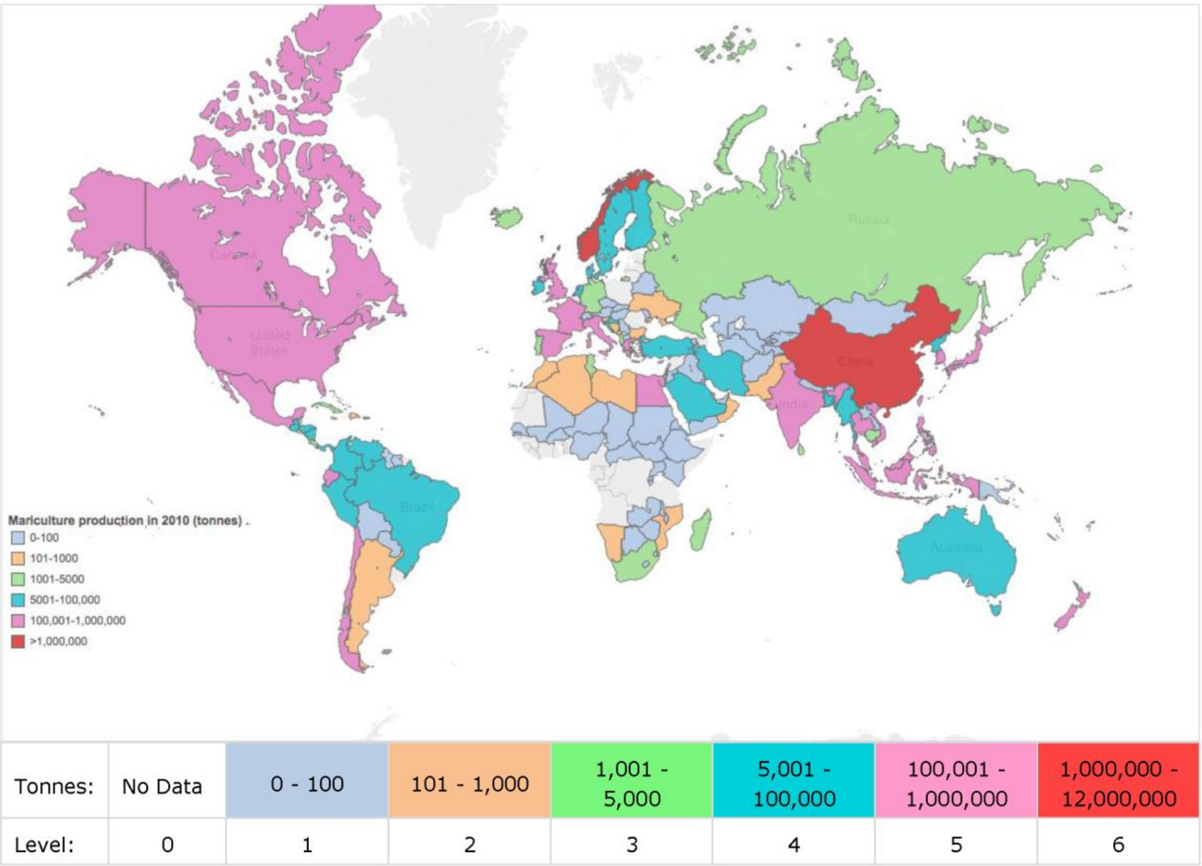


FIGURE 5.10. GLOBAL CAPTURE FISHERIES AND AQUACULTURE PRODUCTION SINCE 1990 AND PROJECTED TO 2030 [123]

5.5.2 GEOGRAPHIC LOCATION(S)

At present, the global mariculture market for both food fish and algae is dominated by Asia. China alone produced over 60% of the world's food fish and almost 50% of its algae in 2016. For marine aquaculture finfish in particular (shown in Figure 5.11), however, the market is more spread between Asia (57%) and Europe (28%), with Norway and the UK within the top ten European producers [123].

Areas which could benefit from the integration of ocean energy and mariculture include China, the Philippines, Japan, Taiwan, Indonesia, New Zealand, and Canada, as they all have a large production of finfish and good ocean energy resources [109]. Further studies are necessary to provide more information in this regard.



Tonnes:	No Data	0 - 100	101 - 1,000	1,001 - 5,000	5,001 - 100,000	100,001 - 1,000,000	1,000,000 - 12,000,000
Level:	0	1	2	3	4	5	6

FIGURE 5.11. GLOBAL MARICULTURE PRODUCTION BY 2010 [109] [131].

5.5.3 POWER REQUIREMENTS

At present, an analysis of the energy requirements of the aquaculture sector as a whole was not found. Energy requirements in aquaculture farms depend on the size and location of the production facilities as well as the species of fish or algae being farmed.In the US, the Department Of Energy [87] found the power needs of aquaculture installations to be in the range of 4,000kWh/yr to 715,000kWh/yr. FAO found that, for finfish farming, which in 2016 represented 68% of total aquaculture production and 57% of the total first-sale value generated [123], the energy required may be derived from a Scottish Aquaculture Research Forum report [132]. There, the average yearly energy usage of salmon farms was reported to be around 229,500kWh/year, with the different energy processes shown in Table 5.6. For sea cage finfish production, the energy input required to produce a kilogram of fish is between 7.8kWh and 13kWh[12] [133] [134]. This means that in 2016, when 6.6 million tonnes of finfish where produced in mariculture, between 50TWh and 90TWh of energy were required to power the sector.

Troell et al. [135] found that the ratio between the industrial energy input and the protein energy output from seaweed farming (7:1) is similar to that of sheep and rangeland beef farming. Most algal production facilities rely on human labour for seeding and harvesting and, thus, the power requirements of the sector are unclear. However, some of its activities are also common to fish farming, such as power safety, navigation and maintenance equipment, pumps for nutrients and structure controls, refrigeration and ice production, drying operations, marine sensors, recharging AUVs, hotel loads for living quarters, and transport vessels. For this reason, similarities are expected with respect to the power needs of both sectors [87].

TABLE 5.6. ENERGY REQUIREMENTS OF A TYPICAL FINFISH FARM [109] [132]

Energy process	Existing fuel	Use pattern	Criticality	Average site energy usage
Feed system	Diesel generator burning marine diesel	Day	Critical – Growth/ Performance. Could be down for short while	17,136 gallons/yr marine diesel for feed barge This is equivalent to around 229,500 kWh/year
Underwater lighting	Diesel generator burning marine diesel	At night and seasonal depending on the day length and photoperiod required for the stage of growth	Critical – Growth/ Performance. Could be down for short while	
Supplementary aeration	Battery, recharged from diesel generator	Used during medical treatments and during summer months	Critical – Growth/ Performance. Could be down for short while	
Acoustic deterrent devices		Potential 24hr	Critical – Predator control. Could be down for short while	
Navigational lighting	Usually standalone solar powered with battery	Charging during the day and on at night	Critical – Safety	
Other systems (monitoring equipment, underwater camera, alarms, etc.)	Battery/ UPS backup	Potential 24hr	Critical – Predator control. Could be down for short while	

5.5.4 OPPORTUNITY FOR OCEAN ENERGY

The expansion of aquaculture production further offshore carries with it a series of advantages which may result attractive for large farmers, e.g., increased exploitable area (thus larger production

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[12] Figures originally provided as 28MJ and 48MJ in the sources [133] [134]. The units were converted to maintain consistency throughout the report.

levels), access to higher water quality, with optimum concentrations of dissolved oxygen and less anthropogenic pollutants, and last but not least, reduced conflicts with other users [136].

Before this shift happens, technical, environmental, regulatory, and social challenges must be overcome. For instance, offshore farms would require consideration of additional power sources, and the further offshore, the higher the difficulties to get those at an affordable cost. Given that high quality air and water is a must for the industry, utilization of polluting energy sources would not be supported in the long-term. Due to their co-location, a cleaner viable alternative is ocean energy.

Wave energy might be more suitable for integration with offshore aquaculture than tidal stream, as normally aquaculture farms avoid highly energetic tidal sites as it complicates feeding and other activities [132]. Some wave energy companies that have been developing devices tailored to the needs of the aquaculture sector or with a strong interest to link both activities include Albatern, Wave Dragon, Waves4Power, Atmocean, and Columbia Power Technologies. Co-location of both wave energy extraction and aquaculture would result in lower operation and maintenance expenditures, and in addition wave energy farms could provide some shelter to mariculture installations by reducing the energy from the incident wave field [137].

5.6 DESALINATION

Desalination is a process by which the salts and other minerals dissolved in saline water are removed in order to produce water for human uses. Depending on the salinity of the output water, this may be used directly for consumption or for irrigation in agriculture, amongst others. Feedwater sources may include seawater, brackish water, or wells. However, more than 76% of global desalination plants operate with seawater [138].

Global desalination production has notably been increasing since the 1960's, rising to 95 million m^3/day in 2018, as shown in Figure 5.12. This amount is produced by around 16,000 operational desalination plants spread over 177 countries worldwide, but with 48% of the activity happening in the Middle East and North Africa [139]. The total freshwater produced accounts for around 1% of consumption worldwide, based on global water withdrawals of around 4,000 billion m^3 per year [140]. In some areas, the share can be much higher; e.g. in Saudi Arabia more than 70% of the country's water needs are met by desalination [141].

Desalination is a highly energy intensive process, with energy costs making up more than 50% of the total water costs [142]. In 2018, the global desalination market consumed over 500GWh/year, and it is expected to reach to almost 900GWh/year by 2030 based on a recent study [143].

At present, only around 1% of the total number of desalination plants are powered by renewable energies [140] [144]. Given the projected growth in energy demand from the desalination sector, it is essential that desalination plants stop relying on fossil fuels to meet their energy needs.

Although not quantified thus far, the market opportunity for ocean powered desalination systems (OPDS) seems promising considering the co-location of both sectors. This has been suggested throughout the literature for decades [145]. However, as highlighted by Leijon and Boström [146], most of it has just focused on proving technology viability, rather than conducting any real case application. Therefore, there is a lack of research regarding potential sites for development of OPDS.

Historically, literature on the topic has mainly been interested in reverse osmosis technologies [147]. Reverse osmosis is a membrane-based desalination system which relies upon a partially permeable membrane and a pump pressurizing the feedwater beyond osmotic pressure. Since the 1970's, it has experienced a significant drop in its specific energy consumption from 17kWh/m^3 to around 3kWh/m^3, which has contributed to its market predominance (Figure 5.12); in 2018, 69% of the total desalinated water was produced through reverse osmosis [139].

In reverse osmosis, between 25% and 40% of the electricity supplied is used to pump water at high pressures [148]. Ocean energy could be used in combination with reverse osmosis plants to produce high pressurized water, avoiding the need of producing electricity, increasing the efficiency of the process [149] and reducing overall costs.

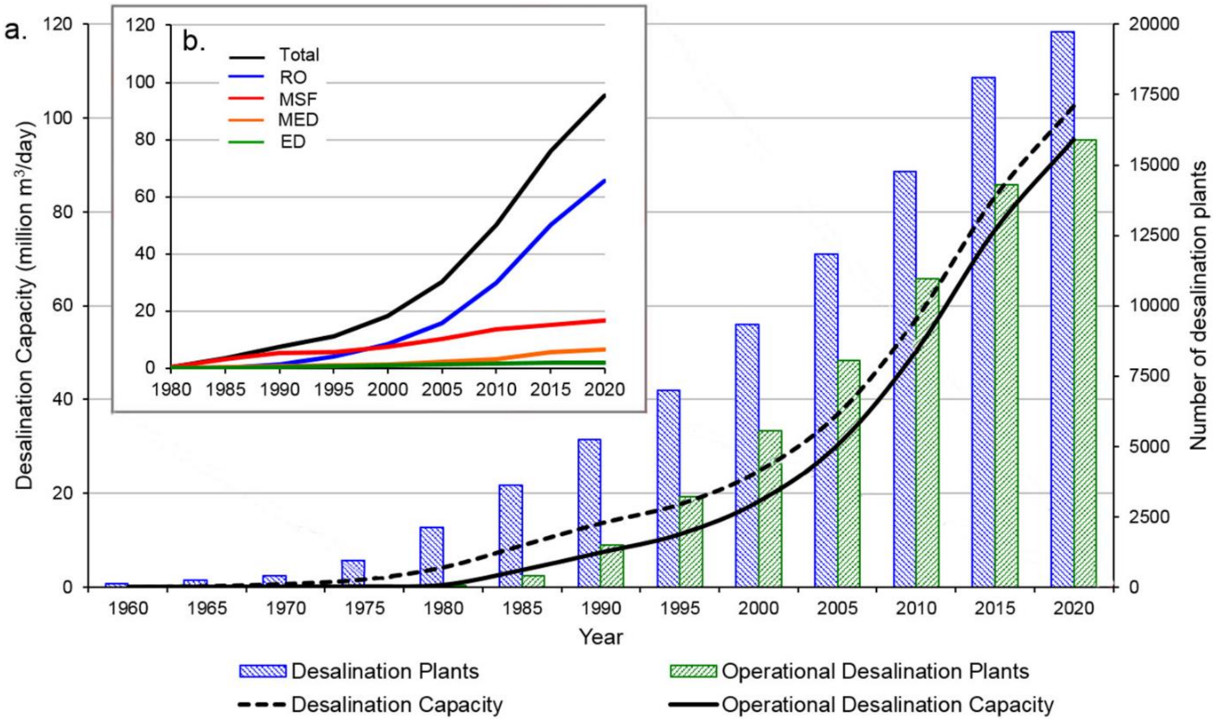

FIGURE 5.12. GLOBAL DESALINATION BY (A) NUMBER AND CAPACITY OF TOTAL AND OPERATIONAL DESALINATION FACILITIES AND (B) OPERATIONAL CAPACITY BY DESALINATION TECHNOLOGY [139]

5.6.1 FUTURE OF THE MARKET

Freshwater is a vital natural resource for every living form, and in particular for human beings. Growth of both population and water consumption per capita, together with decreasing water supplies due to climate change and contamination, are intensifying water scarcity in many regions [150] [151]. Estimates in 2013 suggested that 40% of the population faced severe freshwater scarcity, and this figure is projected to increase to 60% by 2025 [152].

Measures for enhanced water management are required to ensure water availability, yet these are likely to be insufficient unless they are combined with alternative water supplies. One already popular solution is desalination of saline water, which currently produces over 95.37 million m^3/day of freshwater, and it is projected to almost double by 2030 as shown in Figure 5.13 [139]. Along with it, energy consumption of the sector under the business as usual scenario is expected to reach 2.4GWh/day (876GWh/year) by 2030 [143].

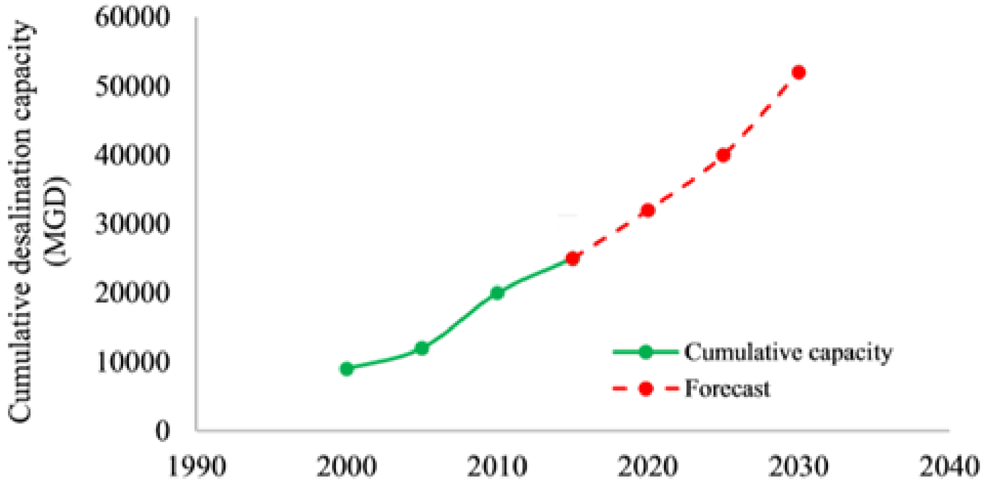

FIGURE 5.13. GLOBAL PRESENT AND FUTURE CUMULATIVE DESALINATION CAPACITY [153]

5.6.2 GEOGRAPHICAL LOCATION(S)

In 2018, there were 15,906 operational desalination plants worldwide spread over 177 countries with a total generation capacity of 95.37 million m^3/day (Figure 5.14). Almost half of that production took place in the Middle East and North Africa region, with Saudi Arabia being the largest single producer [139]. This is shown together with other selected regions in Figure 5.15.

Globally, sites with potential for realistic development of OPDS will meet several of the following criteria:

- Good ocean energy resource,
- Limited water availability,
- Low energy security or high reliance on fossil fuels, and
- High cost of water.

A non-exhaustive list of regions with previous research/commercial interest in OPDS is included in Table 5.7.

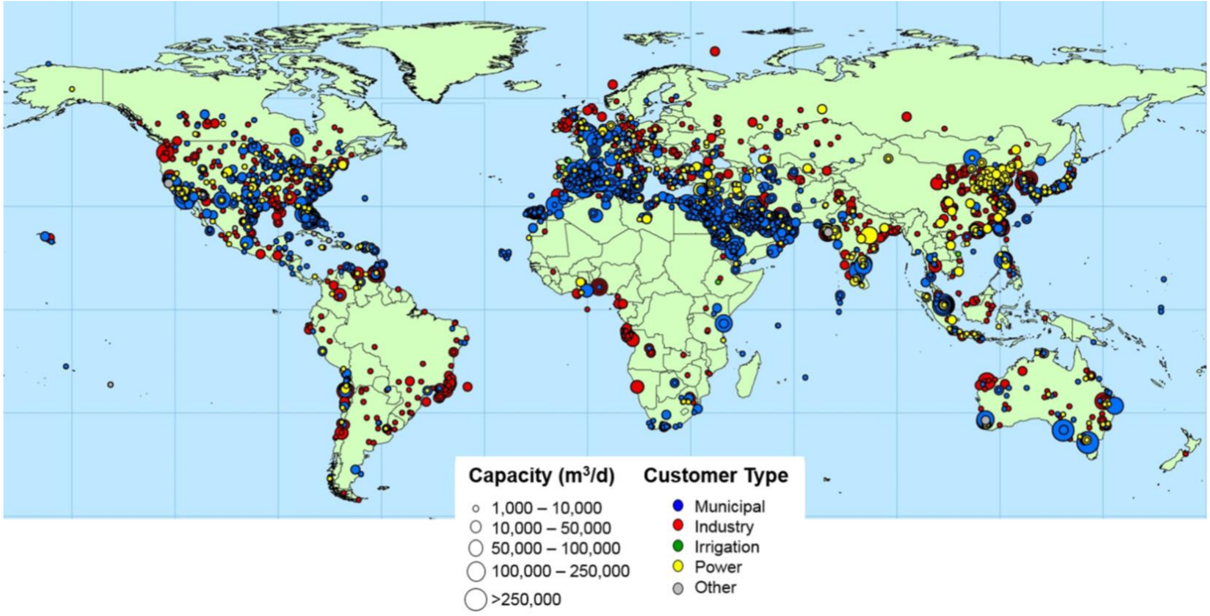

FIGURE 5.14. GLOBAL DISTRIBUTION OF OPERATIONAL DESALINATION FACILITIES BY SECTOR USER [139]

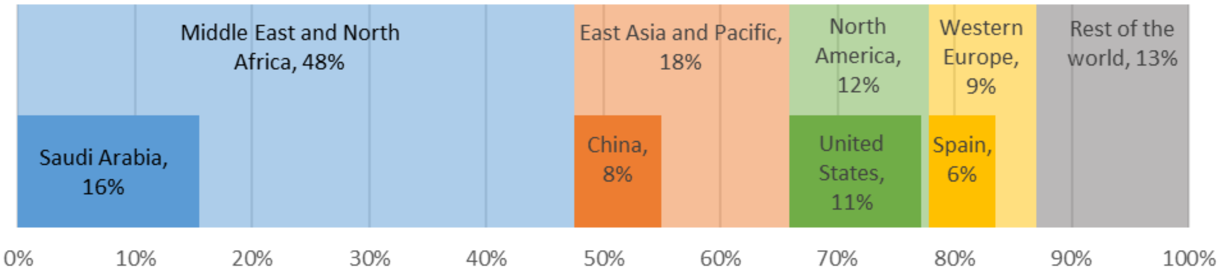

FIGURE 5.15. GLOBAL DESALINATION CAPACITY DISTRIBUTION FOR SELECTED REGIONS [139].

TABLE 5.7. NON-EXHAUSTIVE LIST OF COUNTRIES WITH RESEARCH INTEREST IN OCEAN POWERED DESALINATION SYSTEMS

Region	Country	References
Europe	Spain	[154]
	Italy	[155], [156] [157] [158]
Africa	Morocco	[159]
	Kenya	[159]
	Somalia	[159]
	South Africa	[159], [160]
	Madagascar	[93]
Asia	Oman	[159]
	India	[161]
North America	Barbados	[159]
	Bermuda	[159]
	USA	[149]
Oceania	Australia	[162]

5.6.3 POWER REQUIREMENTS

In 2012, IRENA estimated that desalination plants worldwide producing 65.2 million m^3/day of freshwater consumed at least 75.2TWh/year, which equalled to about 0.4% of the electricity consumption at that time [140]. In Gulf Cooperation Council countries[13], this rate is even higher, making up as much as 12% of the electricity consumption [163]. For instance, in 2012 in Saudi Arabia, which is the largest desalinated water producer in the world, 895.5TWh (77 Mtoe) were consumed to produce freshwater [164], over 12% of an annual energy production of 7,268.8TWh (625 Mtoe) [165].

Energy requirements per desalination plant depend on the size of the plant, the desalination process and the feedwater salinity, among others. Size of desalination plants may vary from a few tens of cubic meters per day in isolated or remote areas (e.g., La Graciosa, Canary Islands has a capacity of 75 m^3/day [166]) to hundreds of thousand cubic meters per day in large utilities (e.g., Jeddah, Saudi Arabia with a capacity of 880,000 m^3/day [167]). Desalination techniques may generally be classified into distillation-based (e.g., multi-stage flash and multiple effect distillation) and membrane-based (e.g., reverse osmosis, nanofiltration, and electrodialysis).

Reverse osmosis comprises most of the desalination market (69% in 2018 [139]) and has become the most energy-efficient technology at industrial scale [147]. Using seawater as a feed, at present reverse osmosis consumes as low as 3kWh/m^3 of freshwater produced [168]. The sector is aiming to decrease their specific energy needs in order to reduce their carbon footprint. Although technology improvements may result in 15% to 30% energy consumption reductions [169], it has been suggested that the potential for the largest reductions lies in substituting fossil fuels by renewable energy [147].

5.6.4 OPPORTUNITY FOR OCEAN ENERGY

Globally, only 1% of the desalinated water is produced through renewable energies [140] [144], the rest being mostly obtained burning fossil fuels. General reasons for low integration of renewable energies thus far are varied, but historically the main ones have been cost of energy generation and intermittency. A large portion of the world's top producers (i.e., Gulf Cooperation Council countries) have always had access to inexpensive oil, and hence a low economic incentive to shift to renewables. Primarily, the integration of renewable energy in these countries has responded to environmental incentives. Although desalination plants operate more efficiently with a stable, predictable power input, forecasts of energy demands almost doubling by 2030 [143] within a sector already highly energy intensive have contributed to the decision to shift the traditional view concerning renewables.

Ocean renewable energy is a potential alternative which may offer some advantages with respect to other renewable sources:

- Co-location; ocean energy is inherently located close to the seawater used by most desalination plants.

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[13] Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates.

- Direct provision of high pressurized water without the need of producing electricity, which may make the total opportunity cost more attractive with respect to other renewable sources [149].

The synergies between ocean energy technologies and desalination systems can enable the creation of a circular economy. These innovations form a potential pathway to sustainability.

Two-fifths of the world's cities of 1-10 million people are located near coastlines, and fourteen out of seventeen of the world's megacities[14] live near the coast [170]. Since over three-quarters of the desalination plants operate with seawater, this means that most desalination plants are placed near large urban areas, with connection to the grid. That is to say that, in these regions, OPDS would have to compete with a range of power sources feeding the grid. Therefore, the highest opportunity short-term for OPDS would likely be found in remote populated areas, with low energy security or at a high price, and scarce water resources.

5.7 SUMMARY OF OTHER MARKETS

Additional to the niche applications previously described in sections 5.3 through 5.6, alternative and prospective applications have been identified. These mostly include synergies with industries and services such as coastal resiliency and disaster recovery, ocean observation and navigation, and underwater mining, among others. Given the emerging or small-scale nature of these applications, it has been rather difficult to quantify current power requirements and, thus, a potential market size. Nevertheless, they might serve as stepping stone for the development of ocean energy technologies such as wave and tidal stream and be of interest for device and project developers, researchers, and investors and funding bodies. This section presents an overview of the alternative applications identified.

5.7.1 COASTAL RESILIENCY AND DISASTER RECOVERY

Climate change consequences such as sea level rise, more frequent and intense storms, as well as other extreme weather events such as tsunamis and flooding are threatening coastal areas all over the world. Between 1998 and 2016, coastal areas such as Puerto Rico, Honduras and Myanmar were amongst the most affected by extreme weather events [171]. In 2017, it is still coastal areas such as Puerto Rico, Sri Lanka and Dominica at the top of the list of the most affected countries [171]. Extreme events may limit access to freshwater and electricity and increase public health risks, thereby disrupting communities and eventually forcing them to be displaced. With the close proximity of the continuously rising global population to the coast and the potential impacts of climate change, it is imperative to integrate resiliency and disaster recovery planning into decision-making processes and adapting planning and development practices to mitigate these events. Coastal communities are addressing these threats by developing mitigation strategies and increasing their preparedness for such events, response and recovery operations, and improving the overall resiliency of fundamental infrastructure and emergency assets. Thereby, coastal communities increase their security of supply and meet emergency needs such as water treatment and supply.

There are opportunities for ocean energy to play and important role in the support of these adaptation and mitigation strategies. Ocean energy technologies can support shoreline protection

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[14] City with more than 10 million people.

efforts by powering marinas, ports, local communities, or aiding in sand replenishment of beaches. Furthermore, ocean energy devices can be integrated into protection solutions such as breakwaters as in the case of the Mutriku, Spain, where a multi-turbine facility was integrated with vertical breakwaters [172] or the case of the Eastern Scheldt in the Netherlands where the largest storm surge barrier in the world has also been equipped with five tidal turbines [173].

Another important opportunity for ocean energy is disaster recovery. The U.S. Department of Homeland Security has identified in its National Response Framework [87] the power needs that arise after an extreme event has occurred and these include:

- Electricity is needed to have communication systems enabling public information and warning,
- Lighting, heating/cooling, and communications in emergency management centres;
- Electricity is required to augment fuel for vehicles (hybrid or electric) and other means of evacuation such as boats;
- Electricity is needed for medical assistance, refrigeration for morgues, among others;
- Electricity is needed to provide water pressure and pumping services for fire management and suppression; and
- Power is required for constructing and running temporary shelters, processing clean potable water, and providing emergency first aid.

In these markets, ocean energy will have to compete with solar and wind power as well as battery energy storage systems and will have to prove its reliability. However, given the nature of ocean energy, it can create valuable partnerships with coastal and harbour planning and management organizations as well as civilian and volunteer organizations who might be interested in seizing the ocean energy potential and, thus, investing in these technologies for shoreline protection and disaster recovery applications.

5.7.2 OCEAN OBSERVATION AND NAVIGATION

This market includes instruments used for:

- Ocean observation, including meteorological and oceanographic monitoring buoys, sensors mounted on ships, moorings and coastal stations [174]; and
- Navigation purposes, e.g., maritime traffic buoys, air horns, and lights.

These devices are powered locally by batteries and solar panels, or remotely via cables connected to shore. However, these configurations present some disadvantages such as the limited battery capacity, data storage, and transmission to shore that could benefit from an integration with wave and/or tidal stream. These ocean energy devices can be co-located with ocean observation sensors, navigation markers, and subsea inspection vehicles.

There are no accurate estimates for the power requirements of ocean observation systems. Some ocean observation buoys and navigation aids have power requirements that range between 10 and 600kW per installation [175], whilst buoys operated by the National Oceanic and Atmospheric Administration (NOAA) require power that ranges from 40 to 200W [87]. Furthermore, these technologies change rapidly making it difficult to value the market. However, as of December 2019, there are approximately 8,800 elements in the Global Ocean Observing System[15] that could potentially be powered by ocean energy technologies. Furthermore, there are efforts worldwide seeking to support further research and exploration of the oceans. This implies that new instruments, platforms, and tools are being developed at the moment and, thus, the ocean observation market is expected to expand. Small-scale wave and tidal stream arrays could change the way oceanographic measurements are taken.

5.7.3 UNMANNED UNDERWATER VEHICLES

Unmanned underwater vehicles (UUVs) are vehicles operating subsea without an occupant. There are remotely operated vehicles (ROVs) normally tethered to a surface ship where the human controller is, and autonomous underwater vehicles (AUVs) which are not connected to a surface vessel and are operated independently. ROVs are used both for industrial purposes, such as internal and external inspections of underwater pipelines and the structural testing and monitoring of offshore platforms, and for scientific purposes, such as ocean exploration. Most ROVs are equipped with a still camera, video camera, and lights, but may also be equipped with a manipulator or cutting arm, water samplers, and other sampling instrumentation.

AUVs are used for observation, surveillance, persistent monitoring, ocean observation, and inspections of subsea infrastructure, and can be equipped with ocean sensors to provide ocean observations and measurements. Most AUVs are battery-powered, with an endurance ranging from 10-20 hours to beyond 400 hours for hybrid energy systems using diesel fuel in conjunction with a battery. As such, AUVs need periodic retrieval from the sea to be recharged on a vessel and download the data they have collected, which may represent an additional cost of $30,000 (~€27,175) or more for each day vessels are used [87]. Besides, by surfacing, being retrieved and redeployed, AUVs are spending unnecessary time off mission.

Underwater docking stations could partially improve these conditions, while also reducing the amount of carbon emissions from the vessels involved. In this underwater docking stations, AUVs would recharge their batteries and even store their data, thereby extending the mission duration and reducing the reliance on surface vessels. While power sources used in AUVs are still undergoing research and development, there is potential for supplying these structures with local, clean ocean energy. The energy requirements for a generic AUV depending on the different types of rechargeable power sources that have been typically used in AUVs to date (or are in progress of development in conjunction with a specific AUV program) are compared in Table 5.8. These figures can help potential developers to estimate the size of the arrays that could be developed to meet these power requirements with ocean energy technologies.

The AUV market is expected to grow from $2.69bn (~€2.44bn) in 2017 to $5.2bn (~€4.7bn) by 2022 [176] due to increasing deep-water offshore O&G production and increasing maritime security threats demanding, therefore, more commercial applications such as surveys and seabed mapping, offshore drilling, and pipeline inspections. This market is expected to experience the highest growth

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[15] The Global Ocean Observing System (GOOS) is a programme executed by the Intergovernmental Oceanographic Commission (IOC) of the UNESCO: https://www.goosocean.org/. The IOC currently accounts with 150 member states: http://www.ioc-unesco.org/index.php?option=com_oe&task=viewDocumentRecord&docID=4017 .

in Africa given the discovery of new regions for O&G exploration between this continent and the Gulf of Mexico making it a prospective area for ocean energy development.

TABLE 5.8. TYPICAL PERFORMANCE OF ELECTROCHEMICAL, RECHARGEABLE POWER SOURCES IN A GENERIC AUV OF A TOTAL VOLUME OF 1.2M^3. ADAPTED FROM [177].

Technology	Energy density (Wh/dm^3)	Endurance (h)
Lead-acid	10-20	4-8
NiCd/NiMH	10-30	4-12
Silver-zinc	30-50	12-20
Lithium ion (D-cells)	40-70	16-28
Lithium polymer (poach)	50-75	23-30

5.7.4 DEEP SEA AND SEAWATER MINING

The potential depletion of some minerals currently extracted from land has encouraged research to harvest ores from non-conventional sources, such as the deep sea and seawater.

DEEP SEA MINING

The deep sea is generally considered to be the region of the oceans beyond the continental shelf, outside the area of the territorial sea, starting at an average depth of 200m [178]. It accounts for 95% of the oceans volume, with an average depth of around 4,000m [179] [180]. In spite of being the largest ecosystem on Earth, the deep sea remains mainly unexplored, with scientists estimating that less than 0.01% of the deep sea-floor has been sampled and studied in detail [181]. And yet lately the deep sea is increasingly gaining attention, for its rich ecosystem and content of minerals.

Programmes for extraction of minerals from the seabed have been on-going since the 1970s in the Clarion-Clipperton Zone [179], but none took place. This may change in the next few years as the International Seabed Authority (ISA), the UN body that regulates the seabed in international waters, has issued exploration for fifteen years in several regions of the Pacific, Indian and Atlantic oceans which amount to over 1.5 million km^2, a surface roughly the size of Mongolia. These areas contain ferromanganese nodules and crusts, and seafloor massive sulphides, strongly enriched with minerals such as Ni, Cu, Mn, Co, Zn, Au, and Ag, among others. These metals are essential for different high-tech, green-tech, emerging-tech, and energy applications [182].

Mining operations and energy requirements depend on the type of resource (nodule, crust, or seafloor massive sulphides) and depth at which it is deposited, as well as the extraction technique used. There are ultimately four different techniques to mine for a mineral deposit: "*Scraping it from the surface; excavating it by digging a hole; tunnelling to a deposit beneath the surface; or directly drilling into it. Once the resource is obtained through one of these methods, it must then be transported, processed, and refined into a marketable product*" [179]. As the processes, vessels and even ROVs used will require energy at sea, there is potential for integration with ocean powered energy systems.

SEAWATER MINING

Seawater contains a large number of dissolved minerals and gases. For some materials, the amount found in the oceans surpasses by far that on land (see Figure 5.16). For example, over 4Gt of uranium are contained in the oceans, almost a thousand times the quantity available on land [183]. However, some of these materials are highly dissolved, with low concentration levels. Using again the previous example, uranium has a concentration in seawater of 0.0033 parts per million (ppm), whereas commercial land ores typically have concentrations over 1,000 ppm [183] [184]. This makes extraction technically challenging and potentially cost-prohibitive. That is to say that huge volumes of water need be processed in order to obtain significant amounts of minerals, which may result in a very energy-intensive process, depending on the extraction method.

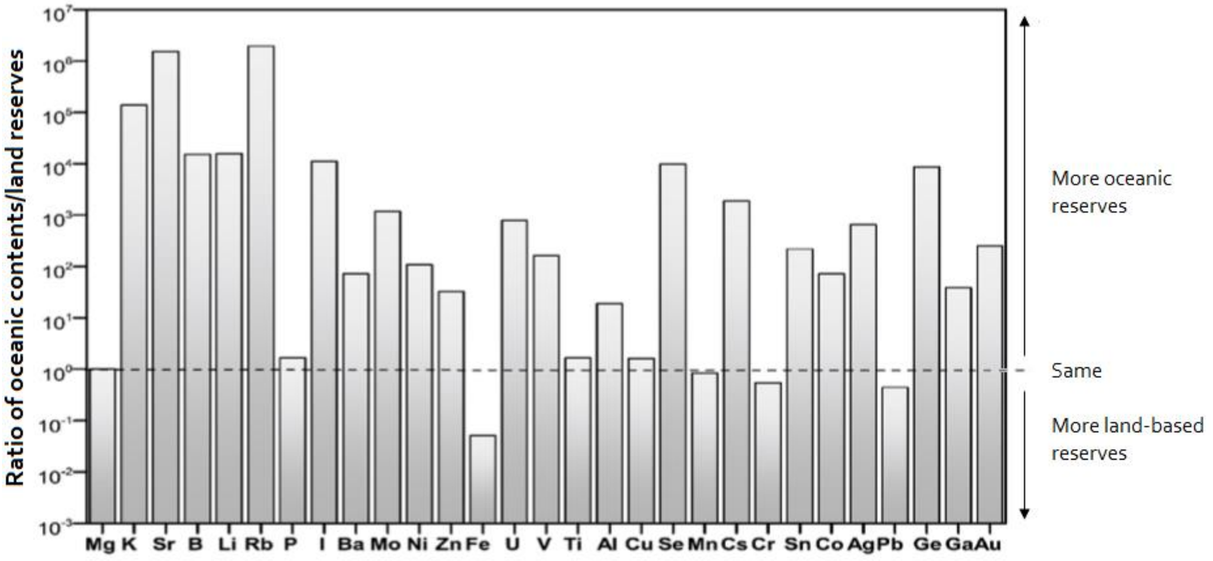

FIGURE 5.16. ESTIMATED RATIO OF THE AMOUNT OF SOME OCEANIC MINERALS TO LAND RESERVES [185]

When concentration levels are very low as, e.g., that of uranium, available strategies to process such volumes of water ultimately rely on synthetic adsorbent membranes [186] [185]. Membranes are capable of collecting minerals on their surfaces through a process called adsorption. The two common ways of using these membranes are by active or passive adsorption. Active adsorption involves pumping seawater through the membrane, whereas in passive adsorption the membrane is simply dropped into the sea to wait for ocean currents to transport the minerals to the surface of the membranes.

Active adsorption of seawater has repeatedly been reported as non-energy efficient due to the energy required to pump the water [183] [187]. However, there is a major synergy between desalination plants and seawater mining which may lower the overall production costs [185]. Desalination plants pump seawater to produce freshwater, and in the process seawater brine is discarded. Seawater brine contains all the minerals of seawater at nearly 2.5 times its normal concentration levels [185] [87]. If brine is used as a feed for mining, part of the operational costs derived from the low concentration levels of some minerals could be reduced. At the same time, part of the environmental concerns arising from brine management in desalination plants could, to some extent, abate.

This synergy between desalination plants and seawater mining could be further enhanced by integrating ocean powered desalination systems[16]. Ocean energy could provide a local, sustainable means to pump high pressurized water to reverse osmosis desalination plants, or simply be used to power any mechanical or electrochemical system required [87].

In passive adsorption, membranes are deposited under the sea to wait for ocean currents or thermal diffusion to bring the minerals to the surface of the adsorbent membrane [188] [189]. In comparison with active adsorption, no pumping of water is required; however, energy is still needed to place/retrieve membranes from the sea site and extract the minerals from them. Placing and retrieval of membranes may be carried out in different ways, for example, membranes may be placed by themselves or attached to existent offshore structures [190]. However, the potential symbiotic role of ocean energy in these configurations will ultimately be reduced to: 1) power transport systems, such as vessels, to bring the membranes on-site, and 2) power mechanic retrieving and mineral processing systems.

Powering of marine transportation crafts through ocean energy may be a market on its own right, with several possible concepts currently under research. Ocean energy could, e.g., power electric charging stations, such as the ones introduced in section 5.7.3, or supply energy for hydrogen electrolysis production to fuel vessels with hydrogen-powered propulsion systems.

5.7.5 MARINE DATACENTRES

Computer datacentres require significant amounts of cooling, so companies are investigating locating them in locations where this is more easily provided, such as arctic regions. As a significant proportion of the world population lives close to the coast, another solution is to locate them underwater, and use the surrounding water for cooling purposes. This also offers an additional opportunity to supply the significant power requirements for datacentres using nearby ocean energy sources.

Microsoft recently installed a second underwater datacentre at the EMEC test site in Orkney, UK as phase two of Project Natick [191]. This is powered by the local grid, although that includes a high proportion of renewable generation including wave and tidal stream. It is stated that in future they will explore the option of having co-located ocean-based renewables to power the datacentre, in order to minimise the impact on overstressed electricity grids.

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[16] For a complete review of the market opportunity for ocean energy in desalination, see section 5.6.

6. DISCUSSION

Considering the advancements in the ocean energy sector during the past few years in terms of both technology and market readiness, it is appropriate to review the potential opportunities for these energy technologies in the current global state.

6.1 ECONOMIC FEASIBILITY OF WAVE AND TIDAL STREAM AND POTENTIAL MARKETS

Renewable energy is becoming the lowest-cost source of new power generation in several regions around the world. The global weighted average LCOE of solar photovoltaics, onshore wind and offshore wind have fallen substantially from $371 (~€336), $85 (~€77), and $159 (~€144)/MWh respectively in 2010 to $85 (~€77), $56 (~€51), and $127 (~€115)/MWh in 2018 respectively and are expected to continue falling potentially reaching the estimates presented in Table 6.1 [192]. This is a result of considerable investment in these energy sectors. Solar photovoltaic capacity has gone from a modest 808MW in 2000 to over 480GW in 2018 whilst onshore and offshore wind capacity have increased respectively from 17GW and 67MW in 2000 to over 540GW and 23GW in 2018 [193]. These three technologies are the biggest competitors to ocean energy in the grid market. Moreover, wave and tidal stream technologies must compete as well with offshore wind applications in non-grid connected markets with high power requirements such as the offshore O&G market. Alternative markets with lower power requirements such as remote areas, ocean observation and navigation, or UUVs where energy prices are currently high can contribute to a faster cost recovery for the demonstrators, thereby serving the purpose of facilitating the development of wave and tidal stream technologies to achieve higher levels of technology readiness.

The wave and tidal stream sectors can learn from the success of solar and wind energy that within 20 years have established thriving and continuously expanding markets. With the appropriate regulatory and financial support, wave and tidal stream technologies can grow and achieve industrial roll-out in the next few years. Ocean energy can contribute to the global efforts of decarbonisation and tackle some of the sustainable development challenges that society faces at present.

TABLE 6.1. COMPARISON OF ECONOMIC AND TECHNICAL PARAMETERS OF KEY RENEWABLE TECHNOLOGIES AND OCEAN ENERGY TECHNOLOGIES [38] [192]

	LCOE ($/MWh)			Capacity Factor (%)		
	2010	2020	2025	2010	2018	2025
Solar PV	371	48	-	14	18	-
Onshore Wind	85	45	-	27	34	-
Offshore Wind	159	108	-	38	43	-
Wave*	-	-	222	-	-	30
Tidal Stream*	-	-	167	-	-	37.5

*Targets from the SET-Plan (European Commission), as detailed in Table 4.2

6.2 BARRIERS AND ENABLERS TO WAVE AND TIDAL STREAM

Additional support mechanisms and initiatives for the wave and tidal stream sectors are fundamental for the road ahead. Projects such as DTOceanPlus can support the development of wave and tidal stream technologies. Work Package 2, in particular, sought to guarantee that the tools produced by DTOceanPlus cover real industrial needs towards the development and deployment of cost-effective ocean energy devices and arrays. In this sense, WP2 gathered requirements based on the experience of user-groups including public funders, commercial investors, insurance providers, innovators and developers, project developers, utilities and supply chain, policy-makers, regulators, and standardisation bodies. With this input, detailed functional, operational, user, interfacing, and data requirements were identified and used to direct the efforts for tool development. The tools developed in work packages 3, 4, 5, and 6 empower the ocean energy sector to appropriately and efficiently target the market opportunities identified and described in this report.

It is important to keep in mind that there are additional non-technical barriers and enablers to ocean energy that must be considered. These are discussed in other studies such as Hannon et al. [55], van Velzen et al. [194], MacGillivray et al. [195], Green and Krohn [196] and are summarised below:

- **Public financing of ocean energy**. As mentioned in section 3.4, public funding is the most important source of financial support at early stages of development for wave and tidal stream technologies. High capital costs, low revenue projections and high investment risks due to uncertainties at early stages of development makes it challenging to obtain support from private investors. Furthermore, the immaturity of the technologies at these stages increase insurance premiums and limits the willingness of, e.g., commercial banks or utilities to support these energy sectors. Providing public funds has proven to be helpful in realising some of the targets and ambitions set for the ocean energy sector and to the development of wave and tidal stream devices.
- **Private financing of follow-up steps**. At later stages of development, having tested the concepts and gathered some operational experience, private financing can be acquired from venture capital and OEMs who are willing to accept high risk and may have a good understanding of the technologies. As the technologies jump into the demonstration, pre-commercial and roll-out stages, private financing from utilities, state-backed banks, commercial banks, and institutional investors may be available. The involvement of these investment sources reduces the investment risk, increasing the confidence in the technologies and attracting more interested parties.
- **Insurance**. There are a limited number of insurers willing to underwrite wave and tidal businesses given that this insurance market is still at an embryonic stage. Furthermore, typically, insurers are reluctant to offer a full insurance coverage, i.e., insure full replacement values and third party liabilities associated with a specific technology. An option has been to have insurers work collectively to insure ocean energy devices. Another option has been to work with some dedicated marine insurers and not only dedicated renewable energy or offshore energy insurers given their better understanding of the nature of these technologies and the environment that they operate in. However, some challenges remain. For example, Defect Exclusion and technology Series Losses Clauses are narrower for ocean energy than for offshore wind farms. Ultimately, this sector expects to see the same shift of insurance buying control, i.e., as ocean

energy technologies develop and more capacity is deployed, developers might start to control the insurance making Delay in Start-Up and Business Interruption coverage more accessible.

- **Continued cost reduction**. Ocean energy has reached lower LCOE than expected at this stage of development [38]. As more capacity is deployed, innovations are introduced, and lessons learned implemented, the benefits of economies of scale can be perceived and improvements in capital and operational expenditures as well as advancements in efficiency and specialisation (thus affecting the annual energy production) will drive further cost reductions in the wave and tidal stream sectors. These cost reductions along with the design and implementation of sustainable and effective business models, such as those to be developed in Task 8.4 of the DTOcean Plus Project, will contribute to the cost-competitiveness of the ocean energy sector and to make these technologies important players of the global decarbonisation efforts.
- **Supportive consenting and regulation**. Technology-specific support policies and regulations are necessary to make these emerging technologies competitive with more mature technologies. It is important to acknowledge the emerging nature of the wave and tidal stream sectors when designing these policies and regulations as to avoid being out-competed for subsidies or incentives on a cost basis by better established renewable energy technologies such as wind and solar. This entails separating wave and tidal stream from CfD allocations and/or avoiding these technologies being bundled into wider ocean energy RD&D programmes as to not have them compete with more developed technologies such as tidal range or OTEC. Similarly, enabling streamlined consenting processes such as the one in Scotland, the Marine Scotland – Licensing Operations Team, can simplify and consolidate the supporting legal framework for wave and tidal stream technologies.
- **Infrastructure**. Grid expansion and upgrades are necessary to enable the integration of offshore energy into the power utility market. The development and strengthening of the grid networks in areas of significant wave and tidal resource are an important enabler for these technologies and should be made a priority.
- **Standards and certification**. Stage-gate metrics regarding reliability, survivability, and performance reduce the risks associated with deployment and increase confidence in the technologies. Similarly, the adoption (or development) of standards for the wave and tidal stream sectors can aid validating the performance and quality of the devices developed. Furthermore, obtaining certifications for the materials and processes involved can contribute to reduce scepticism and attract more potential funding sources. In this regard, the wave and tidal stream sectors can benefit from cross-sector knowledge exchange, particularly from the offshore wind and O&G industries.
- **Innovation**. The development of an innovation scheme for wave and tidal stream entailing and enabling knowledge development and exchange, entrepreneurial experimentation, resource mobilisation, and mechanisms to create niche markets can provide legitimacy to these emerging technologies, shaping and strengthening the market, and making it competitive with other more mature ones.
- **Cross-sectoral interlinkages**. As mentioned in section 5, wave and tidal stream technologies can plan an important potential role linking different markets and contributing to the creation of smart local energy systems and powering the blue economy. An example would be the production of hydrogen via electrolysers and electricity generated from wave and tidal stream and later used as fuel for transportation or as storage for grid stabilisation and added flexibility.

- **Ethical and environmental concerns.** There may also be ethical and environmental concerns from some developers and funders when deciding whether to part-take in some of these markets. This is particularly true of O&G, seabed/seawater mining, and military applications, which may be seen to be at odds with the green environmental credentials of ocean renewable energy.

6.3 ENERGY STORAGE

One of the drawbacks of all renewable energy generation technologies is their inherent variability. An electricity grid has to be finely balanced to match supply (electricity generation) with demand at all times, and this demand varies daily and seasonally. The ability to store energy from variable generation can increase the uptake of renewable technologies and reduce emissions from fossil-fuel power generation. In addition to storage, demand side management can be implemented in electricity grids, as discussed in section 2.3, to adjust demand to better match the amount of variable generation.

Historically, the only method of large-scale power storage has been through pumped-storage hydro-electricity schemes. Analysis by the US DoE shows these make up 97% of global storage capacity [197]. In these schemes, water is pumped uphill to a high reservoir at times of low electricity demand and is thus available for hydro-electric generation at times of peak demand. The number of suitable locations to implement this technology is limited however, as they are very dependent on local topography and are subject to many environmental considerations.

There are a number of other technologies that will help to offset this variability of renewables that are being developed and commercialised. These include batteries of various types, compressed gas storage, high temperature thermal storage, flywheels, and production of hydrogen or other electrofuels (i.e., synthetic fuels produced through “Power-to-X” technologies). These can be categorised by the type of process as shown in Figure 6.1. It should also be noted that each technology and category has advantages and disadvantages, and widely varying performance in terms of discharge time and energy storage capacity, Figure 6.2 [198]. Storage associated with renewable energy generation may need to shift energy on both hourly and daily or longer periods, which may need multiple technologies [198].

The IEA state that the use of hydrogen is one way to reduce emissions associated with the production and use of oil and gas [6]. This could include blending low-carbon hydrogen into existing natural gas networks or use of the hydrogen directly. To reduce emissions, the hydrogen production has to be from low- or zero-carbon sources, which could include ocean energy. It is however noted that intermittent operation of electrolysis facilities may prove an expensive method of hydrogen generation due to the high capital costs involved.

Hydrogen production and storage is already being used in conjunction with ocean energy in the Orkney Islands, UK as part of the “Surf ‘n’ Turf” project [199]. Hydrogen is generated from tidal energy that would otherwise be curtailed, shipped to a nearby port, and used to generate electricity when required through a 75kW fuel cell. Through the “Integrating Tidal Energy into the European Grid” (ITEG) project [200] funded by the Interreg North-West Europe programme, an additional 0.5MW electrolyser will be installed and powered by excess power generated the Orbital O2 2MW tidal turbine due to be deployed later in 2020.

Although not the main focus of this study, integration of storage technologies could make ocean energy more attractive for electricity generation, albeit potentially at a higher cost when accounting for the storage. It should also be noted that these benefits of storage will apply to other renewable energy technologies that ocean energy may be competing with.

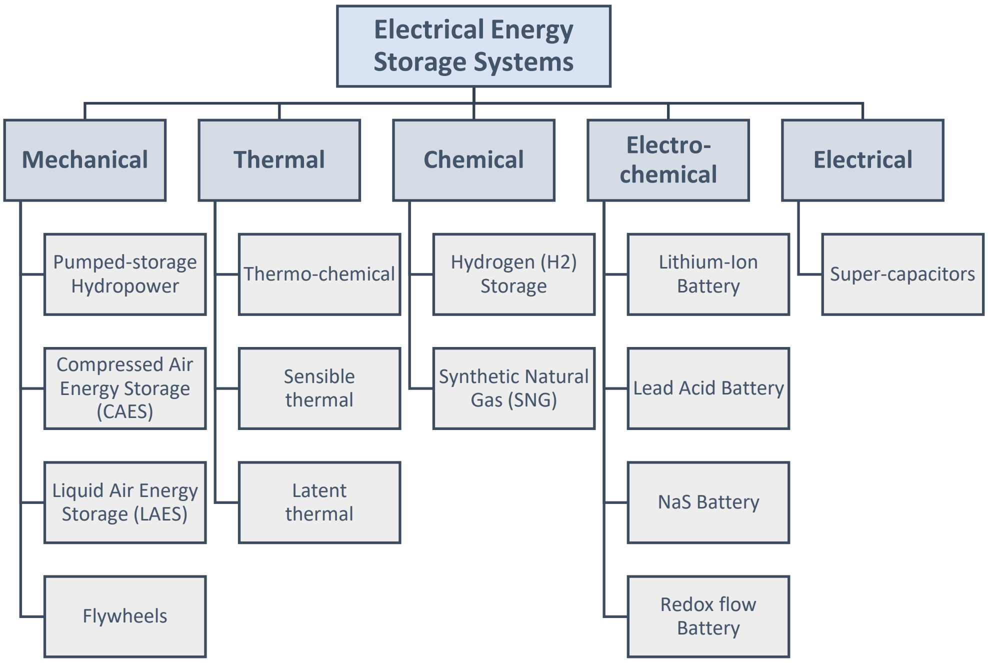

FIGURE 6.1. CATEGORISATION OF ELECTRICAL ENERGY STORAGE SYSTEMS [198]

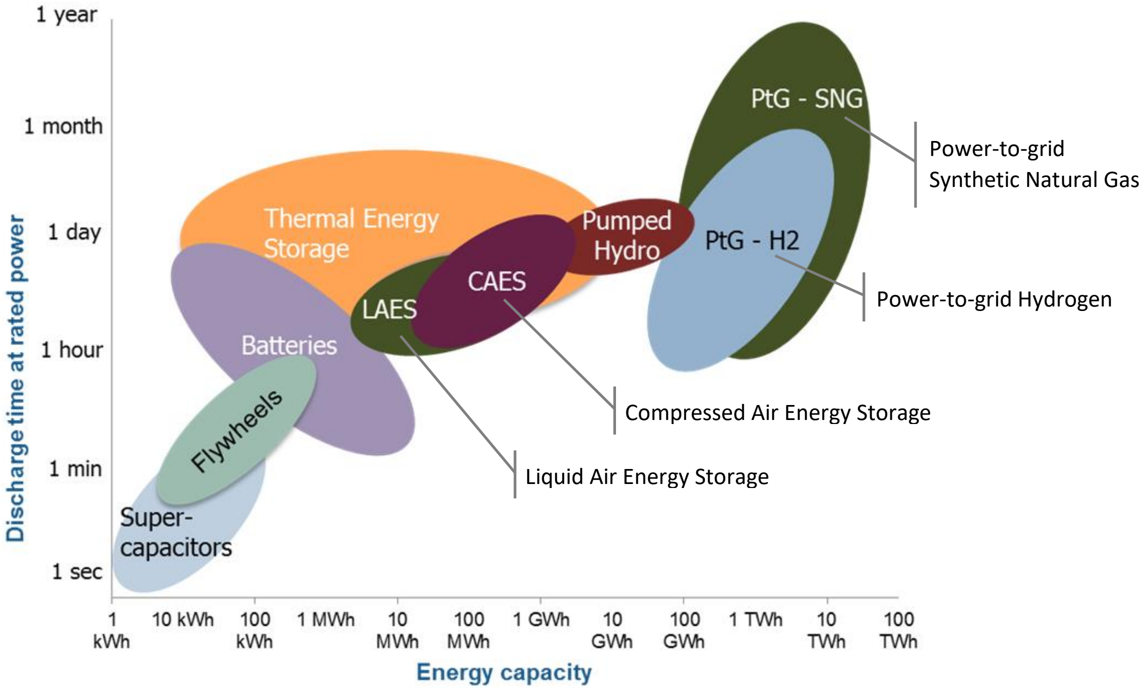

FIGURE 6.2. STORAGE TECHNOLOGIES ACCORDING TO PERFORMANCE CHARACTERISTICS [198]

7. CONCLUSIONS

Information regarding potential market opportunities for wave and tidal stream technologies in the coming years has been summarized, collated, and synthesized in this report. The findings and insight derived from this research are intended to aid the commercialisation of these ocean energy technologies. Wave and tidal stream are not mature markets yet. However, significant progress has been achieved in the last decades resulting in improvements to the reliability and performance of the ocean energy devices and attracting interest and attention to the benefits of ocean energy technologies.

Two types of markets for wave and tidal stream technologies have been examined in this report, namely grid market and alternative (niche) applications. For ocean energy technologies to be able to compete in the grid power market, significant cost reductions and capacity factor improvements must be achieved. However, if these technologies reach industrial roll-out, they can form a part of the global repertoire of low-carbon, sustainable, and environmentally-friendly power generation schemes. The alternative markets identified are specialized applications and imply potential synergies with other markets that can provide dual benefits meeting the energy needs of niche markets while serving as stepping stone for the development of wave and tidal stream technologies. For instance, adopting ocean energy in carbon-intensive industries and services can be beneficial for individual organisations to meet their climate obligations while reducing the public funding requirements to cover the initial high capital costs of these technologies. Wave and tidal stream can be, indeed, attractive options for a power-hungry world faced with numerous challenges of present-day concerning both decarbonisation and sustainable development.

It has not been possible to estimate the total addressable market or potential revenue for these opportunities due to the nascent and rapidly changing nature of the technologies; nevertheless, highly ambitious climate-related targets and strategies such as the European Green Deal are an opportunity to attract support and investments in the market opportunities identified in this report. Further targeted research is necessary to size the potential markets and estimate the total available market. The economics of a market opportunity are specific to circumstances and factors such as location, regulatory and legal framework available, and type of technology, among others. Hence, the valuation of a market opportunity for wave and tidal stream at the moment is a difficult task. This report offers an overview of the large potential that these ocean energy technologies show, yet individual organisations and interested parties will need to further investigate the specific prospective applications.

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Annex I. SUMMARY OF PROJECTIONS AND PROGNOSES USED IN THIS REPORT

This annex offers a brief overview of the projections and prognoses regarding the future of the global energy system considered throughout this report.

The International Energy Agency (IEA), in the World Energy Outlook (WEO) [6] [7] and Energy Technology Perspectives (ETP) [8] reports, explores a number of possible futures in its scenarios, with varying assumptions and input parameters. Here, the key assumptions and findings relevant for the purpose of this report are summarized per scenario:

- The **Stated Policies Scenario (STEPS)** [7], formerly known as the **New Policies Scenario (NPS)** [6], is the IEA-WEO's central scenario. It looks at the development of the energy sector up to 2040 on the basis of already announced policies and plans as well as the likely effects of policy initiatives and energy strategies such as the Nationally Determined Contributions under the Paris Agreement, efficiency standards and schemes, electrification programmes, among others. Electricity plays a relevant role in this scenario as costs for renewable energy decrease and technology advances. Power systems are expected to undergo a rapid transformation and be at the core of the energy systems. Issues such as the need for storage, the interface between electric vehicles and the grid, and data privacy are expected to arise. Under this scenario, carbon emissions continue to rise to 2040 and global temperatures will likely increase by 2.7ºC by 2100. It assumes people and countries will not act consequently to their commitment to the Paris Agreement. In the STEPS, energy demand is set to grow by more than 25% to 2040, electricity generation will rise to 40,000 TWh by 2040, with renewable energy generating around 40% of the total. Electricity becomes the preferred energy carrier in economies with smaller industrial sectors and stronger reliance on services and digital technologies. It is expected to represent approx. 24% of the global final consumption.
- The **Future is Electric Scenario (FiES)** [6] is a scenario specifically designed to highlight the relevant role of electricity in the energy future and included in the WEO's 2018 Special Focus on Electricity report. It is built based on the conditions laid out in the STEPS but seeks to further explore key areas of uncertainty for electricity demand throughout the period under study. It assumes that several electric technologies are adopted as soon as they become cost-competitive. In this scenario, electric mobility, electric heating, and electricity access drive up power demand by 90% in 2040 to 42,000 TWh, an increase of 7,000 TWh relative to the STEPS. Most of this increase is due to transport since it is assumed that almost half the car fleet in 2040 is electric. With the residential and industrial sectors increasingly meeting their energy needs with electricity as well, this energy carrier moves up to represent approx. one-third of the final consumption. Renewables supply around half of the electricity generated in this scenario. Although local pollution will be notably reduced given the emissions avoided from internal combustion engine vehicles (ICEVs), energy-related CO2 emissions will experience only a slight decrease compared to the STEPS. Additional measures are required to guarantee the decarbonisation of the growing power systems and avoid a consequently increase in CO2 emissions from power generation. When further decarbonisation strategies for the power sector are considered such as carbon capture and storage (CCS), CO2 emissions might decrease from approx. 36 Gt CO2e in the SPS to around 21 Gt CO2e in the FiES.

- The WEO's **Sustainable Development Scenario (SDS)** [7]presents the most ambitious scenario in terms of human and global safety. It is assumed that nations work together to successfully limit climate change, transforming the global energy system, providing universal access to clean energy, and reducing the health impacts of energy-related air pollution. This scenario is completely aligned with the Paris Agreement and the energy-related Sustainable Development Goals. The SDS keeps the temperature rise below 1.6 °C with a 50% probability and the energy-related emissions are reduced by three-quarters by 2040. This is achieved by, inter alia, significant effort into energy efficiency measures, which leads to lower levels of electricity demand by 2040 relative to the FiES, i.e., 39,000 TWh in comparison to approx. 42,000 TWh. In the SDS, a higher degree of electrification is achieved, with electricity accounting for 31% of final consumption in 2040 and almost two-thirds of this demand being met by low-carbon technologies. This high share of renewable energy in the energy systems requires an increase in system flexibility. It is also worth mentioning that in the STEPS, 20% of the cars are electric, while in the SDS this share increases to 75%. Overall, in this scenario, energy-related CO2 emissions decrease to approx. 18 Gt CO2e in 2040.

The ETP 2017 report [8] also explores three energy scenarios spanning between 2017 and 2060 that are referred to in this report.

- The **Reference Technology Scenario (RTS)** is broadly aligned with the WEO STEPS. It describes how the energy systems could evolve if energy-related and climate-related commitments, such as the National Determined Contributions (NDC) pledged during the 21st Conference of the Parties in Paris (COP21) in 2015, are adequately kept and implemented. Similar to the WEO's STEPS, this scenario sees the world's average temperature increase by 2.7 °C by 2100. In this scenario, primary energy demand increases by 48% in 2016 relative to 2014. Fossil fuels remain the main energy source. Low-carbon energy (including both renewables and nuclear) accounts for 27% of the final energy demand in 2060. Electricity demand doubles in this scenario, going from approx. 26,000 TWh in 2014 to around 52,000 TWh in 2060. Finally, energy-related CO2 emissions rise from 32 Gt CO2e in 2014 to almost 40 Gt CO2e in 2060.
- The ETP's **2 °C Scenario (2DS)** [8] describes an energy pathway consistent with at least a 50% chance of limiting the average global temperature increase to 2 °C by 2100. It is the ETP's central climate mitigation scenario and lays out an ambitious transformation of the global energy sector. Primary energy demand grows 17% in 2060 relative to 2014 levels and is approx. 20% lower than in the RTS. The share of fossil fuels declines to 35% in 2060, a significant decrease relative to the 67% that these fuels account for in the RTS. Due to strong efficiency measures, final energy demand grows a slightly modest 7% relative to 2014 levels. Low-carbon energy sources account for more than half of the final energy demand. As a result, CO2 emissions fall to approx. one-quarter of 2014 levels by 2060.
- Finally, the ETP's **Beyond 2 °C Scenario (B2DS)** [8] explores the effects of the adoption of technological advancements on the levels of energy-related carbon emissions. This scenario is consistent with a 50% chance of limiting average global temperature increase to 1.75 °C by 2100. The energy sector is expected to reach carbon neutrality by 2060, with the power and fuel transformation sectors becoming sources of negative emissions and relying particularly on the deployment of carbon capture and storage (CCS) technologies. Although technically feasible,

this scenario is highly ambitious aiming to make technology currently at a stage of development, commercially available within the scenario's timespan. Primary energy demand is dominated by renewable energy, which account for approx. 60% of the mix in 2060. Electricity plays a significant role in this scenario given that ground transport and buildings are electrified. Consequently, final energy demand is 10% lower relative to the 2DS and marginally lower (approx. 4%) than 2014 levels. Low-carbon energy accounts for 67% of the mix in 2060.

The scenarios described above present some decarbonisation pathways for the global energy sector. Although some are highly ambitious, they highlight the need to decouple the global economy and CO2 emissions to curtail global warming. Furthermore, they draw special attention to the key role of clean electricity in the future global energy system as a source of negative emissions. It is, thus, crucial to support the fast development and deployment of renewable energy technologies. The future of the global energy sector will depend largely on policy decisions and ambition, together with technological innovation. They will largely determine the future trajectory of energy-related emissions and global warming.

This report also considers the projections of the **"EU Reference Scenario 2016"** report developed by the European Commission [9]. The Reference Scenario models policies and measures adopted by December 2014 at EU level and in the Member States. These policies and measures include, for example, the 2020 Climate and Energy Package, legally binding renewable energy targets, CO2 targets for the fleet of new vehicles, grassland protection measures, a strategy to phase-out HFCs, as well as official infrastructure development plans. Several models such as PRIMES, PROMETHEUS, GEM-E3, GAINS, and CAPRI were used to simulate future trends in the economy, society, and the environment, with details given in the report. Energy consumption and the energy intensity of the EU economy are projected to experience a downward trend. In line with the IEA's projections, electrification if a persisting trend across the EU. Furthermore, high congestion levels and car ownership close to saturation levels slows down the growth of passenger car activity in many EU Member States leading to higher use of collective transport modes. Air transportation activity is projected to grow up by 125% between 2010 and 2050. Decarbonisation measures considered include fuel shift (from oil derivatives to hydrogen and electricity), direct electrification of collective transport modes such as rail, and efficiency and environmental regulations. Finally, renewable energy sources are expected to increase their contribution to electricity generation and supply up to 56% of the net power in 2050 in overall EU28. However, the contribution of variable sources such as solar, wind, and wave or tidal is projected to remain lower. These sources are projected to account for 19% of the total generation in 2020, 25% in 2030, and 36% in 2050. Wind is expected to provide the largest contribution accounting for approx. 25% of total net electricity generation in 2050.

Annex II. RESOURCE STUDIES

TABLE A.1. GLOBAL TIDAL STREAM RESOURCE STUDIES

Region	Annual Resource (Energy)	Resource (Power)	Theoretical/ Technical	References	Modelling methodology/resolution
UK	95TWh	32GW	Theoretical	[201]	MaRS – Crown Estates Marine Resource System, using GIS to identify potential areas for sector development
	94TWh		Theoretical	[202]	ABPmer study – assumes all potentially suitable area of UK waters up to 40m deep are free from exclusion constraints and suitable for tidal technology deployment
	21TWh		Technical	[203]	MEA study, hydrodynamic methodology
Ireland		1.5GW–3GW	Technical	[204]	Estimated total development potential without likely significant adverse effects
	230TWh		Theoretical		
France		6GW	Theoretical	[205]	Based on EDF estimates
	5–14TWh	2.5GW–3.5GW	Technical	[205]	
Japan	6TWh	1.9GW	Theoretical	[206], [207], [208]	NEDO 2011 – Utilises a published web GIS dataset to undertake statistical analyses of tidal current power. Scale of analysis is at approx. 3km resolution in the horizontal with data over a 10-year period.
South Korea		8.3GW	Theoretical	[209], [210]	The technical resource was evaluated as 4,841MW and 3,497MW in the Jang-Juk Strait and the Maenggol-Geocha Strait, respectively – but paper is still in press
China		8.2GW	Theoretical	[211]	Based on 1986 and 2004 sea surveys and the B&V figure that 20MWh can be produced per metre squared where the maximum velocity exceeds 2m/s
Indonesia		6GW+	Technical	[212], [213]	High resolution (20m horizontal, 3m vertical), three-dimensional flow models, validated with real sea data. Note – diurnal tide pattern in Indonesia.
New Zealand		24GW	Theoretical	[214]	Estimates of theoretical potential electricity, 11GW in Kapiara harbour, 13GW in the Crook Strait. Doesn't include consideration of mechanical or technical limitations.
		500MW+	Technical	[214]	Exploration of two potential tidal current sites, using hindcast data and modelled using power curves of existing/generic devices (SeaFlow and SeaGen) to calculate potential power production

Region	Annual Resource (Energy)	Resource (Power)	Theoretical/ Technical	References	Modelling methodology/resolution
Australia		3.4GW	Theoretical	[215]	
India		8GW	Theoretical	[216]	
Chile		600MW+	Theoretical	[217]	Garrad Hassan resource assessment
Mexico		200MW	Theoretical	[218]	
USA	445TWh	50GW	Theoretical	[219], [220]	Assessment of energy production from tidal streams report completed by Georgia tech. Three dimensional Reynolds-averaged Navier-Stokes equations (RANS), ~350m resolution 47 of 50GW are in Alaska
USA	222–334TWh		Technical	[219], [220]	
Canada		42GW	Theoretical	[221]	Report summarising various high resolution finite element models for different regions of Canada, ranging from 5000-130,000 nodes
Canada – Bay of Fundy		7GW	Technical	[222]	Two-dimensional finite element numerical simulations of the Bay of Fundy – Gulf of Maine system

Annex III. ELECTRICITY MARKET SIZE IN SMALL ISLANDS AND DEVELOPING STATES

TABLE A.2. ELECTRICITY DEMAND IN SIDS

Country	Electricity consumption (GWh/yr)	Notes
American Samoa	157	2015
Anguilla	89	Electricity generation in 2013
Antigua and Barbuda	308	
Aruba	990	Electricity generation
Bahamas	1,650	2015
Bahrain	26,110	
Barbados	990	
Belize	453	
Bermuda	605	
British Virgin Islands	118	
Cape Verde	367	
Cayman Islands	612	
Northern Marianas	-	
Comoros	39	
Cook Islands	32	
Cuba	16,160	
Curacao	968	
Dominica	104	
Dominican Republic	15,640	
Fiji	850	
French Polynesia	630	
Grenada	185	
Guadeloupe	1,729	Electricity generation in 2013
Guam	1,600	-
Guinea-Bissau	36	
Guyana	790	
Haiti	406	
Jamaica	2,850	
Kiribati	27	
Maldives	374	
Marshall Islands	605	
Martinique	-	-
Mauritius	2,730	
Micronesia	179	
Montserrat	22	-
Nauru	22	
New Caledonia	2,740	

Country	Electricity consumption (GWh/yr)	Notes
Niue	3	
Palau	89	Electricity generation in 2011
Papua New Guinea	3,240	
Puerto Rico	19,480	2015
Saint Kitts and Nevis	193	
Saint Lucia	343	
Saint Vincent and the Grenadines	146	
Samoa	123	
Sao Tomé and Principe	61	
Seychelles	326	
Singapore	47,690	
Sint Maarten	196	Electricity generation in 2012
Solomon Islands	96	
Suriname	1,750	
Timor-Leste	125	
Tonga	48	
Trinidad and Tobago	9,870	
Turks and Caicos Islands	200	Electricity generation in 2015
Tuvalu	-	-
U.S. Virgin Islands	794	Electricity generation in 2015
Vanuatu	59	
TOTAL	165,997	

[a] Electricity consumption data for 2015, except where noted differently. Data has been obtained from [223], except for Anguilla, Aruba, Guadeloupe, Palau, Sint Maarten, Turks and Caicos Islands, U.S. Virgin Islands [106].

Annex IV. ELECTRICITY PRICES AND CONSUMPTION IN 104 SELECTED COUNTRIES

TABLE A.3. ELECTRICITY PRICES AND CONSUMPTION IN SELECTED COUNTRIES IN 2017. DERIVED FROM [4] AND [23].

Country	Electricity Consumption (TWh)	Price of electricity (US$ per MWh)	Country	Electricity Consumption (TWh)	Price of electricity (US$ per MWh)
Malta	2	170	Iraq	46	9
Gabon	2	189	Hong Kong, China	47	15
Jamaica	3	223	Peru	47	17
Botswana	4	144	Singapore	52	10
Namibia	4	135	Portugal	52	25
Senegal	4	173	Romania	54	5
Nepal	6	114	Israel	60	11
Armenia	6	76	Greece	60	19
Albania	6	87	Switzerland	64	12
El Salvador	6	167	Algeria	65	2
North Macedonia	7	128	Bangladesh	66	9
Cameroon	7	141	Czech Republic	70	12
Tanzania	7	126	Colombia	73	13
Cambodia	7	180	Chile	75	9
Latvia	7	99	Austria	75	9
Honduras	8	172	Finland	85	11
Luxembourg	8	106	Philippines	86	16
Kenya	8	215	Belgium	89	15
Congo, Dem. Rep.	9	100	Kazakhstan	92	5
Estonia	9	85	Pakistan	111	18
Panama	9	188	Netherlands	115	10
Costa Rica	10	144	United Arab Emirates	123	11
Uruguay	10	169	Norway	125	10
Guatemala	10	194	Argentina	133	15
Trinidad and Tobago	11	67	Ukraine	134	7
Georgia	11	65	Sweden	137	10
Ghana	11	222	Malaysia	152	11
Lithuania	12	83	Poland	163	13
Zambia	13	47	Egypt, Arab Rep.	166	8
Bosnia and Herzegovina	13	162	Vietnam	185	12

Country	Electricity Consumption (TWh)	Price of electricity (US$ per MWh)	Country	Electricity Consumption (TWh)	Price of electricity (US$ per MWh)
Sri Lanka	15	169	Thailand	198	12
Mozambique	15	104	South Africa	227	14
Slovenia	15	146	Indonesia	235	10
Tunisia	17	97	Australia	244	23
Dominican Republic	17	204	Spain	258	24
Croatia	17	176	Taiwan, China	260	11
Lebanon	18	132	Turkey	262	10
Jordan	19	239	Iran, Islamic Rep.	270	5
Iceland	19	100	Mexico	278	11
Azerbaijan	21	54	Saudi Arabia	315	7
Ecuador	26	117	Italy	315	19
Nigeria	27	136	United Kingdom	327	17
Bahrain	28	48	France	483	13
Ireland	28	197	Canada	522	13
Serbia	33	73	Brazil	528	16
Morocco	33	123	Korea, Rep.	548	8
Belarus	34	117	Germany	574	32
Denmark	34	203	Russian Federation	978	8
Bulgaria	37	124	Japan	1028	18
New Zealand	41	115	India	1269	17
Hungary	42	176	United States	4099	17
Qatar	43	40	China	6302	15

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