ISSN 1831-9424

European Commission

CLEAN ENERGY TECHNOLOGY OBSERVATORY

Ocean Energy in the European Union

STATUS REPORT ON TECHNOLOGY DEVELOPMENT, TRENDS, VALUE CHAINS & MARKETS

2024

EUR 40068

Joint Research Centre

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JRC139325

EUR 40068

PDF ISBN 978-92-68-20967-7 ISSN 1831-9424 doi:10.2760/1244922 KJ-01-24-071-EN-N

Luxembourg: Publications Office of the European Union, 2024

How to cite this report: European Commission, Joint Research Centre, Tapoglou, E., Mc Govern, L., Georgakaki, A., Mountraki, A., Letout, S., Ince, E., Gea Bermudez, J., Schmitz, A. and Grabowska, M., *Clean Energy Technology Observatory: Ocean Energy in the European Union - 2024 Status Report on Technology Development, Trends, Value Chains and Markets*, Publications Office of the European Union, Luxembourg, 2024, https://data.europa.eu/doi/10.2760/1244922, JRC139325.

Contents

Abstract

Ocean energy has been acknowledged in the context of the European Energy Union as a fundamental research and development priority to achieve the 2050 climate objectives. The European Green Deal, which aims to make Europe the first climate-neutral continent, included ocean energy in the technologies necessary for a transition to climate neutrality. Since then, ocean energy has been supported by multiple policy frameworks, including the Renewable Energy Directive (RED III), the Offshore Renewable Energy Strategy, Horizon Europe, the European Union's Blue Economy Strategy, and the State Aid Guidelines for Climate. These policies have created a favourable environment for the development and deployment of ocean energy technologies, which have the potential to contribute significantly to the European Union's energy mix and decarbonisation goals.

The aim of this report is to provide an update of the state of the art of ocean energy technology, highlighting the progress made in recent years and the challenges that still need to be overcome. The report provides an analysis of R&D trends, focusing particularly on the technology progress made in EU-funded research until the end of 2023. It assesses the current status of ocean energy technologies, including tidal, wave, and other forms of ocean energy, and evaluates their potential to contribute to the European Union's energy mix.

Foreword on the Clean Energy Technology Observatory

The European Commission set up the Clean Energy Technology Observatory (CETO) in 2022 to help address the complexity and multi-faced character of the transition to a climate-neutral society in Europe. The EU's ambitious energy and climate policies create a necessity to tackle the related challenges in a comprehensive manner, recognizing the important role for advanced technologies and innovation in the process.

CETO is a joint initiative of the European Commission Joint Research Centre (JRC), who run the observatory, and Directorate Generals Research and Innovation (R&I) and Energy (ENER) on the policy side. Its overall objectives are to:

- Monitor the EU research and innovation activities on clean energy technologies needed for the delivery of the European Green Deal .
- Assess the competitiveness of the EU clean energy sector and its positioning in the global energy market.
- Build on existing Commission studies, relevant information & knowledge in Commission services and agencies, and the Low Carbon Energy Observatory (2015-2020).
- publish reports on the Strategic Energy Technology Plan (SET-Plan) SETIS online platform.

CETO provides a repository of techno- and socio-economic data on the most relevant technologies and their integration in the energy system. It targets in particular the status and outlook for innovative solutions as well as the sustainable market uptake of both mature and emerging technologies. The project serves as primary source of data for the Commission's annual progress reports on competitiveness of clean energy technologies. It also supports the implementation and development of EU research and innovation policy.

The observatory produces a series of annual reports addressing the following themes:

- Clean Energy Technology Status, Value Chains and Market: covering advanced biofuels, batteries, bioenergy, carbon capture utilisation and storage, concentrated solar power and heat, geothermal heat and power, heat pumps, hydropower & pumped hydropower storage, novel electricity and heat storage technologies, ocean energy, photovoltaics, renewable fuels of non-biological origin (other), renewable hydrogen, solar fuels (direct) and wind (offshore and onshore).
- Clean Energy Technology System Integration: building-related technologies, digital infrastructure for smart energy system, industrial and district heat & cold management, standalone systems, transmission and distribution technologies, smart cities and innovative energy carriers and supply for transport.
- Foresight Analysis for Future Clean Energy Technologies using Weak Signal Analysis.
- Clean Energy Outlooks: Analysis and Critical Review.
- System Modelling for Clean Energy Technology Scenarios.
- Overall Strategic Analysis of Clean Energy Technology Sector.

More details are available on the CETO web pages.

Acknowledgements

The authors would like to thank JRC colleagues Nigel TAYLOR (CETO project leader) for the coordination and support, Catriona BLACK for her review, edits and comments JRC.C.6 energy system modelling teams for providing energy scenarios:

- from POTEnCIA: Wegener, M., Jaxa-Rozen, M., Salvucci R., Neuwahl, F., R., Sikora, P., and Rózsai, M.
- from POLES: Schade B., Keramidas, K., Fosse, F., Dowling, P, Russ, P.

The authors are particularly grateful for the comments and contributions received from Matthijs SOEDE (RTD), Enrico DEGIORGIS (RTD) and Vera KISSLER (ENER).

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1 Executive Summary

The ocean energy sector holds considerable promise for enriching the European Union's (EU) energy portfolio and advancing its decarbonisation targets under the EU's Renewable Energy Directive (RED III) and the European Green Deal. The EU's Offshore Renewable Energy Strategy further underscores ocean energy's pivotal role in meeting the EU's climate and energy ambitions, setting a goal to install a minimum of 1 GW of ocean energy capacity by 2030, and an ambitious 40 GW by mid-century.

This report delivers a comprehensive analysis of the current ocean energy technology landscape, scrutinising its supply chains, growth necessities, and impediments. The EU boasts an estimated potential of 2 800 TWh for wave energy and 50 TWh for tidal energy each year, predominantly along the Atlantic seaboard. Globally, tidal energy leads as the most mature ocean energy technology, with 41% of key tidal energy firms headquartered within the EU. Similarly, the EU is home to a majority of wave energy innovators, housing 52% of the sector's active companies.

Wave and tidal stream energies are the foremost ocean sub-technologies in terms of deployment, innovation, and prospective impact within the EU. As of 2023, fresh installations in the EU have been sparse, yet numerous projects are slated for future development. Presently, only a select few devices have attained a stage of pre-commercial or technological maturity, and commercial deployment of ocean energy devices remains limited. Market expansion is contingent upon a myriad of factors, encompassing technological, financial, and environmental considerations.

Ocean energy technology costs are project-specific, yet achieving substantial cost reductions is critical for the sustainability and market viability of these technologies. Public funding has been instrumental in fostering the growth and rollout of ocean energy solutions, with the EU at the forefront of public research and development investment. Concurrently, private sector funding is on the rise, evidenced by the fact that 39% of worldwide patent filings in the sector originate from EU-based innovators.

Navigating the uncertainties of ocean energy technology adoption poses a challenge, given the infancy of these technologies and the unpredictable nature of future costs and performance. Nevertheless, the industry is ripe with potential for expansion, particularly within the tidal and wave energy domains. The EU is well-positioned to lead the ocean energy market, provided it can secure enhancements in performance, drive down costs, and enact supportive policies for European industrial players to bolster regional exports.

Table 1. Ocean energy major strengths, weaknesses, opportunities and threats (SWOT)

Strengths	**Weaknesses**
• Tidal energy is a predictable source of energy, while wave can produce energy even under the mildest conditions. • Reduced visual impact, leading to increased public acceptance. • Multiple European companies have project experience and knowledge. • The EU is in a good position in terms of publications, patents, private and public R&I.	• Due to the immaturity of the sector there are still high initial costs (CAPEX) that need larger deployment levels to reduce. • Maintenance can be costly/ difficult, leading to higher operational costs (OPEX). • Limited data on the length of lifetime leads to conservative assumptions when calculating levelised costs. • Geographically limiting factors, especially for tidal energy where most of the developed devices require strong tidal currents in order to operate.
Opportunities	**Threats**
• The ocean energy sector has significant potential for growth and development, particularly in the areas of tidal and wave energy (ref: 1). • The EU has the potential to take a leading role in the ocean energy market, with opportunities for export and job creation (ref: 1). • The sector can benefit from advancements in technology, such as improved materials and designs, to reduce costs and increase efficiency.	• The number of planned commercial projects has increased but more is needed to achieve ambitious targets and drive costs down. • Administrative barriers, including consenting challenges, lack of standardisation and certification frameworks, and complex regulatory frameworks, can create uncertainty and delays for developers and impact the sector's ability to grow and develop. • Ocean energy technologies are more costly compared to other marine renewables.

Source: JRC, 2024.

1.1 Scope and context

The ocean contains vast renewable energy potential, which could support economically sustainable long-term development and be a crucial component in the world's emerging "blue" economy. Ocean energy - including wave, tidal salinity gradient and ocean thermal energy conversion technologies - can provide reliable and stable electricity, and support other components of this economic sector, such as aquaculture and desalination.

The purpose of this report is to provide an assessment of the state of the art of ocean energy technology, to evaluate the value chains, to identify their development needs and barriers, and to assess the market. The analysis focuses primarily on tidal and wave energy technology, considering their potential to provide a significant contribution to the European energy mix in the coming years. This report is organised into three main blocks: (i) Technology assessment and state of the art, (ii) Value chain analysis and (iii) EU position and global competitiveness.

The report analyses the status of the main technology indicators and their future development. Chapter 2 introduces the current technology readiness level (TRL) of the main technologies in the ocean energy sector. This is followed by an analysis of key indicators on deployment and an outline of modelling projections at EU and global levels. Chapter 2.3 analyses present and future cost developments in ocean energy with the latest estimates on LCoE, CAPEX, OPEX and WACC. Competitiveness indicators measuring public & private R&D funding, patenting trends and scientific publications are presented in chapters 2.4 to 2.7, followed by an analysis of the impact and trends of EU-supported research and innovation.

Chapter 3 focuses on the ocean energy value chain and includes an analysis of macroeconomic indicators (turnover, Gross Value Added (GVA), employment and production data) and a mapping of indicators on environmental and socioeconomic sustainability.

Chapter 4 gives an insight into the EU's global position and competitiveness by assessing the market shares of EU and global market leaders in ocean energy.

For the identification of the technology trends, needs and barriers, the technology roadmaps and reports from various organisations and initiatives have been used, such as the International Energy Agency (IEA), Ocean Energy Europe (OEE), IEA Ocean Energy systems (OES), and the European Technology and Innovation Platform for ocean energy (ETIP Ocean).

This report is an update of the 2023 CETO report (Tapoglou et al., 2023).

1.2 Methodology and Data Sources

The report has been written following the CETO methodology that addresses three principal aspects:

a) Technology maturity status, development and trends

b) Value chain analysis

c) Global markets and EU positioning

The method to assess the Technology Readiness Level (TRL) of the technologies considered in this report follows the definition described in (European Union, 2014). To determine the TRL of a sub-technology we assume that there should exist at least one project at the specific TRL assigned.

In Chapter 2, the technological state of the art is presented, together with the current status in investments, patenting and research activity. The review of the current status of the different ocean energy technologies is based on a variety of sources, from SET Plan actions, to scientific articles and online information from credible sources, including the International Energy Agency (IEA), Ocean Energy Europe and Ocean energy systems. In the patenting activities section the data are sourced from the Joint Research Centre (JRC) based on data from the European Patent Office (EPO). Patent data are based on PATSTAT database 2021 autumn version. The methodology behind the indicators is provided in Fiorini (2017), Pasimeni et al. (2019), and Pasimeni (2019).

In the Impact and Trends of EU-supported Research and Innovation section, the main sources are CORDIS and internal databases for identifying the EU co-funded projects. On the technology readiness assessment, the focus is on projects granted through FP7, H2020 (2014-2020) and Horizon Europe funding. It should be noted that in most cases the technology readiness level achieved at the end of a project is not clearly indicated within the project outputs. In such cases, expert judgement of results is applied.

In Chapter 3, the value chain is assessed. The role of EU companies globally is highlighted and the environmental and socioeconomic sustainability is discussed. Data for this chapter originate from the PRODCOM database.

In Chapter 4, the position of the EU in the ocean energy sector is discussed. Trading data from COMEXT are used to assess the import and export balance as well as the need for raw materials for the development of ocean energy devices.

Annex 1 provides a summary of the indicators for each aspect, together with the main data sources. Annex 2 provides a list of the EU funded projects for ocean energy projects, while in Annex 3 there is a description of the POTEnCIA and POLES-JRC models.

2 Technology status and development trends

2.1 Technology readiness level

The oceans contain the largest untapped source of renewable energy. While ocean power technologies represent the smallest share of the renewable energy market, they are steadily advancing towards commercialisation (IRENA, 2021).

To take advantage of the constant energy present in different forms in the oceans, different technologies have been developed throughout the years. Depending on the source of energy they are using, they can be divided into four main categories: Tidal energy, Wave energy, Ocean Thermal Energy Conversion (OTEC) and Salinity Gradient technologies. In this report, tidal and wave energy will be discussed in detail due to their relevance in the EU market.

The ocean energy sector has significant potential to contribute to the energy mix and therefore to the decarbonisation of the EU, with a theoretical potential of about 2 800 TWh for wave and 50 TWh for tidal energy annually (Magagna D, 2020). In Europe the largest potential exists along the Atlantic coast. OTEC, due to its nature, is only deployable in tropical seas and in EU overseas islands.

Tidal energy can be extracted in two main ways, by taking advantage of the water level between different times of the tidal circle, namely tidal range, and by taking advantage of the tidal currents through tidal stream technologies. While tidal range has the largest installed capacity amongst all ocean energy resources, it is not typically pursued due to its limited site availability, large initial cost and environmental implications. Currently in the EU a limited number of projects are operational, with the biggest one being La Rance, France, while only one is in the pipeline (Brouwersdam, Netherlands).

On the other hand, tidal stream has an increasing number of deployments, for different scales (small-scale and full-scale) and in a range of TRLs. Tidal stream ocean energy originates from horizontal water currents that are created by the vertical variation of water levels caused by tides. Technologies that take advantage of the tidal stream are the following:

- Horizontal axis turbines (HAT): the tidal stream passes through a turbine, causing the rotors to rotate around the horizontal axis, generating power. HAT devices can be both fixed on the seabed and floating.
- Vertical axis turbines (VAT): Similar to the horizontal axis design, but in this case the rotors rotate around a vertical axis.
- Enclosed tips (ET): A funnel-like device that sits on the seabed. The flow of the tidal current drives a turbine directly or the induced pressure differential in the system drives an air-turbine.
- Oscillating hydrofoil (OH): A hydrofoil is attached to an oscillating arm. The tidal current flowing causes the hydrofoil to lift. This motion drives fluid in a hydraulic system and is converted into electricity.
- Tidal kite: A kite carrying a turbine below its wing and is tethered to the sea bed. As the kite 'flies' in the tidal stream, the turbine is rotating, thereby producing electricity.
- Archimedes screw: a helical corkscrew-shaped device that draws power from the tidal stream as the water moves up/through the spiral turning the turbines.

The most prominent sub-technology of tidal stream devices is the HAT. There, both floating and bottom fixed HAT designs are considered, and currently there are multiple devices that have a high maturity level (TRL 8-9). Installed devices have a capacity of 100 kW, up to 2 MW per device. Multiple designs proposed for HAT have reached TRL 8-9, with most demonstration projects located in the UK, Portugal, France, the Netherlands and Canada. Tidal kites are also currently being tested at full scale (TRL 7-8), with currently installed devices having a capacity of 100 kW and a licence for an array development reaching 80 MW.

As opposed to tidal devices, in wave energy there is a greater design variance with no dominant sub-technology preferred. The main device types are:

- Point absorbers (PA): Floating structures that take advantage of the motion of the device produced by passing waves.

- Oscillating wave surge converters (OWSC): Submerged devices that take advantage of the pendulum movement of a flat surface, caused by the movement of water in the waves.
- Oscillating water column (OWC): A partially submerged, hollow structure that is open to the sea below the water line, enclosing a column of air on top of a column of water. Waves cause the water column to rise and fall, which in turn compresses and decompresses the air column. This trapped air flows through a turbine to generate electricity.
- Rotating mass (RM): A hollow device that encloses an eccentric weight of a gyroscope. As the device is moved by the waves, the weight rotates, producing electricity.
- Other: six more are identified, presenting unique characteristics and specific designs.

There are significant differences between the several types of wave energy devices, based on how devices are operated and on the power conversion system (PTO) employed, ranging from linear direct drive generators to mechanical and pneumatic systems.

Devices currently deployed show the capability to survive wave loadings, however reliability is still to be fully proven. Information regarding the electricity generation from wave energy deployment is limited.

In **Table 2** the different wave energy technologies, together with the current TRL of the majority of the devices, are presented.

Table 2. Technological readiness level for different types of Ocean energy

	TRL (Technology Readiness Level)								
Sub-Technology	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Tidal energy									
Wave energy									
OTEC									
Salinity gradient									

Source: JRC, 2024

The predictability of tidal energy, coupled with the possibility of ensuring almost 20 hours of generation per day, has led to exploratory projects where electricity that cannot be used by the grid is directed towards the production of hydrogen.

A characteristic example of ocean energy storage is Nova Innovation's Tidal Energy Storage System, which uses a 300 kW tidal array coupled with a Tesla Battery to provide baseload electricity to the Shetland Islands (Nova Innovation, 2019).

Similarly for wave energy, the sector is investigating use of the technology for sectors other than the utility-scale electricity market. Methods that combine wave energy, for example the Resolute Marine Energy OWSC device, with desalination are currently being tested. OPT Power Buoys in conjunction with ENI and Premier Oil highlight the possibilities that wave energy technology offers to provide clean power to stand-alone applications, such as environmental data gathering and transmission (OPT, 2018). The MoorPower scaled demonstrator project uses wave energy to directly power aquaculture activities and Wave2O uses wave energy to power a desalination system.

Hybrid approaches that incorporate more than one renewable energy sources are also starting to be deployed at a small scale. Incorporating ocean energy devices into offshore wind, floating offshore wind and floating PV technologies will help lower the cost of ocean energy technologies through sharing facilities and procedures (e.g. maintenance procedures), while maximising and stabilising the energy outcome. W2Power Wind and the Wave system concept, by Pelagic Power, combines a semisubmersible offshore wind turbine platform with multiple oscillating body wave energy. Poseidon Wave and Wind system by Floating Power Plant combines three wind turbines and multiple wave energy devices in the same platform.

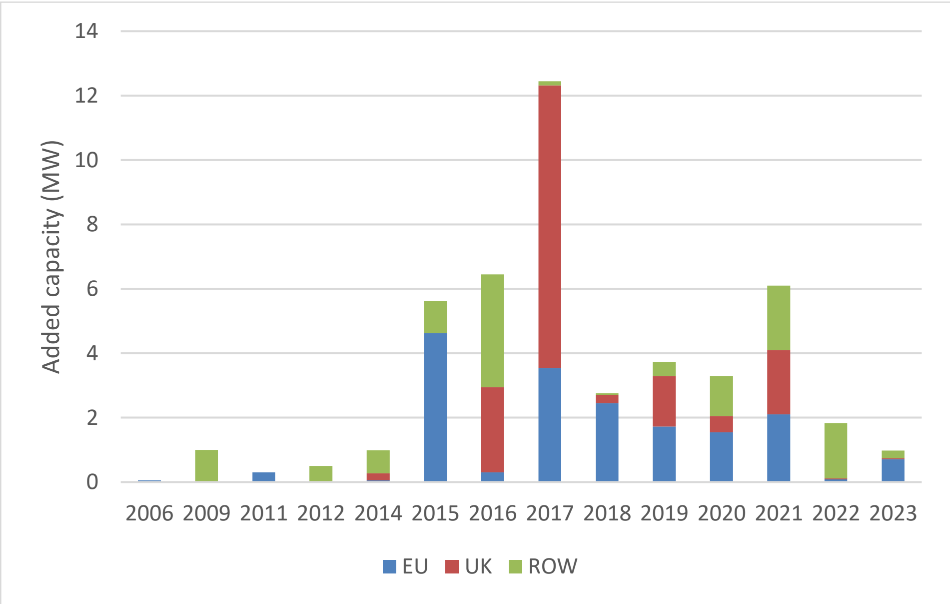
OES has identified six projects to demonstrate the capabilities of ocean energy in alternative markets, ranging from desalination and aquaculture applications to multi-use platforms (OES, 2021).

2.2 Installed Capacity and Production

In the last decade, installed capacity has been increasing for all types of ocean energy, with tidal technologies dominating the deployed capacity. More than 98% of the total combined capacity that is currently operational (521.5 MW) is tidal range technology. Three main projects account for the majority of the installed capacity – a 254 MW plant in the Republic of Korea (since 2011), a 240 MW plant in France (since 1966) and a 20 MW station in Canada (since 1984). Despite the dominance of this technology, no tidal barrage power plants of relevant scale have been developed in almost 10 years, and there is relatively low resource potential to be explored at a high environmental and financial cost. Smaller installations (e.g. Tocardo's 1.2 MW tidal power station in Eastern Scheldt Storm Surge Barrier, Netherlands) have recently been developed, but their application is limited geographically.

In terms of tidal stream and wave energy capacity, the pace of deployment peaked in 2017 (**Figure 1**). In 2023 there were very limited new installations in the EU, while global new installed capacity accounted for less than 1 MW.

Figure 1. Annual added capacity installation of tidal stream and wave energy plants in the EU, UK and rest of the world, 2006-2023

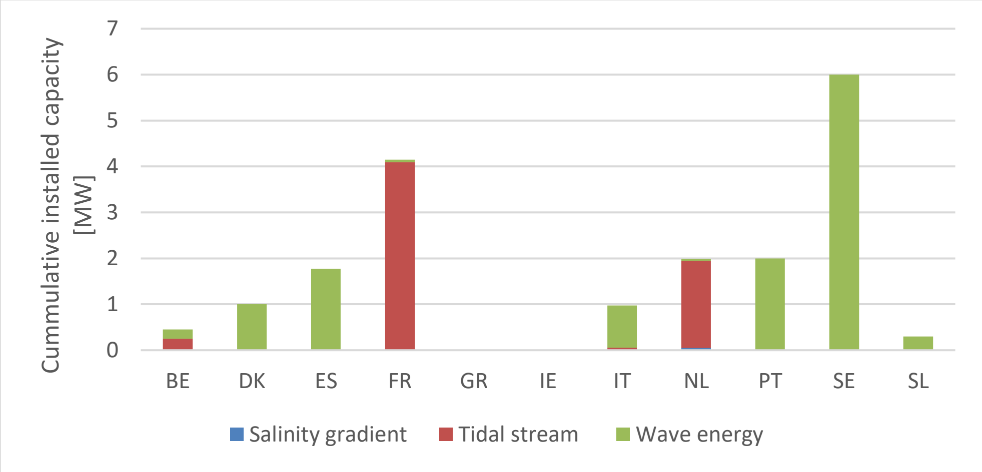


Source: JRC database, 2024

For tidal devices, Europe dominated new deployments with multiple Nova Innovations devices being deployed in the UK (200 kW), and France (50 kW), while EEL energy deployed an Undulating membrane device in France (30 kW). Outside Europe, devices were predominantly deployed in the US (111 kW), Korea (80 kW) and Canada (420 kW). In terms of wave energy, multiple full scale devices were deployed in the EU with Portugal (Cor Power - 300 kW), Italy (Eni - 260kW) and Spain (Rotary wave - 20 kW) adding the majority of the capacity.

In terms of individual EU countries, France and the Netherlands have the majority of cumulative installed capacity in terms of tidal stream energy, while Sweden, Portugal, and Spain are leading the deployment of wave energy devices (**Figure 2**).

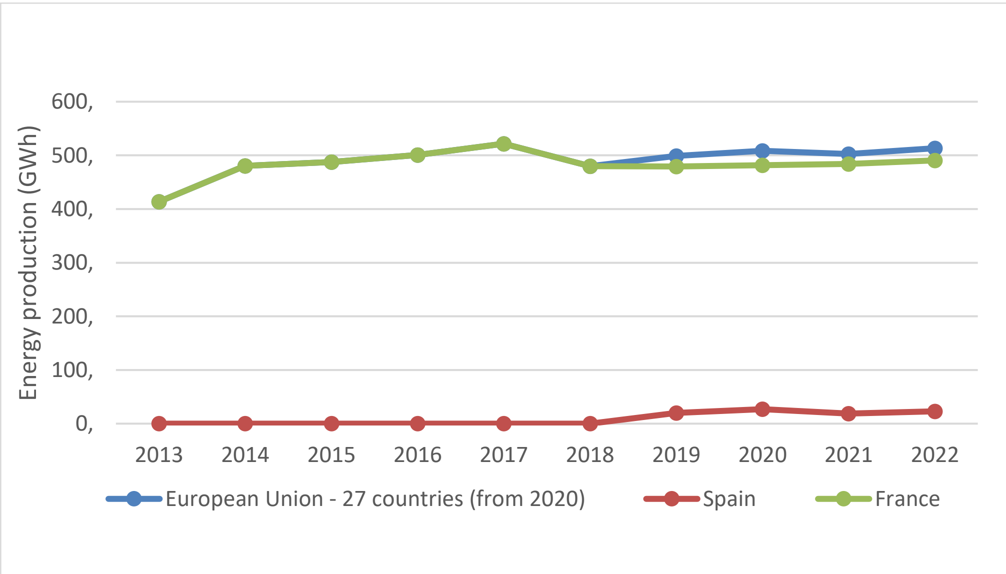
Figure 2. Ocean energy cumulative installed capacity in the EU in 2023



Source: JRC database, 2024

Figure 3 shows the annual production for all types of ocean energy (including tidal range) in the EU, according to Eurostat. The majority of the energy presented in this graph comes from the La Rance Tidal power station (France), with an installed capacity of 240 MW and an annual production of approximately 400-500 GWh. The rest of the power production is attributed to smaller ocean energy projects in Spain and Portugal that are connected to the grid. Currently, a lot of deployments are at demonstrator level (TRL 6-7), and do not contribute to the network grid, hence their production is not taken into account in Figure 3. Most Member States with marine energy demonstrators or prototypes do not include them in the official capacity and production data communicated to Eurostat

Figure 3. Annual ocean energy production in EU countries. The figure includes data for all types of ocean energy present in EU waters (i.e. tidal range, tidal stream, wave energy and salinity gradient).

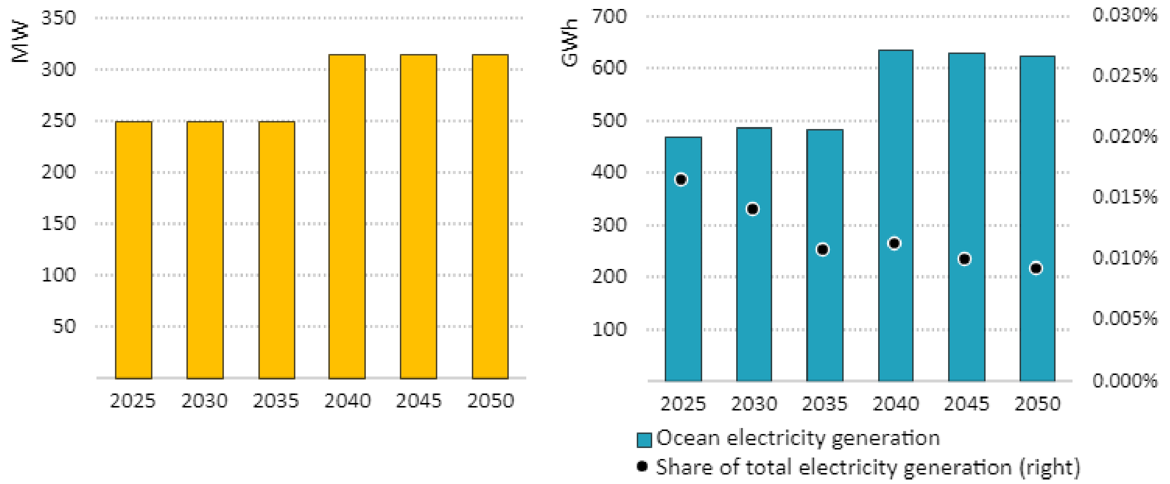


Source: Eurostat, 2024

Energy system models may face challenges in predicting the adoption of ocean energy technologies due to the nascent stage of these technologies. As a relatively new and unestablished field, the costs associated with ocean energy technologies have not yet stabilised, making it difficult to accurately forecast their future development and deployment. Furthermore, the current scale of ocean energy deployments is small compared to more established technologies. As a result, energy system models can be highly sensitive to the cost reduction trajectories of other dominant technologies, which can overshadow the potential impact of ocean energy technologies. This can lead to predictions highly sensitive to the inputs and the model assumption, as the models may not be able to capture the unique characteristics and growth patterns of ocean energy technologies. Additionally, the uncertainty surrounding the future costs and performance of ocean energy technologies can amplify the impact of assumptions in the model, further complicating the prediction of their deployment. However, these models are useful to assess the current status of the ocean energy sector.

Under the POTEnCIA CETO 2024 Scenario (see Annex 3), the POTEnCIA model projects ocean devices' installed capacity to reach 250 MW in 2030 and then around 320 MW in 2050 in the EU (**Figure 4**). In terms of electricity generation, POTEnCIA projections indicate that although ocean electricity is projected to almost double in 2050 compared to current levels, its contribution would remain limited to less than 0.01% of total electricity generation throughout the time horizon. The presented values on installed capacity and electricity generation are lower than the ones reported in 2023. This is due to changes in the model techno-economic inputs, not only for the ocean energy sector but also in other renewable energy technologies (for example reduced CAPEX of offshore wind). This deployment level, which is mainly driven by the low financial competitiveness of ocean energy with other renewable sources, is significantly lower than the EC's target of the offshore renewable strategy of 1 GW by 2030 and 40 GW by 2050. This highlights the need for a step change in the ocean energy sector in order to rapidly reduce costs and enhance the financial competitiveness vis-a-vis other technologies, as required to achieve the ambitious goals of the offshore renewable energy strategy. The full details of the model can be found in the The POTEnCIA CETO 2024 Scenario report (Newahl et al., 2024).

Figure 4. Gross installed capacity (left) and gross electricity production (right) of ocean energy technologies in the EU according to the *POTEnCIA CETO 2024 scenario*.



Source: JRC, 2024

2.3 Technology Costs

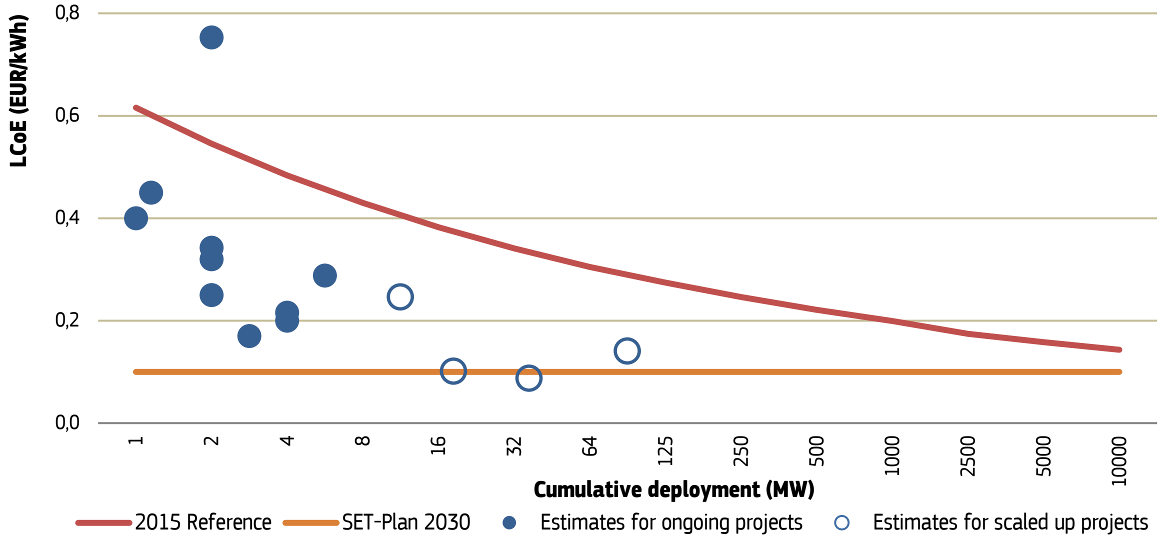
The cost of ocean energy technologies varies from project to project and from one technology to the other. Since most technologies are not mature enough and current deployments consist mostly of single devices, expenses and procedures are not optimised, leading to high initial and operating costs. In order for these technologies to be sustainable and contribute to the energy market in the future, significant cost reductions must be achieved.

The critical key performance indicator (KPI) for the assessment of the cost-reductions needs for ocean energy technology is the LCoE. Current ocean energy projects have an LCoE EUR 0.11–0.48 per kWh for tidal stream and EUR 0.16–0.75 per kWh for wave energy (IRENA, 2021). By 2030, LCoE for tidal energy should reach EUR 0.1 kWh, whilst for wave energy the target is of EUR 0.15 per kWh (European Commission, 2021). For tidal energy, LCoE estimates of current and scaled up projects are presented in **Figure 5**, and for wave energy projects in **Figure 6**.

TIGER project (2022) calculated the current and the future trajectory of LCOE for tidal stream installations in the UK and France. They estimated a current LCOE equal to be around EUR 0.300±0.034 per kWh

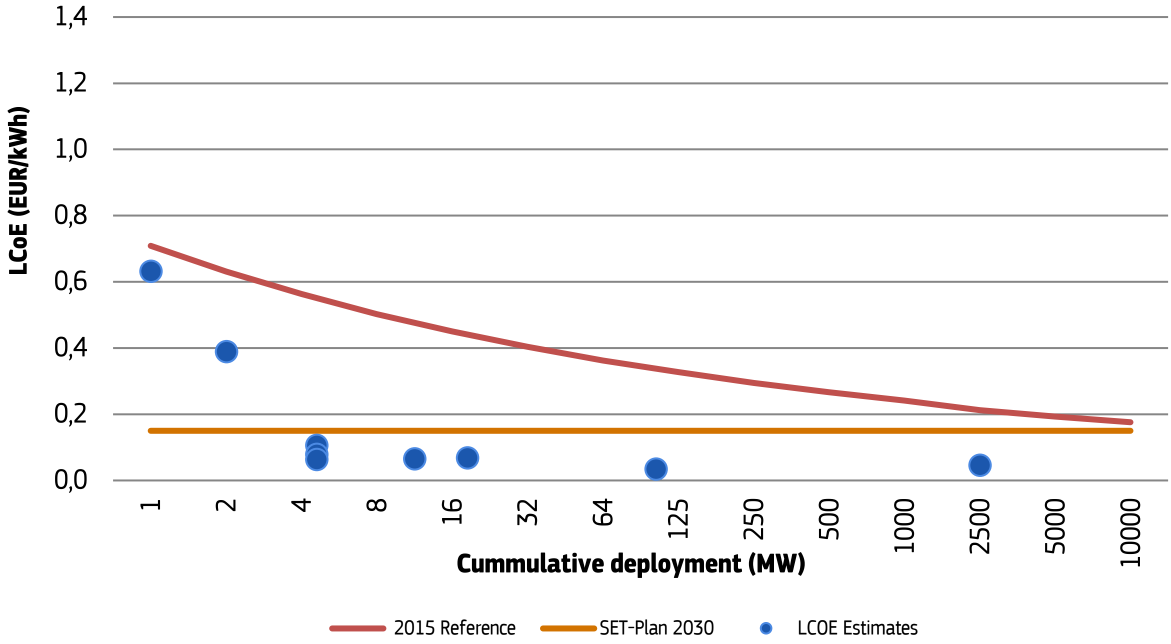
(GBP 0.26±0.030 per kWh), while assuming a cumulative deployment of 877 MW in the UK and 783 MW in France by 2035. They project this value to drop to around EUR 0.090±0.039 per MWh (GBP 0.078±0.025/MWh) by 2035.

Figure 5. Levelised Cost of Electricity (LCoE) of estimated current and scaled up tidal energy devices



Source: Based on JRC database,2023 and IRENA, 2021

Figure 6. Levelised Cost of Electricity (LCoE) of estimated current and scaled up wave energy devices



Source: JRC database, 2023

The LCoE estimates based on IRENA (2021) and JRC database presented in **Figure 6** indicate that several developers foresee the cost of wave energy technology dropping below the 2025 SET Plan targets at a faster rate than expected. This forecast is based on unlocking manufacturing potential as well as improving the performance of individual devices. These improvements could help to make a stronger case for wave energy technologies; however, wave energy converters still need to demonstrate their capabilities to attract investor and manufacturers and unlock economies of scale to reduce cost.

Recent data collected by OceanSET (2022) through a developers survey conducted in 2020 for whole-system TRL 7-9 devices calculatead the key indicators presented in **Table 3,** that reflect the current status of ocean technologies.

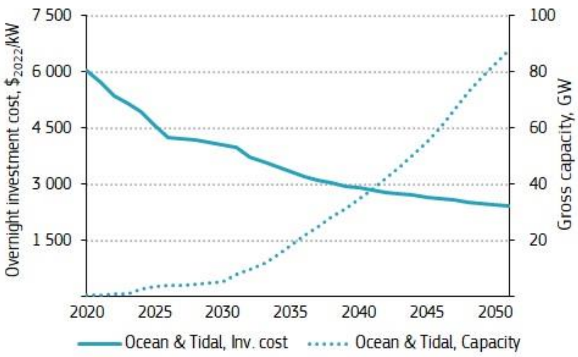
Table 3. Key indicators for whole-system TRL 7-9 devices, for the wave and tidal ocean technologies

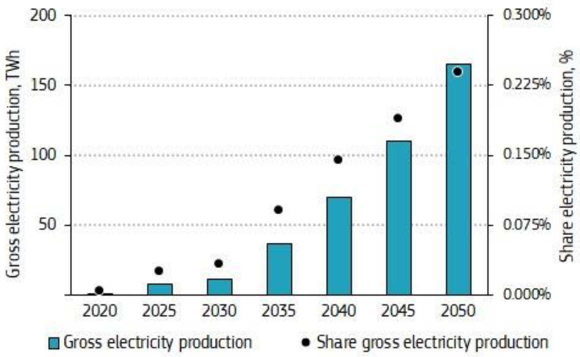
Key indicator	Wave	Tidal
Average CAPEX (Million EUR/MW)	6.4	3.4
Average OPEX (Million EUR/MW/year)	0.5	0.5
Minimum technical lifetime (years)	20	20
Maximum technical lifetime (years)	30	25
Average LCOE (EUR/kWh)	0.27	0.2

Source: OceanSET, 2022

According to the *Global CETO 2°C scenario 2024* (see Annex 3), the overnight investment cost of ocean power installations is expected to drop to about 2 400 $\$_{2022}$/kW by 2050, while global installed capacities of ocean power increase to about 90 MW by 2050, contributing to around 0.25% of the gross electricity production (**Figure 7**).

Figure 7. Global overnight investment cost and gross capacity (left) and global gross electricity production of ocean energy technologies (right)





Source: JRC, 2024

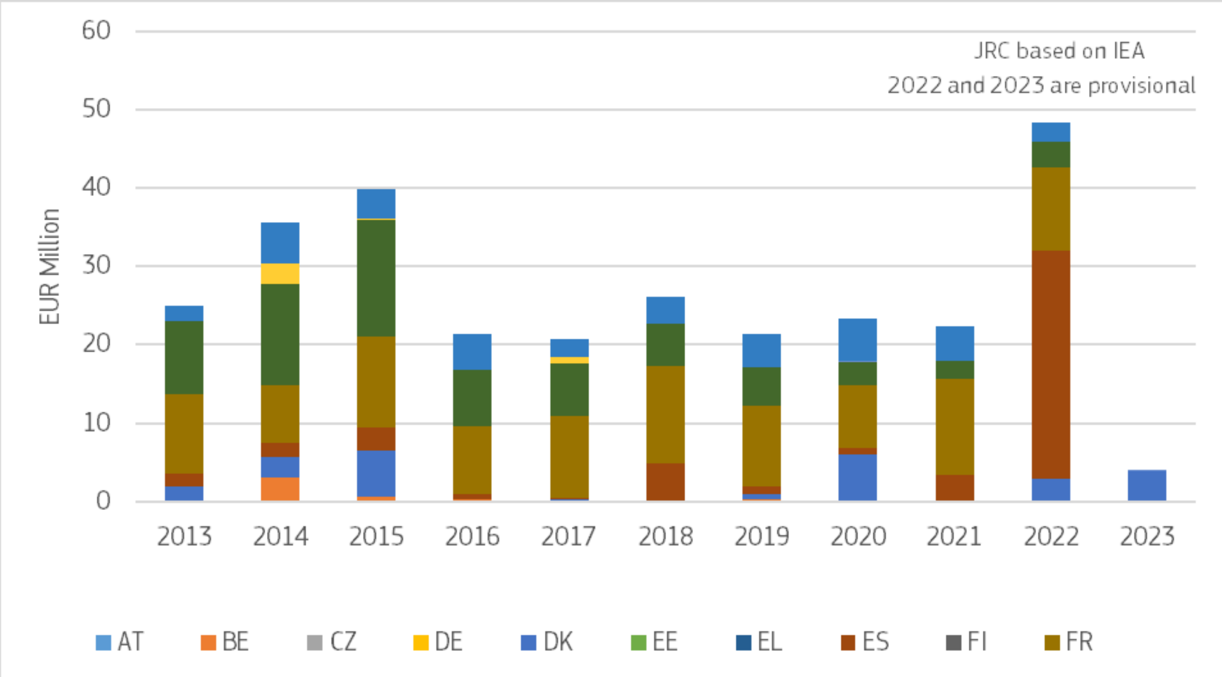
2.4 Public RD&I Funding and Investments

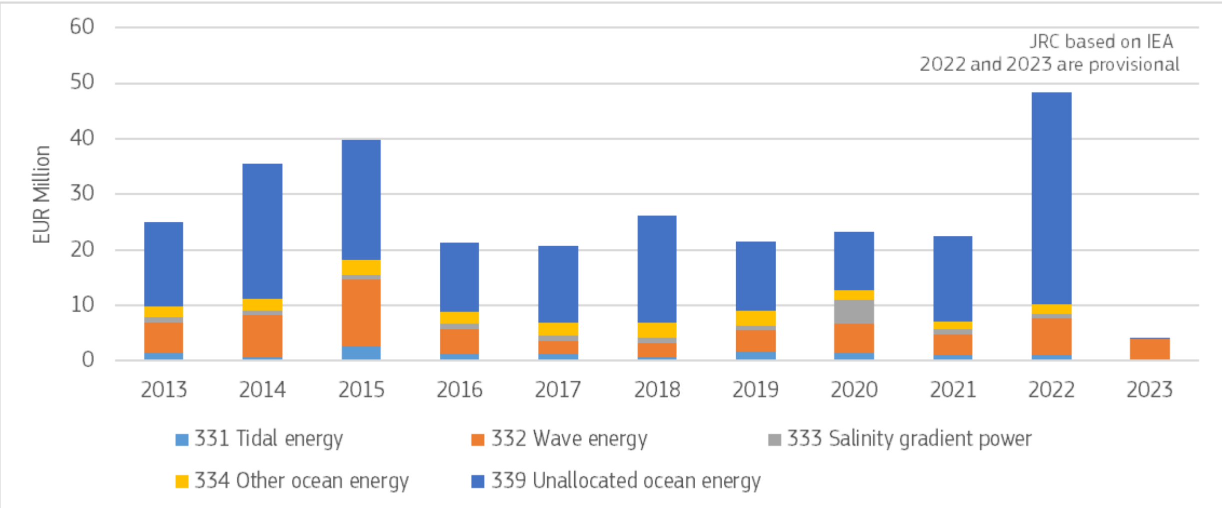
Public investment can have a significant positive effect on the development and deployment of a technology. It creates a positive environment for private initiatives, and affects the number of relevant publications and patent applications. As such, it is an important indicator of the level of development and competitiveness in a given technological area. The following information is based on JRC analysis with data from the IEA (IEA, 2024).

Public R&D Investment in Europe reached its 10-year maximum in 2022 (**Figure 8**), accounting for EUR 48.35 million, a large leap compared to the second best year 2015 where the R&D investments reached EUR 40 million.

Ocean energy technologies supported by public investments are categorised into wave energy, tidal energy, salinity gradient, other ocean energy (including OTEC and ocean current power, as well as siting studies for all types of ocean energy) and unallocated ocean energy (including techniques, processes, equipment and systems related to ocean energy that cannot be allocated to one specific area and where it is not possible to estimate the split between two or more categories. The majority (79%) of the public investments in 2023 fall in the unallocated ocean energy category.

Figure 8. Public R&D investments (in million EUR) in ocean energy in the EU by year and by MS (top graph) and Public R&D investments (in million EUR) in ocean energy in the EU by year and by technology (bottom graph)

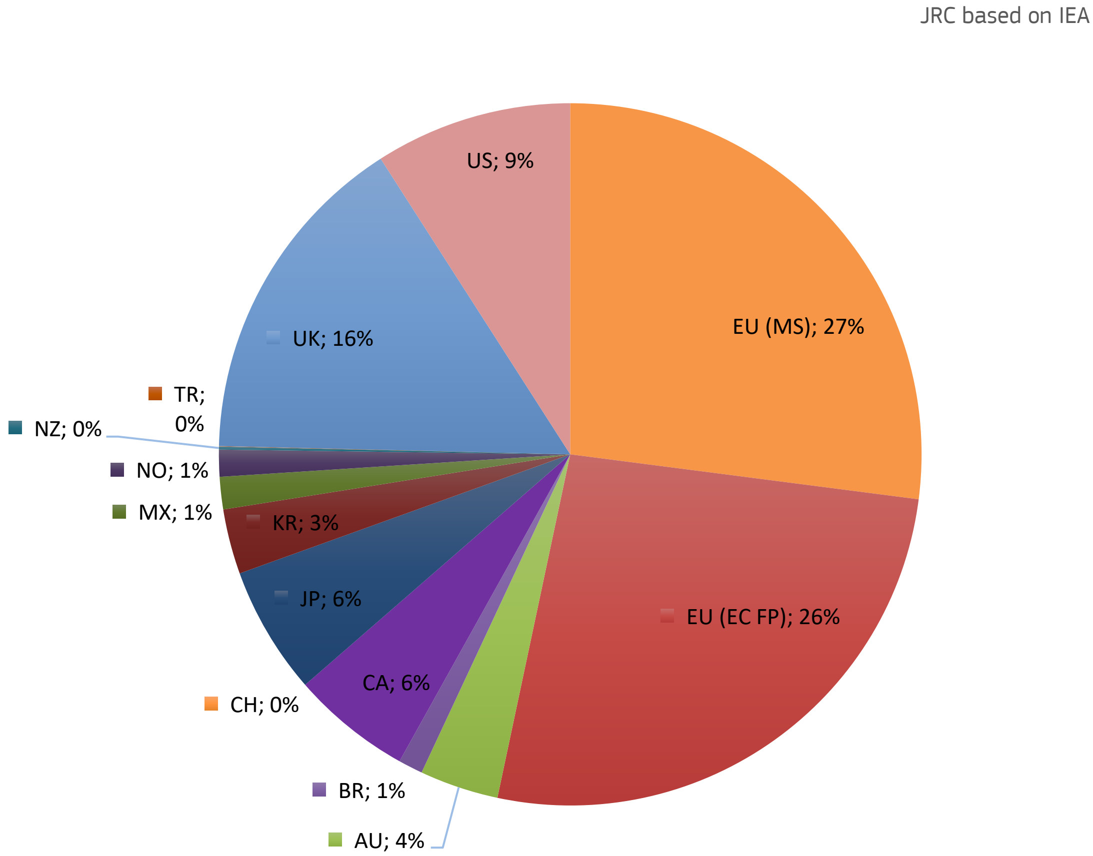




Source: JRC based on IEA, 2024

Globally, the EU is leading in public R&D Investments, accounting for 53% of the worldwide public investments in the last decade (**Figure 9**). This is attributed both to direct investments by the Member States (27% of the total) but also to funding from EU framework programmes (26%). The UK (15.5%) and the US (9%) are second and third.

Figure 9. Global public R&D investments (in million EUR) in ocean energy for the period 2013-2023. EU (EC FP) refers to the EU framework programmes while EU (MS) to the direct investments by the member states. Data for 2022 and 2023 are provisional



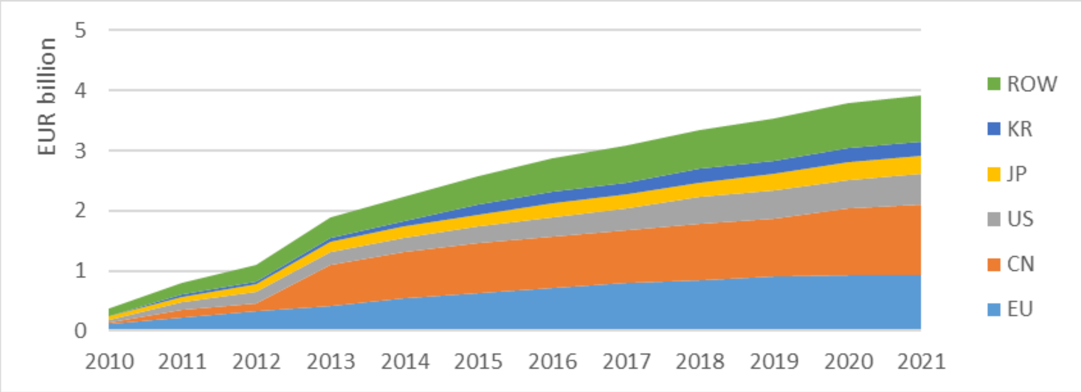
Source: JRC based on IEA, 2024

2.5 Private RD&I funding

The analysis presented in the following is based on the JRC methodology (Pasimeni, Fiorini, and Georgakaki, 2019; Fiorini A et al., 2017), with data referring to the period 2010-2021 (with data for 2020 and 2021 being incomplete). In this methodology, patent data are used as a proxy for extracting information about private R&I funding. This methodology includes two steps: the patent analysis and the R&D estimation procedure. The first step results in a list of all companies active in the ocean energy sector and quantifies the number of inventions per company. Then patent share is used in order to split the R&D effort proportionally for companies that have disclosed their R&D expenditure. In the case of companies for which R&D data is not publicly available, but there is evidence of patenting activity in this technological area, an average unitary expenditure per patent/invention is assigned each year. The sum of this indicative cost, multiplied by the number of patents, provides an estimate of the corporate R&D effort for that year.

Globally over time, EU companies are the second largest investor in ocean energy technologies, investing EUR 922 million (**Figure 8**). China is leading the sector with EUR 1 189 million of investments. However, as will be seen in section 2.6, China has a considerable amount of patent applications. Patents act as a proxy for private investments in this methodology: there is an inherent risk of overestimating investments in countries with larger amounts but less significant patents.

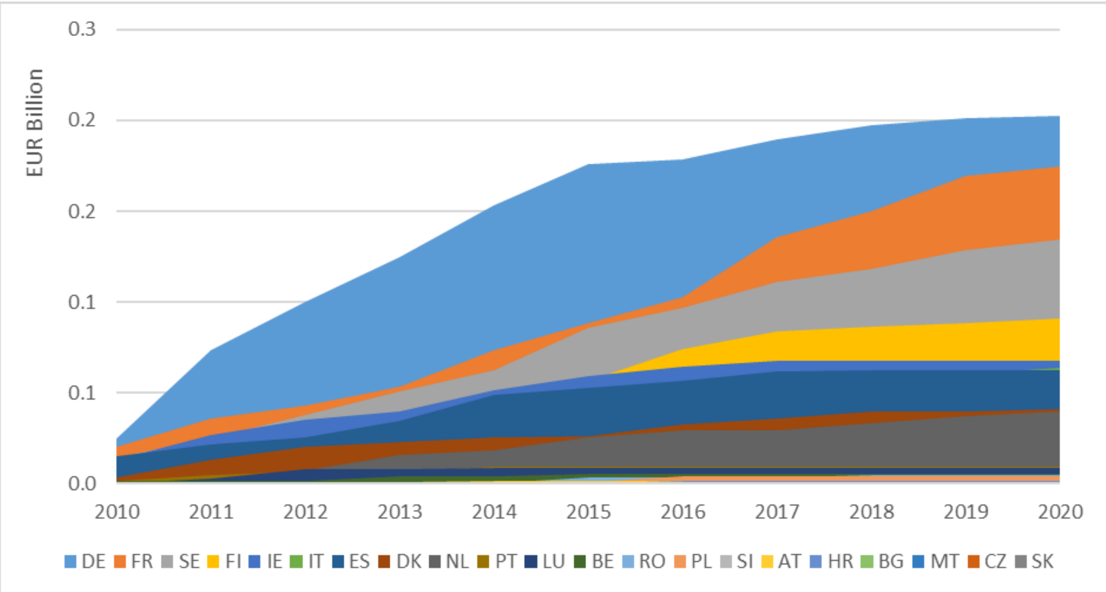
Figure 8. Cumulative global private R&I investments in ocean energy for the time period 2010-2021 (Incomplete data for 2020 and 2021)



Source: JRC SETIS according to Fiorini et al., (2017); Pasimeni, et al., (2019), 2024

In the EU, the most private investments for the period 2010-2021 were reported for Germany, followed by France and Sweden (**Figure 10**).

Figure 10. Cumulative private R&I investments per EU member state for the time period 2010-2020 (incomplete data for 2020)



Source: JRC SETIS according to Fiorini et al., (2017); Pasimeni, et al., (2019), 2024

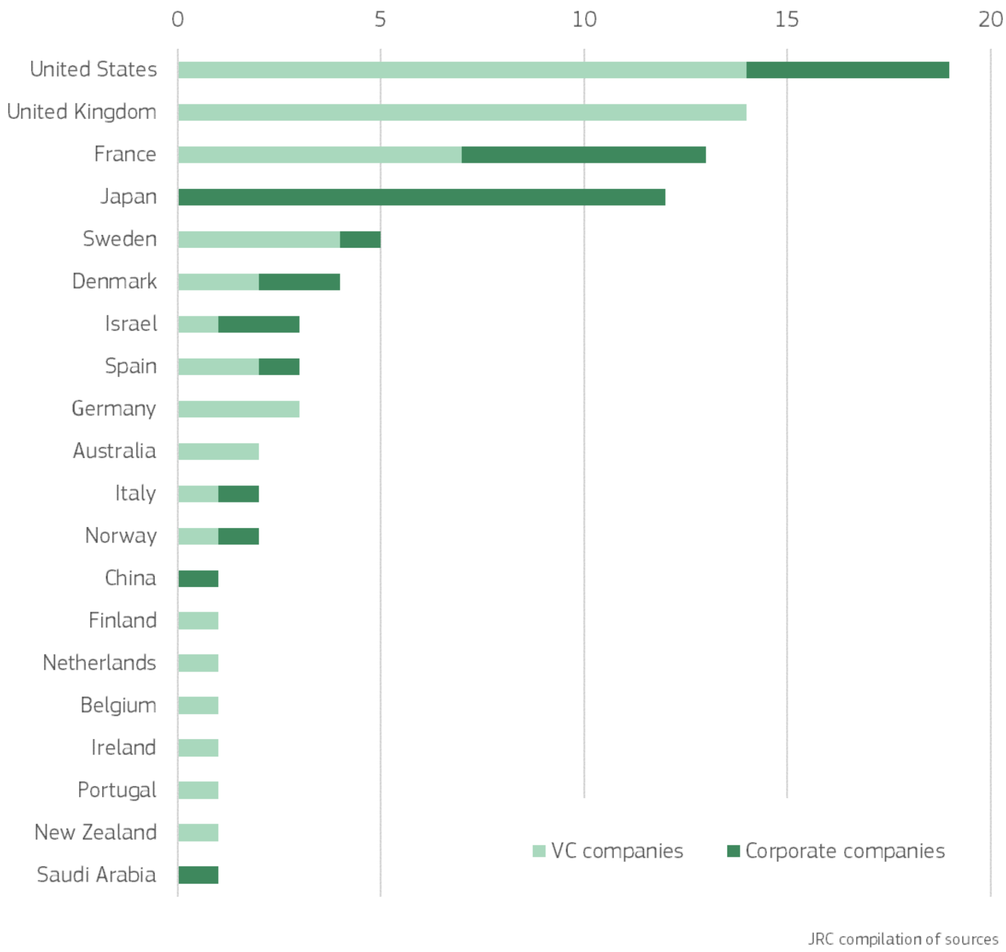
Private investments in the EU peaked in 2014, accounting for EUR 122 million. In total, in the period 2010-2020, EUR 922 million has been privately invested. Top investors in the EU for the period 2015-2020 include AW Energy OY, Naval Energies and Ocean Harvesting Technologies AB. In the global leader board, the majority of the top investors originate from China, followed by Korea. AW Energy OY comes third in the global scene.

The development of ocean energy technologies appears to be mostly driven by venture capital companies (representing 64 % of identified innovators).

The US (1st), the UK (2nd) and France (3rd) all rely on a very strong base of venture capital companies. On the other hand, Japan, ranked 4th in the number of innovating companies, only hosts corporate companies (**Figure 11**).

Supported by innovators in several Member States, the EU accounts for 39% of identified innovators and is well positioned to develop leadership.

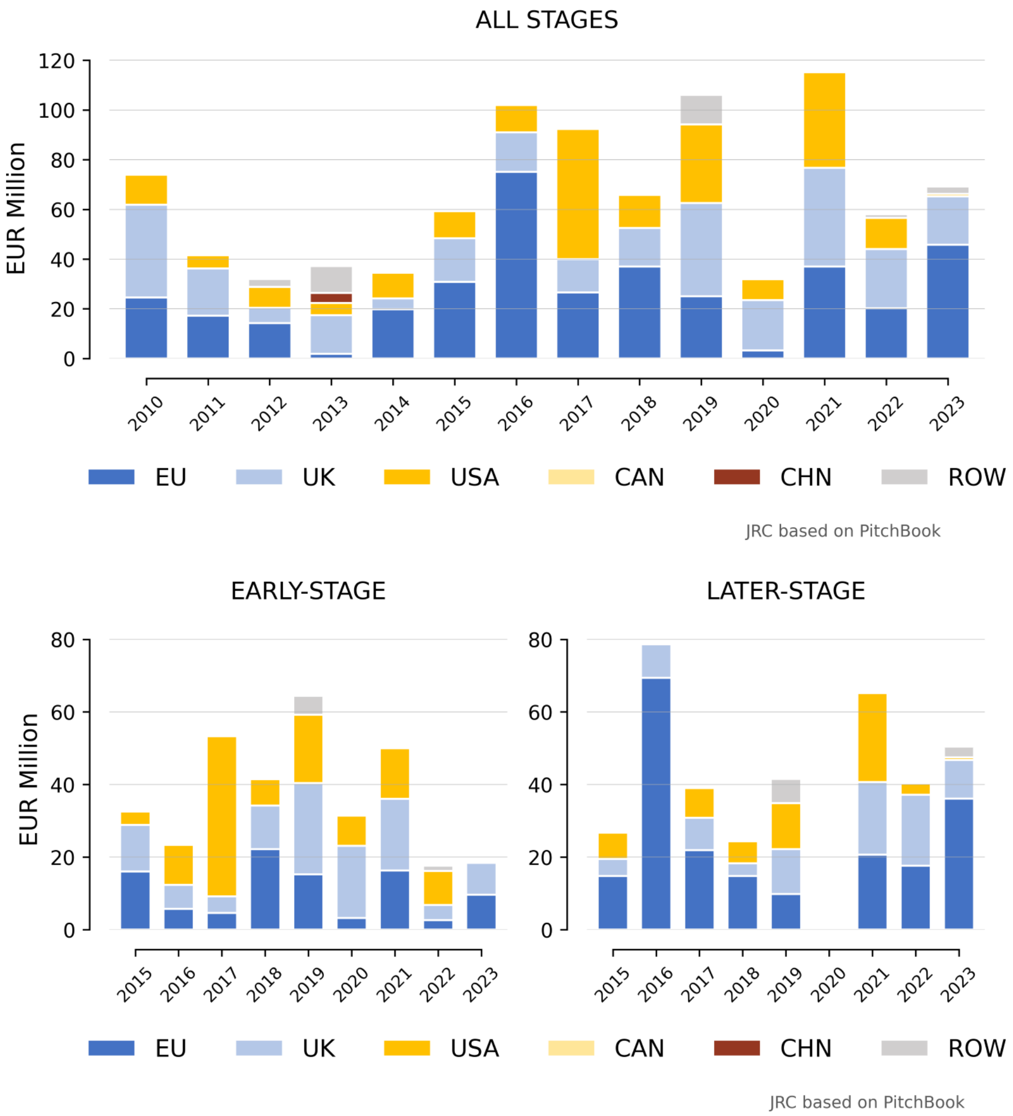
Figure 11. Number of innovating companies in the ocean energy sector (2017-2022) by country of origin



Source: JRC, 2023.

Venture Capital (VC) early and later stage investments are considered. Earlier stage investments tend to focus on backing innovative startups with high growth potential, often providing seed funding to help them refine their products and build their teams. In contrast, later stage investments typically look for established companies with proven business models, providing larger funding amounts to support their expansion and scaling efforts. Early stage investments include grants, Angel & Seed as well as early stage VC, while later stage investments include small M&A, growth private equity and late stage VC, but exclude buyout private equity and public investments. **Figure 12** presents the size of VC investments per region, divided by early and late investments. There has been an increase in global VC investments over the last decade. However, despite the considerably higher levels (+45% in the period 2017-2022 compared to 2011-2016), investments seem to be stagnating. Early stages still account for a large share (53%) of global VC investments outside of the EU, while later stage investments are largely predominant in the EU.

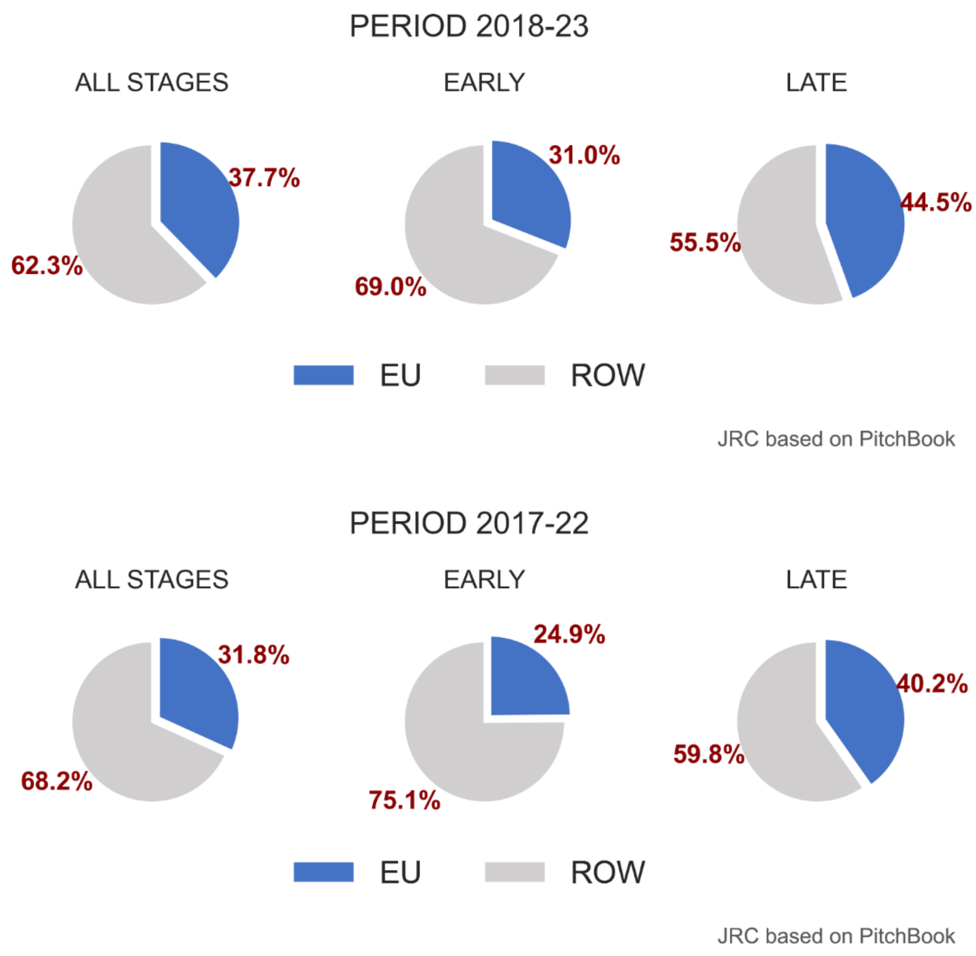
Figure 12. Venture Capital investments in Ocean energy Total investments (top), Early stage investments (bottom left) and Later stage investments for the EU and the rest of the world (bottom right)



Source: JRC based on Pitchbook, 2024.

Overall, as seen in **Figure 13**, VC investments in the EU are dominated by investment in later stages.

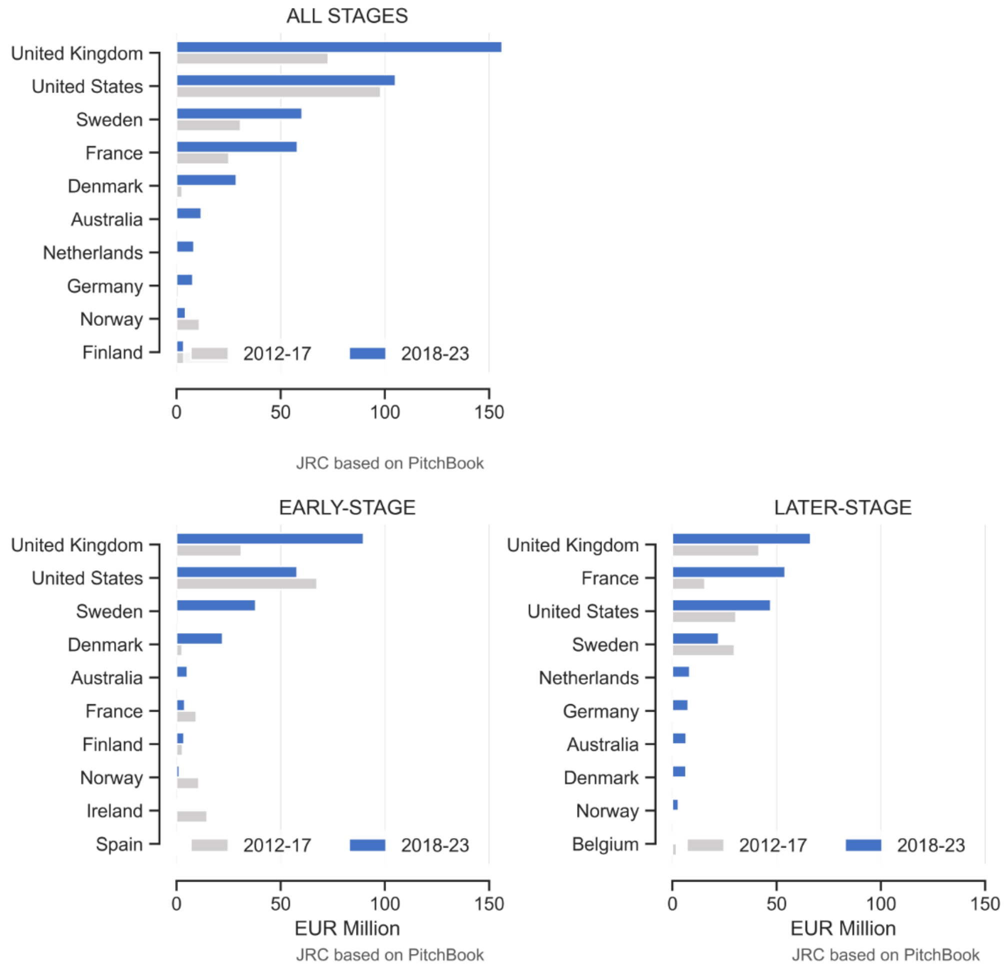
Figure 13. Investments by stage and region (Share of capital invested)



Source: JRC based on Pitchbook, 2024

In terms of individual countries, overall, the United Kingdom has the largest total early and later stage VC investments globally for the period 2018-2023 (**Figure 14**). In terms of EU countries, Sweden is leading in total and early stage investments, while France is leading in the later stage investments.

Figure 14. Venture Capital investment by country for total investments (top left), Early stages investments (top right) and Later stage investments (bottom)



Source: JRC based on Pitchbook, 2024

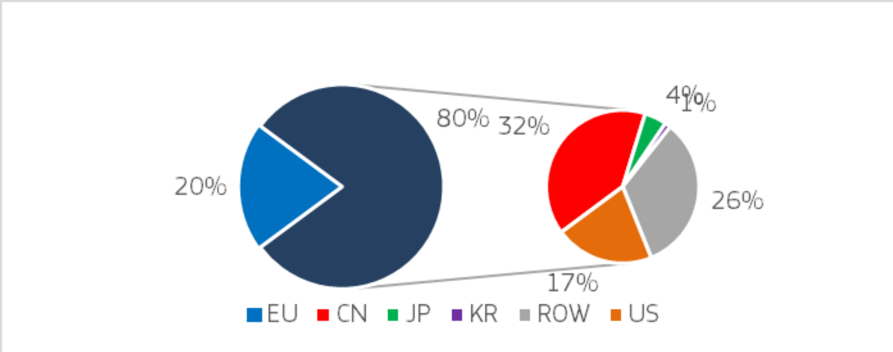
2.6 Patenting trends

Patenting trends are evaluated using the methodology developed by the JRC (Fiorini A et al., 2017; Pasimeni, 2019; Pasimeni, Fiorini, and Georgakaki, 2019; Pasimeni, Fiorini, and Georgakaki, 2021) and based on data derived from the PATSTAT database 2022 autumn version and based on patent codes Y02E 10/30 and Y02A 20/144.

Inventions (or patent families) can measure the inventive activity of a country or a region. Patent families include all documents relevant to a distinct invention (e.g. applications to multiple authorities), thus preventing multiple counting. A fraction of the family is allocated to each applicant and relevant technology. High-value inventions refer to patent families that include patent applications filed in more than one patent office. International inventions are the inventions that are protected in more than one countries and the flow of inventions indicates where inventions are filed and in which countries they are protected. The development of patenting data in the latest three years provide more insight about the development of the technology and the market, compared to the 10 year data aggregation. For the rest of the analysis the latest three-year data (2019-2021) will be used to reflect the current trends.

Globally, in the period 2019-2021, a total of 1 368 patent applications concerning ocean energy were submitted, of which 455 were granted, 168 were high value and 49 were international. China alone accounts for 76% of the patent applications from all entities, with 59% of those applications originating from Universities and Government/non-profit organisations. EU inventions account for 5% of the applications, originating predominantly (40%) from companies. China is also leading for the first time in high-value inventions, accounting for 32% of the total, followed by EU with 20% of those inventions (**Figure 15**). Compared to previous reports (Magagna D, 2020), the number of patents is smaller, especially for Germany and China. This is attributed to the reclassification of patent codes by EPO. Earlier studies used patent codes that have since been deleted. After the reclassification, one of the codes was maintained (Y02E 10/30) and one newly introduced (Y02A 20/144).

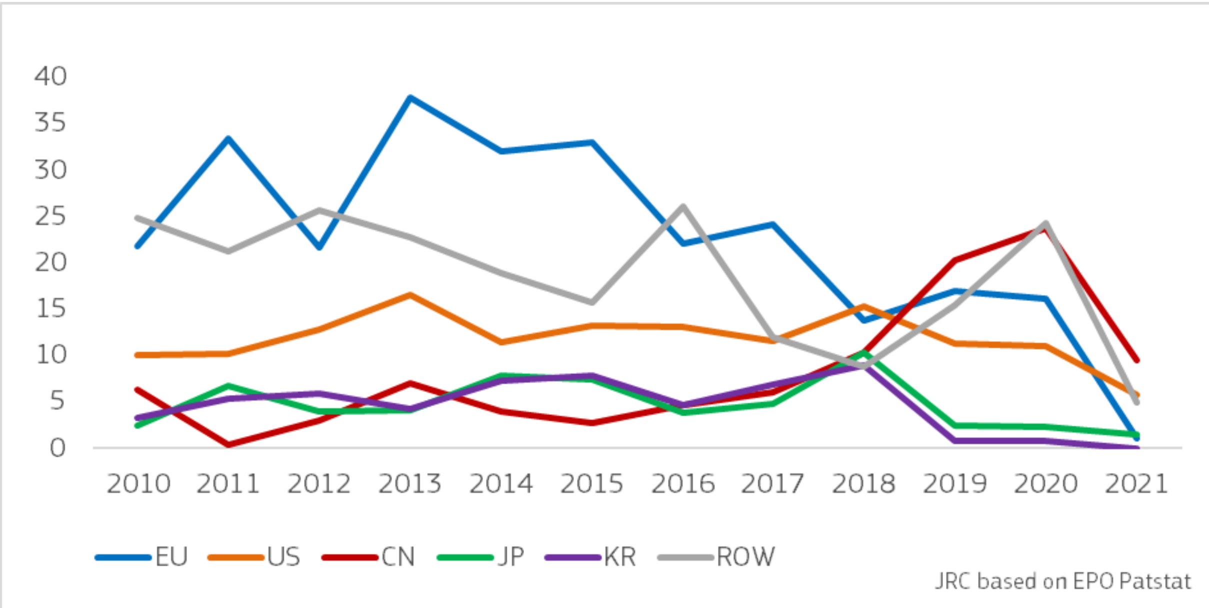
Figure 15. Share of global high-value inventions (2019-2021)



Source: JRC based on EPO Patstat, 2024

The number of high-value inventions globally peaked in 2013 and since then it has been steadily decreasing (**Figure 16**). EU high-value inventions have been following the global trend. On the other hand, there is an increasing trend for China since 2015, which accelerated in 2019.

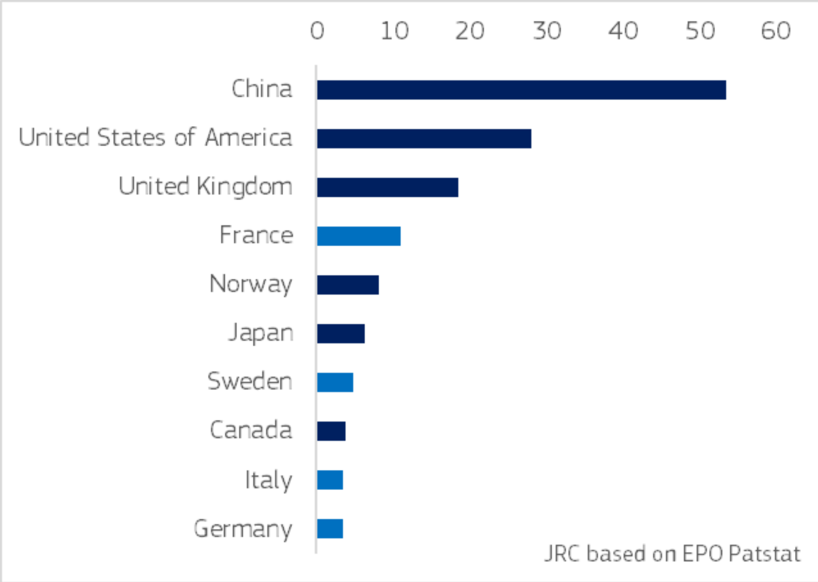
Figure 16. Number of high-value inventions over time



Source: JRC based on EPO Patstat, 2024

In terms of individual countries, China is leading the way, followed by the US, the UK and France (**Figure 17**). Within the top 10 countries in terms of high-value inventions, four originate from the EU.

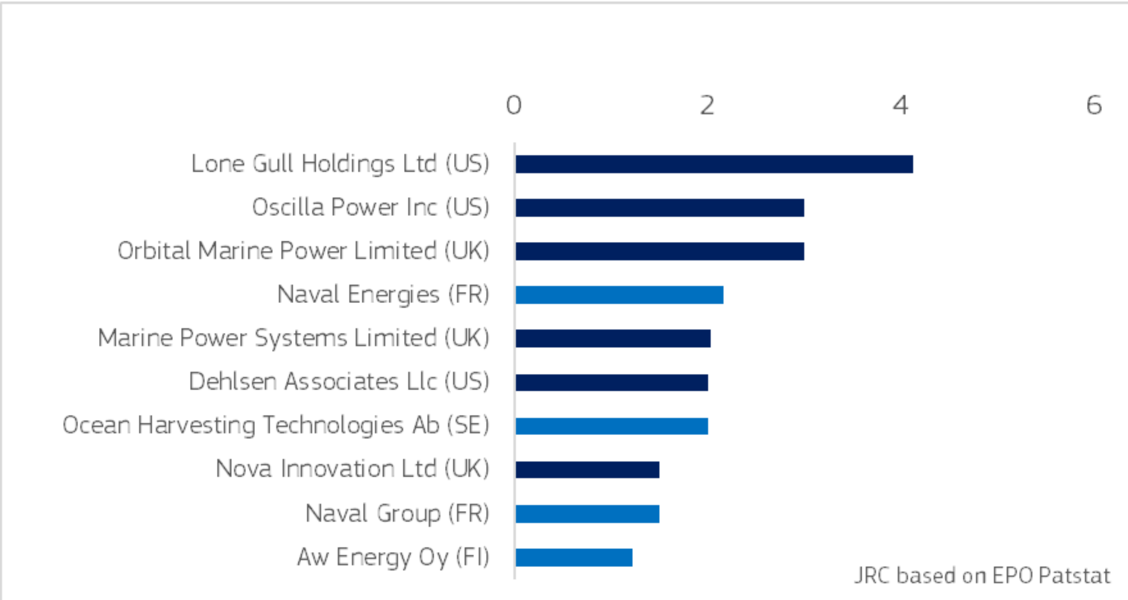
Figure 17. Number of high value inventions for the top 10 countries in the time period 2019-2021



Source: JRC based on EPO Patstat, 2024

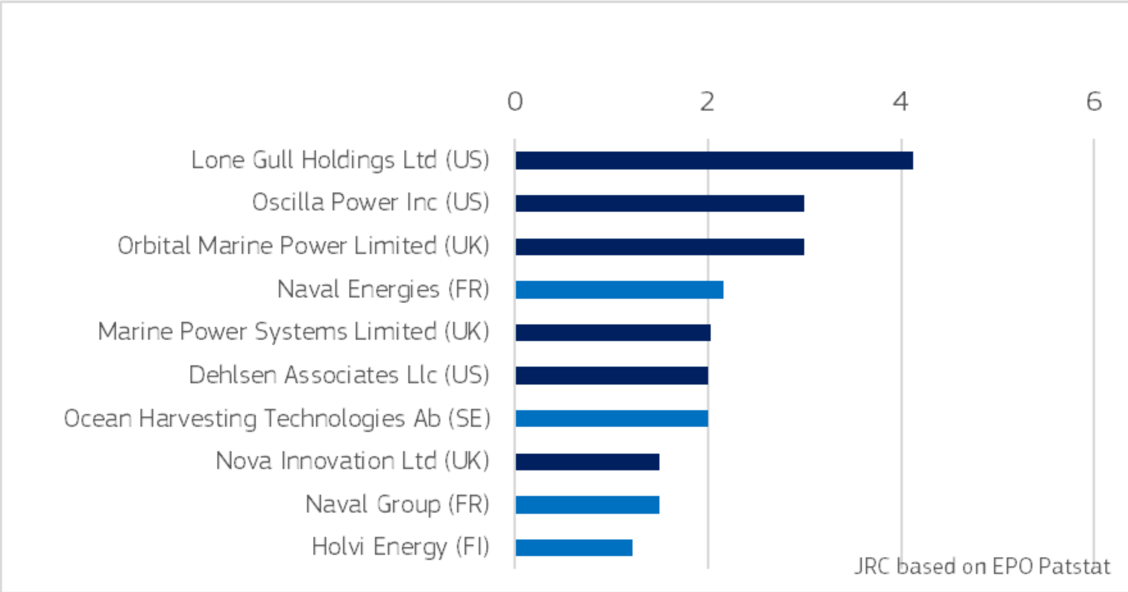
The global top companies in terms of high-value inventions are presented in **Figure 18**, while the European top companies are presented in **Figure 19**. The French company Naval Energies, is currently mainly active in OTEC technology and floating offshore wind, and has also been active in tidal energy.

Figure 18. Number of high value Inventions for the top 10 companies in the time period 2019-2021



Source: JRC based on EPO Patstat, 2024

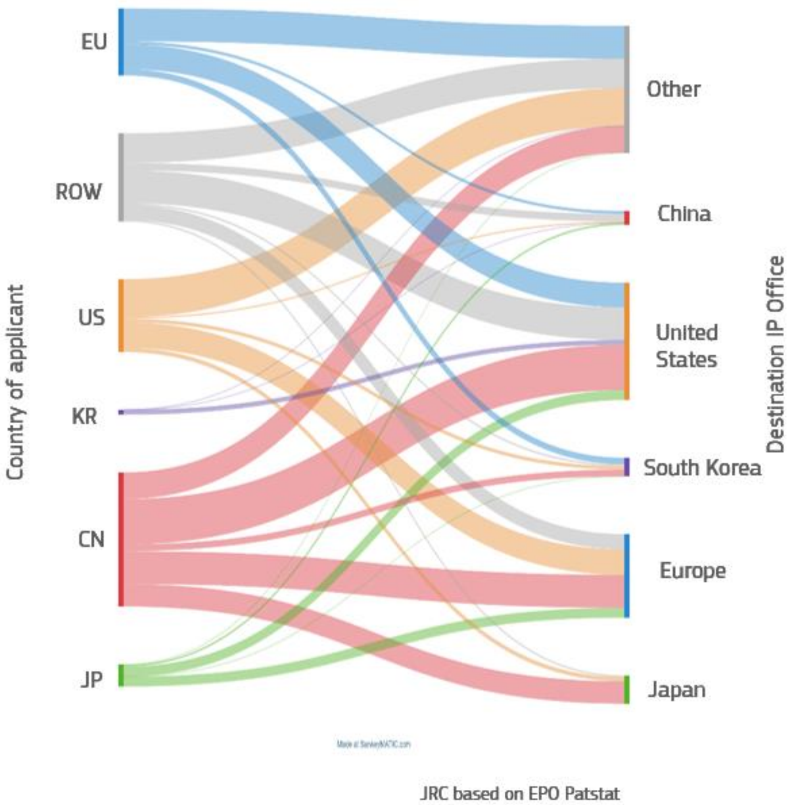
Figure 19. Number of high value Inventions for the top 10 EU companies in the time period 2019-2021



Source: JRC based on EPO Patstat, 2024

In terms of international protection, international activity inventions originating from the EU account for 17% of the total international inventions. Around 21% of the EU inventions are protected internationally. The flow of inventions' international protection for all countries is presented in **Figure 20**.

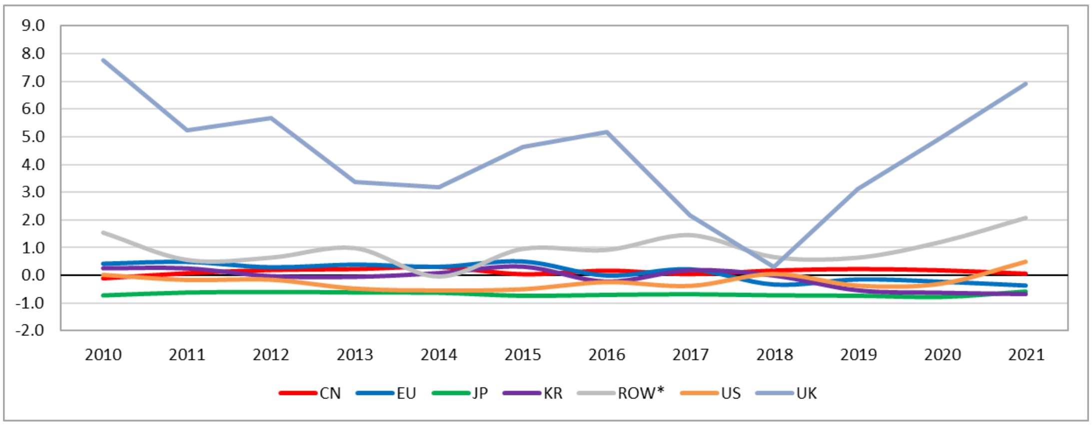
Figure 20. International protection of high value inventions for the time period 2019-2021



Source: JRC based on EPO Patstat, 2024

The Specialisation Index (SI) represents the patenting intensity in a technology for a given country related to the rest of the world. When SI=0, the intensity of a given country is equal to the rest of the world, when SI<0, the intensity is lower than the world and when SI>0 the intensity is higher than the rest of the world. SI is calculated for each year separately and the index values for the technologically dominant countries are presented in **Figure 21**.

Figure 21. Specialisation index for the period 2010-2021.



Source: JRC based on EPO Patstat, 2024

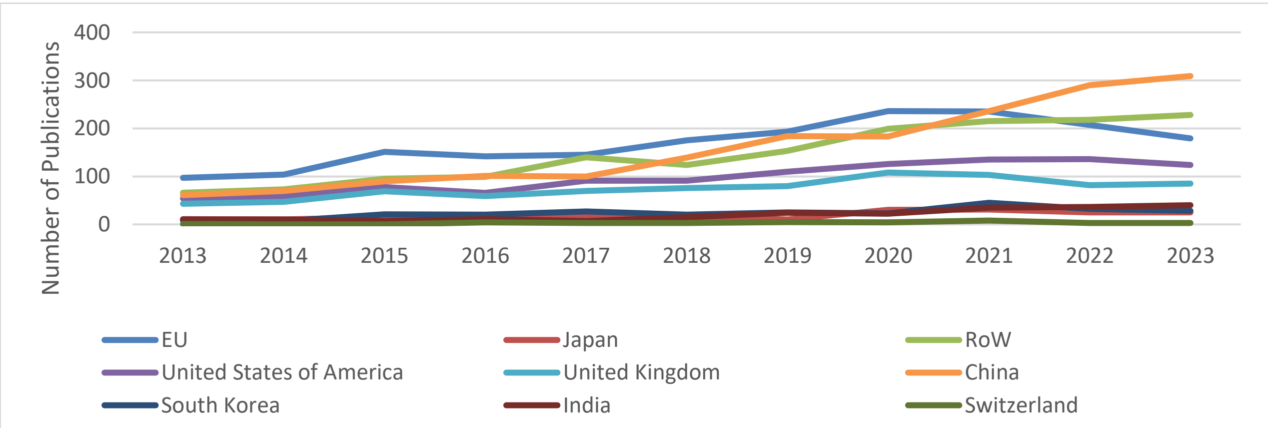
Here the predominant trend is the decline of SI for the UK through the years, that rebounded in the last two years, remaining ahead of the rest of the world (SI=6.9 for 2021). The EU's SI fluctuates around zero, meaning that the intensity of ocean energy activities is similar to the rest of the world (the average SI for 2010-2021 is 0.13). The remaining countries follow a similar trend, with China displaying a positive trend but still having a positive SI (0.12 for 2021).

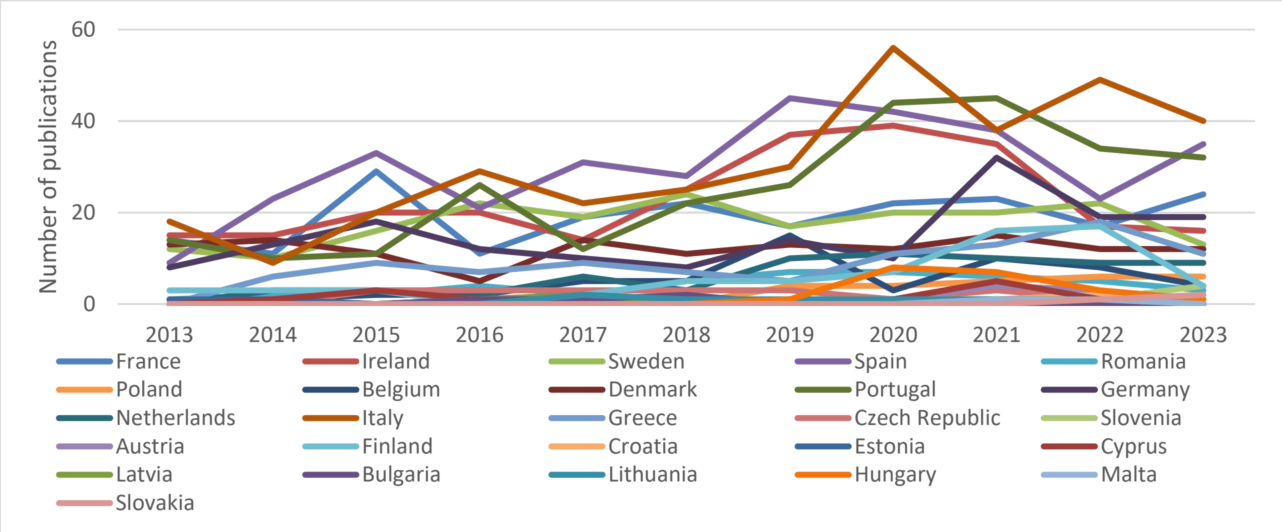
2.7 Scientific publication trends

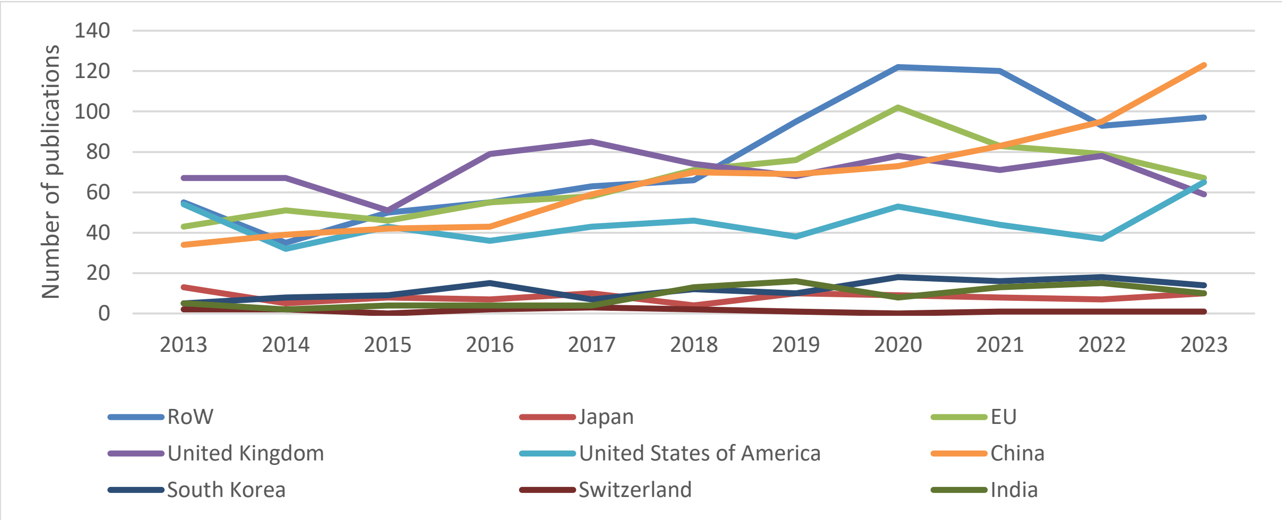
An analysis of scientific peer-review articles is useful to understand the impact of a developing technology over the years. Here we assess the evolution of ocean energy technologies.

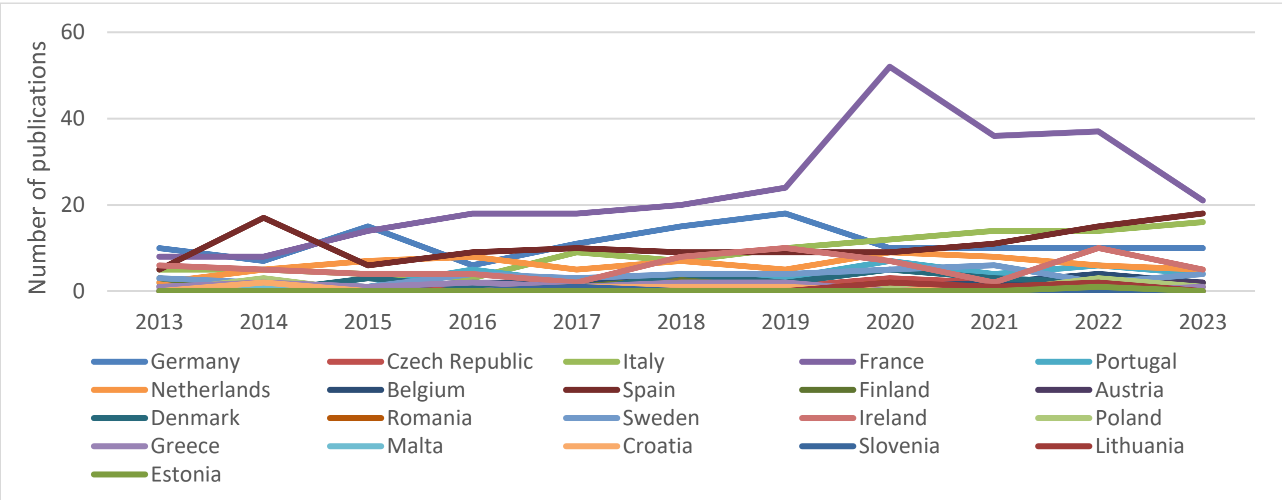
In the last decade, peer-reviewed publications in the field of tidal energy have been growing steadily, both globally and in the EU (**Figure 22**). In 2023 there was an increase compared to 2022 in the absolute number of publications both in wave and in tidal energy. China overtook the EU in the number of publications and is now leading both the wave and the tidal sector. EU is performing second in both ocean energy categories, followed closely by the US. In the EU Italy is leading in number of wave energy related publications, while France is leading in the tidal energy sector. Countries that account to less than 1% of the total publications are not presented in the figure.

Figure 22. Peer-reviewed publication evolution for (a) wave energy related publications globally, (b) wave energy related publications in the EU, (c) tidal energy related publications globally and (d) tidal energy related publications in the EU









Source: JRC based on TIM, 2024

Other than the quantity, the quality of the publications is important for the assessment of the level of technology in a country or region. The quality is often assessed by using the number of highly cited papers as well as by using citation indices.

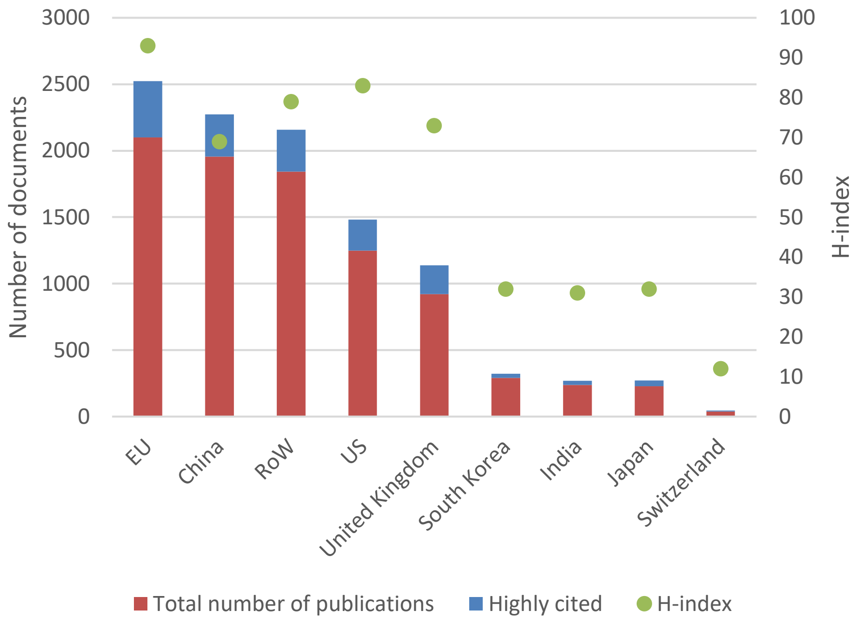
Highly cited articles are defined as those which fall within the highest 1%, based on the number of citations when compared to articles published in the same field and year.

Citation indices are also commonly used. The h-index incorporates both the productivity and citation impact of publications. It is defined as the maximum value h, where the given country has published at least h articles that have been cited at least h times.

The Field-Weighted Citation Impact (FWCI) is the ratio of total citations received and the total citations that would be expected based on the average of the specific fields. FWCI values larger than 1 mean that an article performed better than the average in its field, while values less than 1 correspond to an underperforming publication.

In the wave energy sector and for the period 2013-2023, the EU is leading globally, having the largest number of total publications, highly cited articles, and h-index. In terms of FWCI, EU ranks second following the UK, which has a considerably smaller number of publications (**Figure 23**). At EU level, Spain has the largest number of highly cited papers and h-index, followed by Italy and Ireland.

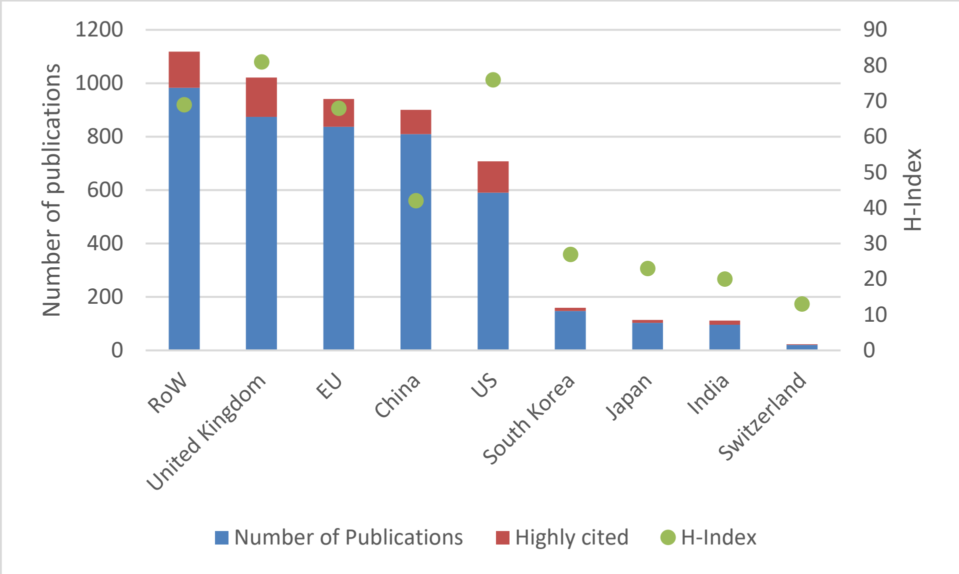
Figure 23. Global publication metrics for wave energy articles: total publications, highly cited articles and h-index



Source: JRC based on TIM, 2024

For tidal energy, the majority of the publications come from the UK, followed by the EU, with the UK also having the largest number of highly cited papers, and h-index. Considering FWCI, the US are leading the field, followed by the EU and the UK. The majority of the publications in this field come from an aggregation of countries not analysed in this report (**Figure 24**). In term of EU countries, France has the largest amount of highly cited articles and h-index, followed by Germany and Spain.

Figure 24. Global publication metrics for tidal energy articles: total publications, highly cited articles and h-index

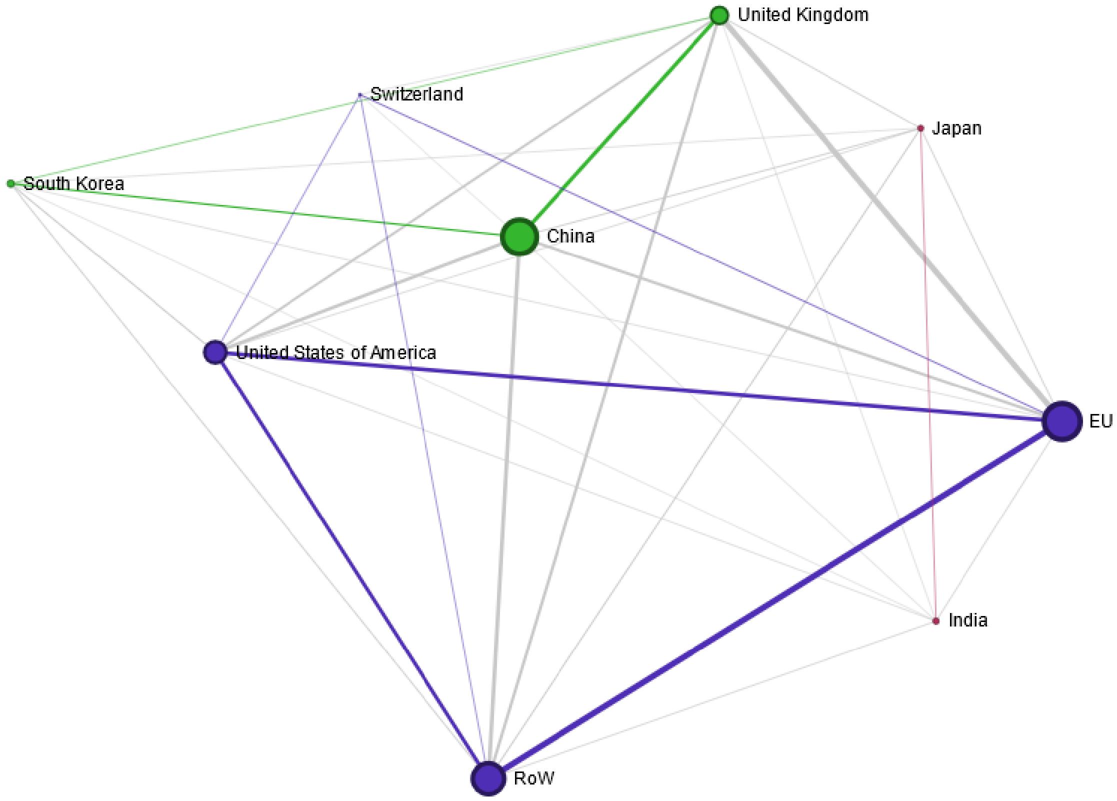


Source: JRC based on TIM, 2024

For wave energy, the main collaboration countries are the US, the UK and Switzerland. This can be attributed to the close collaboration between parties in these countries. Especially for the case of the UK, funding for collaboration between UK and EU countries is still ongoing, leading in the co-authorship of multiple papers. This is further reinforced by the presence of developed testing facilities in the UK, which help significantly in the deployment of new, scaled and testing devices. EU has also increased collaborations with the US. A second cluster of collaborations is also present between the UK, China and South Korea. EU countries also collaborate with other countries with smaller individual impact in the field (**Figure 25**).

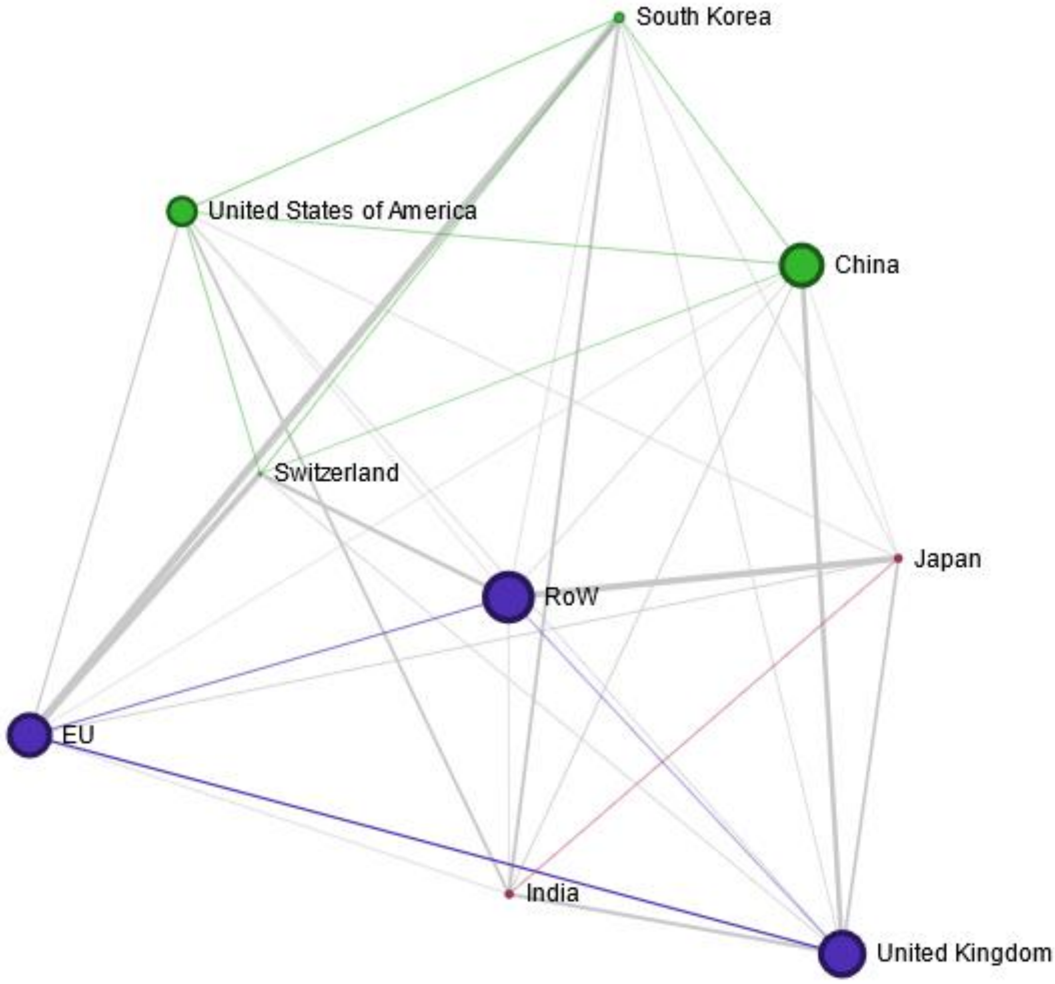
Similarly, for tidal energy (**Figure 26**), there are strong collaboration links between the EU and the UK. Moreover there is extended collaboration with EU countries and countries with a smaller individual contribution.

Figure 25. International collaboration networks in wave energy



Source: JRC based on TIM, 2024

Figure 26. International collaboration networks in tidal energy



Source: JRC based on TIM, 2024

2.8 Assessment of R&I project developments

The European Commission supports multiple activities addressing the development of ocean energy technologies and its subcomponents, as well as initiatives that are crucial for its advancement: professional networks, personal training, social opinion and policy advice, integration with other renewables. EU projects focused at the development of the technology have actively contributed to the progression of technologies and individual devices into higher TRL. In terms of tidal energy, in the last five years efforts have been put into demonstrating tidal device capabilities and refining of the technology, aiming at the reduction of the LCoE. In terms of wave energy, the main focus is the development of the PTO, in order to increase the reliability and the survivability of the system.

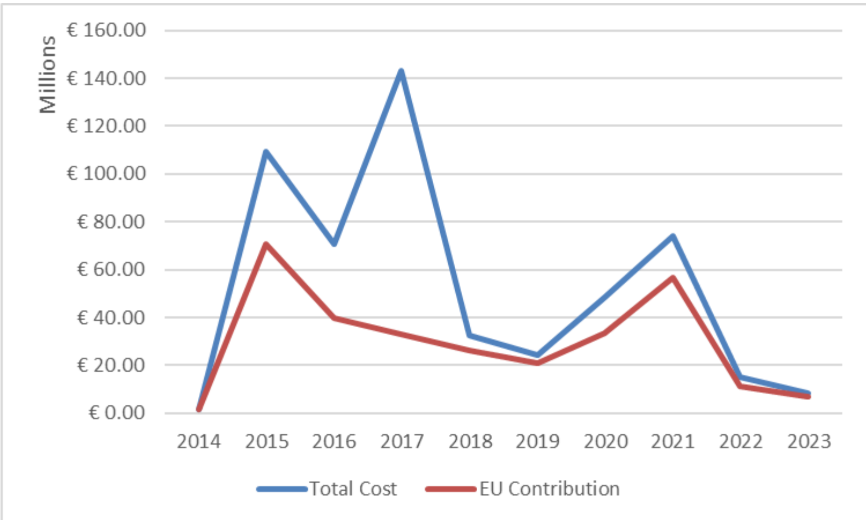
Since 2010, almost EUR 300 million has been invested in projects involving different elements of wave and tidal energy through the Horizon 2020 (H2020) Framework Programme and Horizon Europe. Horizon Europe has been active since 2022, and 13 projects have so far been funded under the scheme. In **Figure *27***, the breakdown between the two different funding schemes, as well as the number of projects funded relevant to each ocean energy sector are presented. Ocean energy category includes projects that can benefit both wind and tidal energy sectors.

Figure 27. Number of project and total net EU contribution (in million EUR) for H2020 and Horizon Europe frameworks, for tidal and wave energy

Source: JRC based on Cordis, 2024

In ***Figure 28*** the EU contribution to ocean energy related projects, together with their total value, is presented.

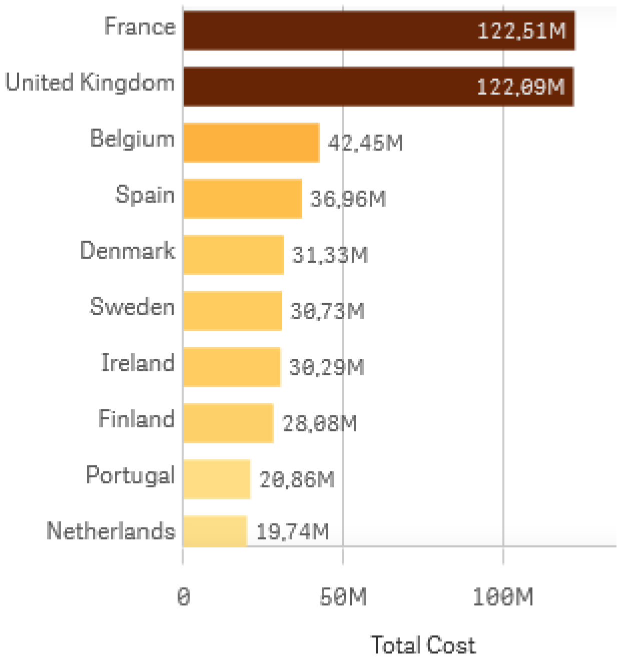
Figure 28: Total cost and EU contribution (in million EUR) for H2020 and Horizon Europe frameworks, for tidal and wave energy



Source: JRC based on Cordis, 2024

The countries where these projects took place together with the sum of the total cost are presented in ***Figure 29***.

Figure 29: Sum of cost (in million EUR) of projects presented in figure 27 per country



Source: JRC based on Cordis, 2024

In 2023 a project was funded with the focus of minimising environmental impacts (off-coustics), and more specifically the acoustic footprint, and another on combining Hydrogen production with wave energy (GreenH2Wave). A full list of the FP7 and H2020 projects for the period 2010-2023 is given in Annex 2.

3 Value Chain Analysis

3.1 Turnover and Gross value added

Ocean energy technologies are still in the development phase, with only a few designs reaching high Technology Readiness Levels (TRL) (See Chapter 1). Consequently, the sector is not yet considered mainstream business, and information regarding market value and value chain is limited. However, according to Market Research Future (2021), the global ocean energy market was estimated to be around EUR 2.17 billion (USD 2.28 billion) in size, with a projected compound annual growth rate (CAGR) of approximately 28% for the period 2021-2027.

ETIP Ocean (2021) conducted an evaluation of the potential economic value that the development and deployment of wave and tidal energy could offer to Europe until 2050. Three scenarios were considered:

Achievement of the SET Plan: targets Assumes Europe and the world reach net-zero emissions in 2050 and 2070, respectively, with an equal split between tidal stream and wave energy in Europe and a 40%-60% split for the rest of the world.

Europe follows the global market: Assumes global net-zero emissions by 2050 with a 40%-60% split between tidal stream and wave energy worldwide. In this scenario, Europe is not a market leader but follows global trends.

Europe leads the global market: Assumes global net-zero emissions by 2050 with a 40%-60% split between tidal stream and wave energy worldwide. In this scenario, Europe takes a leading role in the ocean energy market.

The total potential gross value added benefit to the European economy, resulting from the supply chain activity supporting global ocean energy deployments, ranges from EUR 59 billion to EUR 140 billion across the three scenarios. The study focuses on the pre-Brexit European Union (EU-28). To capture a high market share, Europe must achieve performance improvements, cost reductions, and implement policies that support European industrial activities and strengthen the region's export position. These actions would maximise the economic benefits retained by the European economy.

3.2 Environmental and socio-economic sustainability

Life cycle assessment (LCA) is a widely recognised and used tool for evaluating the potential environmental impact of products, processes and services. The LCA of wave and tidal devices has been the subject of study in multiple scientific publications, however due to the diversity of technologies considered, there is a large variation in their result. Characteristically Paredes et al. (2019) have systematically reviewed 18 LCA studies in ocean energy technologies and concluded to a range of 10-106 g CO_2eq/kWh across them. According to the analysis, the main source of environmental impacts is from raw material extraction of structural components, manufacturing devices, energy consumption and mooring foundations. More specifically, structure (particularly, steel manufacturing, in most cases), mooring and foundations, and the shipping operations, have the greatest impact on total CO_2 emissions (between 40–95% of the total emissions). Other raw materials necessary for the development of ocean energy technologies include copper and iron for cables, as well as potentially magnets used in linear generators.

Ecosystem and biodiversity impacts assessment is necessary to ensure the environmental sustainability of ocean energy technologies. ETIP Ocean (2020) identified key environmental research needs and consenting challenges to facilitate the large scale rollout of ocean energy. The main environmental concerns included, amongst others, collision risk, noise, and electromagnetic fields. However, while it was concluded that there is no evidence of risk to local ecosystems, it was also highlighted that long-term monitoring is essential. In the MaRVEN study (European Commission et al., 2016) the current norms and standards related to noise, vibrations and electromagnetic fields were reviewed. On-site measurements and field experiments to fill priority knowledge gaps and to validate and build on the results obtained in reviews were undertaken. In this way a programme for further research and development was outlined and priorities were identified. Similarly, the state of knowledge concerning the environmental effects of ocean energy devices in the marine environment and how these are driving the permitting process of projects was the subject of a report prepared for OES, concluding that the risks for deployment and operation of single devices and small arrays appear to be low, while for larger arrays further investigations are needed (Copping and Hemery, 2020). Tethys (2023) is a database with documents and information about the environmental impacts of marine renewable energy, supporting the OES-Environmental initiative.

The sea area used for these technologies varies significantly depending on the technology, its capacity and the PTO system. Depending on the conditions and the location, the theoretical power capacity for tidal stream is 0.5 - 8 kW/m^2 and 17-50 kW/m^2 for wave energy. The energy return on energy invested (EROEI) ratio varies depending on the technology. It has been reported that ocean energy technologies are estimated to have EROEI equal to 3.25:1 (Capellán-Pérez et al., 2017), but real life application were also able to achieve better values (as an indication, Pelamis device, which is currently not pursued by any company, was estimated to have EROEI 15:1 (Beloglazov and Shabalov, 2017).

Since ocean technologies are not mainstream yet, international standards have not yet been fully established. Since 2007, the International electrotechnical commission (IEC) Technical Committee has developed international standards for marine energy conversion systems for wave, tidal and other water current converters, which are used to test and assess marine energy equipment. The European marine energy centre (EMEC), that runs one of the main testing facilities in Europe (based in Orkney, Scotland), sets the basis for the certification for marine energy converter units, including a basis for acceptance of operating bodies and mutual recognition of certificates.

3.3 Role of EU Companies

Tidal energy is the most advanced form of ocean energy globally, with companies developing projects globally. 41% of the major tidal energy developers are based in the EU, leading with the Netherlands, France and Ireland. Non-EU players are predominantly based in the UK, Canada, USA and China.

In terms of individual countries, the UK has the largest number of companies, followed by Canada, Netherlands and France.

Some of the leading companies in the sector are presented in **Table 4.**

Table 4. Leading tidal energy developers with technology at TRL 6 or higher.

Name	Country	Website	Type
Andritz Hydro Hammerfest	Austria	www.andritzhydrohammerfest.co.uk	HAT
Guinard Energies	France	www.guinard-energies.bzh/	DT
EEL GEN Energy	France	www.eel-energy.fr/en/	OH
SCHOTTEL	Germany	www.schottel.de/schottel-hydro/sit-instream-turbine/	HAT
Design Pro	Ireland	designprorenewables.com/	VAT
Kobold Turbine	Italy	www.seapowerscrl.com/ocean-and-river-system/kobold	VAT
GEM Ocean Kite	Italy	bluesharkpower.eu/	HAT
Tocardo	Netherlands	tocardo.com	HAT
Magallanes Renovables	Spain	www.magallanesrenovables.com/en/proyecto	HAT
Minesto	Sweden	minesto.com/	TK
Orbital	UK	orbitalmarine.com/	HAT
SIMEC Atlantis	UK	simecatlantis.com	HAT
Nova Innovation	UK	www.novainnovation.com/	HAT
Sustainable Marine Energy	UK	sustainablemarine.com/	HAT
Nautricity	UK	www.nautricity.com/	HAT
Oceanflow / Evopod	UK	www.oceanflowenergy.com/	HAT
Elemental Energy Technologies	Australia	www.mako.energy/projects	ET
Water Wall Turbine Inc	Canada	wwturbine.com/	HAT
New Energy Corporation	Canada	www.newenergycorp.ca/	VAT
Mavi Innovations	Canada	mavi-innovations.ca/project_post/remote-community-tidal-power-project/	HAT
Yourbrook Energy Systems	Canada	www.yourbrookenergy.com	HAT
ZHAIRUOSHAN Tidal Stream energy	China	From OES Report	HAT
Active-Controlled Tidal Current Power Generation System - KIOST	Korea	From OES Report	HAT
Tidetec	Norway	tidetec.com/	HAT
Ocean Renewable power Company	USA	www.orpc.co/	HAT
Verdant Power	USA	www.verdantpower.com/	VAT

Source: JRC database, 2024

Similarly to tidal energy, the majority of companies developing wave energy devices are located in the EU. 52% of active wave energy companies are located in the EU. Denmark has the highest number of developers, followed by Italy and Sweden. Outside the EU, countries with a large number of wave energy developers are the UK, the USA, Australia, and Norway.

Currently the sector of wave energy is showing quick progress, with many devices at lower TRLs, but also an increasing amount of devices in higher TRL and pre-commercial stages. In **Table 5**, the most prominent wave energy device developers are presented.

Table 5. Leading wave energy developers with technology at TRL 6 or higher

Name	Country	Website	Type
Laminaria	Belgium	http://www.laminaria.be/	Other
Wave Dragon	Denmark	http://www.wavedragon.net/	OT
Wave Piston	Denmark	https://www.wavepiston.dk	Other
RESEN Waves	Denmark	www.resenwaves.com/	PA
AW-Energy / WaveRoller	Finland	http://aw-energy.com/	OWSC
Holvi Energy	Finland	https://holvienergy.com/index.html	RM
SBM	France	https://www.sbmoffshore.com/what-we-do/our-products/renewables/	BW
SINN Power	Germany	https://www.sinnpower.com/	PA
Ocean Energy Ltd	Ireland	http://www.oceanenergy.ie/	OWC
SeaPower Ltd.	Ireland	http://www.seapower.ie/	ATT
CETO Wave Energy Ireland	Ireland	https://www.carnegiece.com/ceto-technology/	PA
40South Energy	Italy	http://www.40southenergy.com	OWSC
Wave for Energy	Italy	http://www.waveforenergy.com/tech/iswec	RM
Wedge	Spain	https://www.wedgeglobal.com/en/waveenergy	PA
CorPower	Sweden	http://www.corpowerocean.com/	PA
Seabased	Sweden	https://www.seabased.com/	PA
Waves4Power	Sweden	https://www.waves4power.com/projects/	PA
Mocean Energy Ltd	United Kingdom	https://www.mocean.energy/	ATT
Seatricity	United Kingdom	http://seatricity.com/	PA
AMOG Consulting Limited	Australia	https://amog.consulting/products/wave-energy-converter	PA
BioWave	Australia	http://bps.energy/projects	OWSC
Bombora	Australia	http://www.bomborawave.com/	Membrane
Carnegie	Australia	https://www.carnegiece.com/	PA
Aquanet Power	Hong Kong	https://www.aquanetpower.com/	OWC
EcoWavePower	Israel	https://www.ecowavepower.com/	PA
Fred Olsen	Norway	http://boltseapower.com	PA
Resolute Marine Energy	USA	http://www.resolutemarine.com/	OWSC
Atmocean	USA	https://atmocean.com/	PA
Ocean Power Technologies	USA	https://www.oceanpowertechnologies.com/	PA
Columbia Power technologies	USA	https://columbiapwr.com/	PA
Oscilla Power	USA	https://oscillapower.com/imec-technology/	PA
NWEI - Azura Wave	USA / New Zealand	https://azurawave.com/projects/hawaii/	PA

Source: JRC database, 2024

3.4 Employment

Since ocean energy technologies represent a small fraction of the energy sector and are still not commercially widespread, value chain data are often reported aggregated with other sources of energy or are missing. According to IRENA and ILO(2021), there were around 1 300 people employed in the ocean energy sector globally in 2020. However the database estimating the employment is limited, presenting only four countries globally with ocean energy employment. The majority of employment in ocean energy is in the UK (928 jobs) followed by Spain (350 jobs). These numbers are not a close reflection of reality, since, as discussed in section 3.4, multiple companies are operating in various EU countries and beyond. However, they are representative of the trend in the ocean energy sector, as seen in the previous chapters of this report, where the UK with EU are leading in the development and deployment of ocean energy devices.

According to ETIPOcean (2020) future trends in employment will depend on the uptake of ocean energy in Europe and globally. Assuming that EU targets are reached in 2050 and the wave/tidal energy proportional split is 60/40%, and if Europe follows the global market, 205 000 new direct and indirect jobs will be created for the European economy by 2050. If Europe leads the global markets, 505 000 new direct and indirect jobs will be created.

According to the Blue economy report (EC, 2024), ocean energy projects are estimated to mobilise at least 415 FTE in the EU within specialised ocean energy companies.

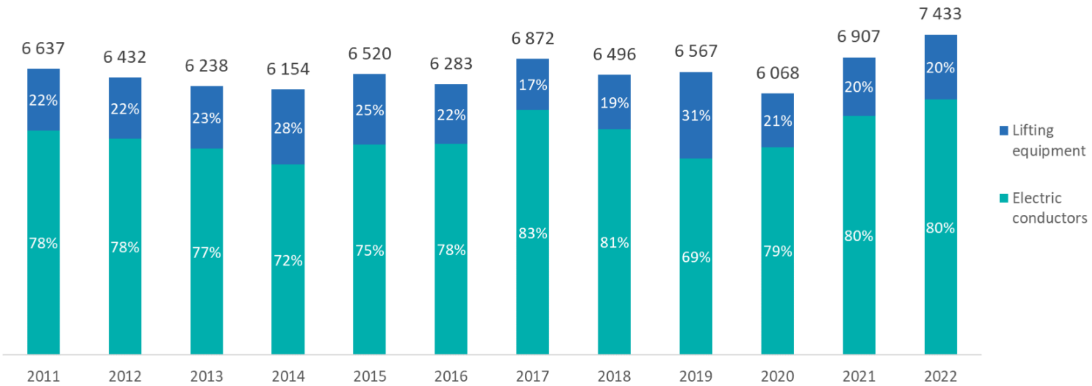
3.5 EU Production Data

Ocean energy technologies are still under development with only a few commercial applications. Accordingly, manufacturing, installation, and trading activities are currently at a small scale and are usually adapted from other industries. Until reaching large, commercial scale installations, the ocean energy sector relies heavily on vehicles, machinery, and products used by other sectors, like offshore wind. The most prominent examples are the cables and the installation vehicles. Consequently, no production or trade codes are directly and exclusively linked to ocean energy technologies. However, equipment related to the manufacturing or installation of ocean energy devices can potentially act as a proxy for understanding the trends in technology development. Therefore, the selected production and international trade codes are related to lifting equipment (prodcom 28221470, HS 842699) and insulated electric conductors (prodcom 27321400, HS 854460).

The production codes used are primarily applicable in multiple other industrial applications, so in absolute numbers their production has high values.

]**Figure 30** shows the EU production in value. Over the past ten years (2013-2022), the overall production value had a 19% increase with an annual compound growth of 2% and an average value of EUR 6.6 billion. In 2022, the total value had an 8% increase compared to the previous year, reaching EUR 7.4 billion. Insulated electric conductors hold the grand majority of the EU production value. Italy and Germany were the top EU producers, holding 32% and 17% of the total EU production respectively. Germany had a balanced production of both commodities, while the 80% of Italy’s production was about insulated electric conductors. However it must be highlighted that technology is still emerging and any trends related to value chain are premature.

Figure 30. EU production value per commodity [EUR Million]



Source: JRC based on PRODCOM data, 2024

4 EU Market Position and Global Competitiveness

4.1 Global & EU market leaders

The leading market players for ocean energy were identified in 3.3 above. The majority of the companies have not announced the value of the project they are involved in. The companies are also involved in a wide range of stages across the overall value chain so it is challenging to derive a market share.

4.2 Trade (Import/export) and trade balance

No dedicated trade code for ocean energy equipment and services has been located up to now. However, due to the limited deployment of ocean energy devices globally and due to the leading position of EU in the sector, in terms of the global annual market it is likely that trade doesn't represents a significant share.

4.3 Resource efficiency and dependence in relation to EU competitiveness

Resource efficiency and critical material dependency are topics that have gained little or no attention in the ocean energy sector. While numerous studies assess the materials needed for ocean energy device deployment under the prism of LCA, material availability is rarely mentioned.

Similar to properties mentioned in other sections of this report, device types differ considerably in terms of design and structural components. This also means that some components and materials are found in certain device types only and are not applicable or not used for others.

The main materials present in all devices in different amounts are steel (mainly in the structure and moorings), cement (mainly for foundations and anchor points of the moorings), magnets (for linear generators), copper and iron (mainly for electrical connections and export cables).

Depending on the device characteristics, other materials and metals are present. Various composite materials (for tidal blades), polymers (for oscillating hydrofoil designs) and polyurethane (for buoys designs) may also be present in large amounts. Uihlein (2016) presented an assessment of materials present in different types of devices as a percentage of their total weight (**Table 6**).

Table 6. Share of material used to produce ocean energy device in % of total weight

Device Type		Steel	Other metals	Electronics	Plastics	Concrete	Sand	Water
Tidal	Horizontal axis turbine	50.2	6.4	0.9	6.9	32.7	0.8	2.1
	Vertical axis turbine	88.4	5.5	1.5	4.6	0	0	0
	Oscillating hydrofoil	77	9.7	1.8	11.2	0.3	0	0
	Enclosed tips	77.8	8	2.8	10.9	0.5	0	0
	Archimedes screw	54.5	12.5	0.4	7.6	25	0	0
	Tidal kite	64.3	2.6	1.5	5.6	25	0	0
	Other tidal	64.5	3.3	0.6	7.1	24.5	0	0
Wave	Attenuator	46.2	7.0	1	6.6	6.3	9	23.9
	Point absorber	50.5	3.8	0.9	11.9	13.6	5.3	14
	Oscillating wave surge	55.1	7.9	3	12.9	8.3	3.5	9.3
	Oscillating water column	60.6	3.1	0.6	4.1	31.6	0	0
	Overtopping	36.7	0.9	0.2	0.9	55.5	1.6	4.2
	Submerged pressure differential	63.1	3.4	0.9	11.2	21.3	0.02	0.05
	Rotating mass	46.1	2.8	0.3	4.9	20.6	6.9	18.4
	Other wave	65.5	3.6	0.5	4.8	25.6	0	0

Source: Uihlein (2016)

The supply risk of raw materials is assessed based on the Critical Raw Materials Act. Particularly rare earth elements used in the permanent magnets of the turbine generators are identified as critical raw materials in the ocean energy sector. Dysprosium, Neodymium, Praseodymium, Terbium and Borate show a high supply risk.

5 Conclusions

The ocean energy sector has significant potential to contribute to the European Union's (EU) energy mix and decarbonisation goals. The sector has made notable progress in recent years, with advancements in technology and the development of new projects. However, the sector still faces several challenges, including high costs, administrative barriers, and competition from other renewable energy sources.

Ocean energy technologies have progressed fast in the last decade. Multiple devices have improved in maturity and some designs have become pre-commercially available. For tidal energy, the most prominent sub-technology that has reached TRL 9 is the horizontal axis device, followed by the tidal kite (TRL 8). However, the wave energy sector is more fragmented, with multiple designs currently being pursued. Point absorbers and OWC devices have reached TRL 9.

Installed capacity is increasing and multiple projects are on the pipeline, but more is needed to achieve ambitious targets.

Wave and tidal energy costs are still high but expected to fall when deployments increase. Currently the average LCoE for wave energy devices is 0.27 EUR/kWh and for tidal energy devices, 0.2 EUR/kWh. According to SET plan, by 2030, LCoE for tidal energy should reach 0.1 €/kWh, whilst for wave energy the target is of 0.15 €/kWh.

In 2022 there was a big increase in public investments reaching its 10-year maximum (EUR 48.35 million). In 2022 the largest amounts of public investment were awarded in Spain and France.

Globally, the EU is leading in public R&D investments, accounting for 53% of the worldwide public investments in the period 2013-2023. This is attributed both to direct investments by the Member States (27% of the total investments) but also to funding from EU framework programmes (26%).

The development of ocean energy technologies appears to be mostly driven by venture capital companies (representing 64% of identified innovators).

Globally, in the period 2018-2020, China is leading in the number of inventions (32%) , followed by the EU with 20% of high-value inventions.

In 2023, there was a increase in the absolute number of scientific publications both in wave and in tidal energy. China overtook the EU in the number of publications and is leading in both the wave and the tidal sector. However, in the wave energy sector for the full period spanning 2013 to 2023, the EU is leading globally, showing the largest number of total publications, highly cited articles, and h-index. For tidal energy, the majority of the publications, the most highly cited papers, and the highest h-index all come from the UK.

Since 2014 more than EUR 300 million has been invested in projects involving different elements of wave and tidal energy, through the Horizon 2020 (H2020) Framework Programme and Horizon Europe. Horizon Europe has been active since 2022 and 13 projects have so far been funded under the scheme.

Market value and chain value has been underdefined, however there will be significant economic benefits if Europe captures a high market share, a goal achievable only through performance improvements, leading in cost reductions, and policy interventions.

Companies active in developing tidal stream devices to a TRL of over 5 have been identified, with the majority (41%) of them located in the EU. In terms of individual countries, UK has the largest number of companies, followed by Canada, the Netherlands and France. Similarly, the majority of companies developing wave energy devices are located in the EU (52%).

The main materials present in all ocean energy devices (in different amounts) are steel (mainly in the structure and moorings), cement (mainly for foundations and anchor points of the moorings), magnets (in the case of linear generators), copper and iron (mainly for electrical connections and export cables). Particularly rare earth elements used in the permanent magnets of the turbine generators are identified as critical raw materials in the ocean energy sector.

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List of abbreviations and definitions

ATT	Attenuator
BiMEP	Biscay Marine Energy Platform
CAGR	Compound Annual Growth Rate
CAPEX	capital expenditure
CORDIS	Community Research and Development Information Service
EC	European Commission
EMEC	European Marine Energy Centre
EU	European Union
EROEI	Energy Return On Energy Invested
ET	Enclosed Tips
ETIP Ocean	European Technology and Innovation Platform for ocean energy
EU	European Union
EPO	European Patent Office
FP7	Seventh Framework Programme
FWCI	Field-Weighted citation impact
H2020	Horizon 2020
HAT	Horizontal Axis Turbine
IEA	International Energy Association
IEC	International Electrotechnical Commission
JRC	Joint Research Centre
KPI	Key Performance indicator
LCA	Life cycle analysis
LCoE	Levelised Cost of Energy
OEE	Ocean Energy Europe
OES	Ocean Energy Systems
OH	Oscillating Hydrofoil
OPEX	Operational Expenditure
OTEC	Ocean thermal energy conversion
OWC	Oscillating Water Column
OWSC	Oscillating water surge Converters
PA	Point absorber
PLOCAN	Plataforma Oceanica De Canarias
PRO	Pressure retarded osmosis
PTO	Power Take-off
R&D	Research and Development
RED	Reversed Electro dialysis
ROW	Rest of the World
RM	Rotating Mass
SET-Plan	Strategic Energy Technology Plan
SWOT	Strengths, Weaknesses, Opportunities and Threats
TRL	Technological readiness Level
VAT	Vertical Axis Turbine

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Annexes

Annex1 Summary Table of Data sources for the CETO indicators

Theme	Indicator	Main data source
Technology maturity status, development and trends	Technology readiness level	JRC analysis
	Installed capacity & energy production	JRC database
	Technology costs	JRC, IRENA
	Public and private RD&I funding	JRC based on IEA
	Patenting trends	Patstat
	Scientific publication trends	CORDIS
	Assessment of R&I project developments	JRC based on Pitchbook
Value chain analysis	Turnover	EurObserv'ER
	Gross Value Added	EurObserv'ER
	Environmental and socio-economic sustainability	JRC analysis
	EU companies and roles	JRC database
	Employment	EurObserv'ER
	Energy intensity and labour productivity	IRENA and ILO
	EU industrial production	PRODCOM
Global markets and EU positioning	Global market growth and relevant short-to-medium term projections	JRC
	EU market share vs third countries share, including EU market leaders and global market leaders	JRC
	EU trade (imports, exports) and trade balance	COMEXT
	Resource efficiency and dependencies (in relation EU competiveness)	JRC

Annex 2 EU Funded projects under H2020 and Horizon Europe

Signature Year	Programme	Project Acronym	Project Status label	Project Start Date	Project Number	Simplified ToA	Project Title	[EuroSciVoc Level 7]	EU Contribution
2018	H2020	ARRECIFE	Closed	2018-02-01	807148	SME-1	Coral Reef wisdom to capture Wave Energy	wave power	50000
2017	H2020	BUTTERFLY	Closed	2017-04-01	774021	SME-1	DEVELOPMENT AND MARKET UPTAKE OF INNOVATIVE SYSTEM TO OBTAIN ELECTRICAL ENERGY FROM OCEAN WAVE RESOURCES	wave power	50000
2015	H2020	CEFOW	Closed	2015-06-01	655594	IA	Clean energy from ocean waves	wave power	16998022.13
2024	HORIZON EUROPE	CoCoS	Signed	2024-09-01	101142449	HORIZON-ERC	Computational Cosmology and Gravitational Waves	wave power	2446893
2019	H2020	CONPARA	Closed	2019-06-03	841388	MSCA-IF	Control parametric resonance of wave energy conversion systems	wave power	196590.72
2016	H2020	D2T2	Closed	2016-10-01	734032	SME-2	Direct Drive Tidal Turbine (D2T2) Accelerator project	tidal energy	2250266
2016	H2020	DEMOTIDE	Closed	2017-01-01	691925	IA	DEMOnstration for Tidal Industry DErisking	tidal energy	20301149.75
2021	H2020	DESTINY	Closed	2021-06-01	101024372	MSCA-IF	Moment-based nonlinear energy-maximising optimal control of wave energy systems to secure a renewable future	wave power	183473.28
2018	H2020	DG Island Mode	Closed	2018-08-01	827525	SME-1	Deep Green Island Mode	tidal energy	50000
2019	H2020	DGIM2	Closed	2019-08-01	872404	SME-2	Deep Green Island Mode 2	tidal energy	2499995
2014	H2020	Direct Drive TT	Closed	2014-10-01	651505	SME-1	Feasibility study for an innovative direct drive tidal turbine	tidal energy	50000
2019	H2020	ECOWEC	Closed	2019-12-01	888528	SME-1	Erosion Control Oscillating Wave Energy Converter	wave power	50000
2016	H2020	eForcis	Closed	2016-08-01	736343	SME-1	eForcis and BeForcis, Wave Energy Generators for marine buoys and devices.	wave power	50000
2019	H2020	ELEMENT	Closed	2019-06-01	815180	RIA	Effective Lifetime Extension in the Marine Environment for Tidal Energy	tidal energy	4984622.5
2019	H2020	ELVER	Closed	2019-12-01	887603	SME-1	Energy from Limited Velocity Estuaries and Rivers	tidal energy	50000
2022	HORIZON EUROPE	EnDorSE	Closed	2023-03-01	101058889	HORIZON-TMA-MSCA-PF-EF	Enhancing Damage detection and characterisation technologies for complex marine Structures under Extreme environmental conditions	tidal energy	239700

2017	H2020	EnFAIT	Closed	2017-07-01	745862	IA	Enabling Future Arrays in Tidal	tidal energy	14914599.5
2020	H2020	EuropeWave	Signed	2021-01-01	883751	PCP	Bridging the gap to commercialisation of wave energy technology using pre-commercial procurement	wave power	11351057
2023	HORIZON EUROPE	EURO-TIDES	Signed	2023-12-01	101136085	HORIZON-IA	EUROpean Tidal energy pilot farm focused on Industrial Design, Environmental mitigation and Sustainability	tidal energy	3192720.63
2021	H2020	EU-SCORES	Signed	2021-09-01	101036457	IA	European Scalable Complementary Offshore Renewable Energy Sources	wave power	34831483.81
2024	HORIZON EUROPE	Farm-noise	Signed	2025-02-17	101149790	HORIZON-TMA-MSCA-PF-EF	Farm-noise: AI-based optimization to minimise tidal turbine noise and the impact on marine fauna	tidal energy	181152.96
2020	H2020	FIBREGY	Signed	2021-01-01	952966	IA	Development, engineering, production and life-cycle management of improved FIBRE-based material solutions for structure and functional components of large offshore wind enerGY and tidal power platform	tidal energy	6499589.75
2015	H2020	FloTEC	Closed	2016-01-01	691916	IA	Floating Tidal Energy Commercialisation project (FloTEC)	tidal energy	9782380.25
2021	H2020	FORWARD-2030	Signed	2021-09-01	101037125	IA	Fast-tracking Offshore Renewable energy With Advanced Research to Deploy 2030MW of tidal energy before 2030	tidal energy	21509866.26
2023	HORIZON EUROPE	GreenH2Wave	Signed	2023-08-01	101113993	HORIZON-CSA	Producing Green Hydrogen Using Power of Ocean Waves	wave power	75000
2018	H2020	HACE	Closed	2018-03-01	815590	SME-1	Making wave energy competitive with wind and solar energy	wave power	50000
2015	H2020	ICONN	Closed	2015-10-01	675659	MSCA-ITN	European Industrial DoCtorate on Offshore WiNd and Wave ENergy	wave power	845838.36
2018	H2020	IMAGINE	Closed	2018-03-01	764066	RIA	Innovative Method for Affordable Generation IN ocean Energy	wave power	3761205
2020	H2020	IMPACT	Signed	2021-01-01	101007071	RIA	Innovative Methods for wave energy Pathways Acceleration through novel Criteria and Test rigs	wave power	3342937.5
2015	H2020	INNOWAVE	Terminated	2016-03-01	676061	MSCA-ITN	Maximising the technical and economic performance of real wave energy devices	wave power	804637.08
2016	H2020	InToTidal	Closed	2017-01-01	730799	IA	Demonstration of Integrated Solution for offshore Tocardo Tidal power plants.	tidal energy	2000000
2019	H2020	InWAS	Closed	2020-02-10	842967	MSCA-IF	Non-linear, control-informed optimisation of innovative wave	wave power	184707.84

							absorbing structures using highly-efficient numerical methods		
2019	H2020	LiftWEC	Signed	2019-12-01	851885	RIA	Development of a novel wave energy converter based on hydrodynamic lift forces	wave power	3404730
2016	H2020	MARINERGI	Closed	2017-01-01	739550	RIA	Marine Renewable Energy Research Infrastructure	tidal energy	1999798.75
2022	HORIZON EUROPE	MAXBlade	Signed	2023-01-01	101096891	HORIZON-IA	Maximising tidal energy generation through Blade Scaling & Advanced Digital Engineering	tidal energy	1373889
2024	HORIZON EUROPE	MEGA WAVE PTO	Signed	2024-05-01	101147321	HORIZON-RIA	MODULAR ELECTRICAL GENERATOR PTO SYSTEM FOR WAVE - MEGA PTO WAVE	wave power	2105638.08
2018	H2020	MegaRoller	Closed	2018-05-01	763959	RIA	Developing the PTO of the first MW-level Oscillating Wave Surge Converter	wave power	4946768.75
2022	HORIZON EUROPE	Micro-magnetron	Signed	2022-11-01	101068135	HORIZON-TMA-MSCA-PF-EF	Development of Micro-Magnetron for Terahertz Imaging Applications	wave power	206887.68
2017	H2020	MoWE	Closed	2017-10-01	752031	MSCA-IF	Mooring of floating wave energy converters:numerical simulation and uncertainty quantification	wave power	200194.8
2016	H2020	MUSES	Closed	2016-11-01	727451	CSA	Multi-Use in European Seas	wave power	1982104.38
2015	H2020	NEARCONTROL	Closed	2016-02-01	661342	MSCA-IF	NEARshore geological CONTROL on coastal morphodynamics: monitoring and modelling in high-resolution	wave power	203200.2
2019	H2020	NEMMO	Closed	2019-04-01	815278	RIA	Next Evolution in Materials and Models for Ocean energy	tidal energy	4981007.5
2018	H2020	NextWave	Closed	2018-08-01	826910	SME-1	Wave Energy Technology Made Mainstream	wave power	50000
2017	H2020	OCTARRAY	Closed	2017-09-01	745855	IA	Scaling up to the Normandie Hydro Open-Centre Tidal Turbine Pilot Array	tidal energy	15000000
2016	H2020	OCTTIC	Closed	2016-12-01	730659	IA	Open-Centre Tidal Turbine Industrial Capability	tidal energy	2990158.16
2017	H2020	OHT	Closed	2017-06-01	775250	SME-1	A hydraulic collection tower, with a novel energy storage device for wave energy arrays	wave power	50000
2019	H2020	OpenWave	Closed	2019-05-01	832140	MSCA-IF	Validation and Optimization of an Open-Source Novel Nonlinear Froude-Krylov Model for Advanced Design of Wave Energy Converters	wave power	171473.28
2015	H2020	OPERA	Closed	2016-02-01	654444	RIA	Open Sea Operating Experience to Reduce Wave Energy Cost	wave power	5741263.75
2017	H2020	OpTiCA	Closed	2017-07-01	748747	MSCA-IF	Optimisation of Tidal energy Converter Arrays	tidal energy	148635.6

2024	HORIZON EUROPE	ORION	Signed	2024-09-01	101158432	HORIZON-RIA	NOVEL DIGITAL COMPONENTS FOR INTERNATIONAL RENEWABLE ENERGY VALUE CHAINS	wave power	3000000
2019	H2020	ParaResWEC	Closed	2019-05-01	867453	MSCA-IF	Nonlinear Rock and Roll - Modelling and Control of Parametric Resonance in Wave Energy Converters	wave power	151850.88
2019	H2020	PivotBuoy	Closed	2019-04-01	815159	RIA	PivotBuoy - An Advanced System for Cost-effective and Reliable Mooring, Connection, Installation & Operation of Floating Wind	wave power	3960065.25
2015	H2020	Post-GFC Monetary Policy	Closed	2016-01-20	657182	MSCA-IF	Forecast of time-varying effects of post-GFC monetary policy + a novel computing application	wave power	158121.6
2015	H2020	PowerKite	Closed	2016-01-01	654438	RIA	PowerKite - Power Take-Off System for a Subsea Tidal Kite	tidal energy	5074363.65
2017	H2020	PowerModule	Closed	2017-10-01	783535	SME-2	Demonstration of the Next Generation Wave Energy Device – POWERMODULE	wave power	2499999
2014	H2020	RiCORE	Closed	2015-01-01	646436	CSA	Risk Based Consenting of Offshore Renewable Energy Projects	tidal energy	1393532.5
2017	H2020	SAFS	Closed	2017-08-01	753156	MSCA-IF	Development of screw anchors for floating Marine Renewable Energy system arrays incorporating anchor sharing	wave power	195454.8
2014	H2020	SEAMETEC	Closed	2014-10-01	651752	SME-1	Smart Efficient Affordable Marine Energy Technology Exploitation using Composites	tidal energy	50000
2023	HORIZON EUROPE	SEASTAR	Signed	2023-12-01	101136149	HORIZON-IA	Sustainable European Advanced Subsea Tidal Array	tidal energy	3360346.26
2020	H2020	SeaTech	Signed	2020-06-01	857840	IA	Next generation short-sea ship dual-fuel engine and propulsion retrofit technologies	wave power	4999243
2018	H2020	SEA-TITAN	Closed	2018-04-01	764014	RIA	SEA-TITAN: Surging Energy Absorption Through Increasing Thrust And efficieNcy	wave power	3890341.75
2024	HORIZON EUROPE	SHY	Signed	2024-04-01	101147456	HORIZON-RIA	SEAWATER HYDRAULIC PTO USING DYNAMIC PASSIVE CONTROLLER FOR WAVE ENERGY CONVERTERS	wave power	3811110.32
2020	H2020	SmartWings	Terminated	2020-09-01	101010259	SME-2	Ground-breaking retractable ship bow foils for unbeatable cost-saving, emission reduction and motion stabilization	wave power	2110092.25
2015	H2020	STARMAS	Closed	2016-05-01	657539	MSCA-IF	Structured Training and Advanced Research in Marine Active Structures	wave power	158010
2017	H2020	SUBPORT	Closed	2017-06-01	775337	SME-1	Subsea socket for offshore Platforms based on Tide turbines	wave power	50000

2015	H2020	SWARMs	Closed	2015-07-01	662107	RIA	Smart and Networking UnderWAter Robots in Cooperation Meshes	wave power	6389046.38
2015	H2020	TEMPERATE CO2	Closed	2015-05-01	672626	SME-1	TEMPERATE WELDING	wave power	50000
2023	HORIZON EUROPE	THANAFSI	Signed	2023-09-01	101109475	HORIZON-TMA-MSCA-PF-EF	Theoretical analysis of fluid-structure interaction problems and applications	wave power	172750.08
2018	H2020	The Blue Growth Farm	Closed	2018-06-01	774426	IA	Development and demonstration of an automated, modular and environmentally friendly multi-functional platform for open sea farm installations of the Blue Growth Industry	wave power	7602873
2015	H2020	TidalHealth	Closed	2015-03-01	663953	SME-1	Health Condition Monitoring of Small Scale Tidal Generators Using Miniature Torque Sensors	tidal energy	50000
2016	H2020	TIPA	Closed	2016-11-01	727793	RIA	Tidal Turbine Power Take-Off Accelerator	tidal energy	4401565.25
2015	H2020	UPWAVE	Terminated	2016-02-01	691799	IA	Demonstration of a 1-MW wave energy converter integrated in an offshore wind turbine farm	wave power	20722489.88
2020	H2020	VALID	Signed	2020-12-01	101006927	RIA	Verification through Accelerated testing Leading to Improved wave energy Designs	wave power	4993651.25
2018	H2020	W2EW	Closed	2019-01-01	831041	IA	New combined solution to harness wave energy full renewable potential for sustainable electricity and fresh water production	wave power	3000000
2017	H2020	W2O	Closed	2018-01-01	789695	SME-1	Demonstration of the economic feasibility of a wave-powered desalination system	wave power	50000
2017	H2020	WATEC	Closed	2017-05-01	773606	SME-1	Development of a novel wave tidal energy converter (WATEC) to lower renewable electricity generation costs.	tidal energy	50000
2019	H2020	Wave Scale	Closed	2019-05-01	867793	SME-1	Bringing wave power to a cost competitive level and commercial scale	wave power	50000
2016	H2020	WaveBoost	Closed	2016-11-01	727598	RIA	Advanced Braking Module with Cyclic Energy Recovery System (CERS) for enhanced reliability and performance of Wave Energy Converters	wave power	3988744
2018	H2020	Wavepiston	Signed	2018-12-01	830036	SME-2	Competitive Wave Energy on Islands	wave power	2499999
2015	H2020	Wavepiston	Closed	2015-02-01	663466	SME-1	Low price wave energy conversion through force cancellation.	wave power	50000
2018	H2020	WAVREP	Closed	2018-05-01	787344	MSCA-IF	WAVe Resource for Electrical Production	wave power	165598.8

2022	HORIZON EUROPE	WEDUSEA	Signed	2022-09-01	101075527	HORIZON-IA	Wave Energy Demonstration at Utility Scale to Enable Arrays	wave power	9636874.38
2015	H2020	WETFEET	Closed	2015-05-01	641334	RIA	Wave Energy Transition to Future by Evolution of Engineering and Technology	wave power	3456883.25

Annex 3 Energy System Models and Scenarios: POTEnCIA and POLES-JRC

AN 3.1 POTEnCIA Model

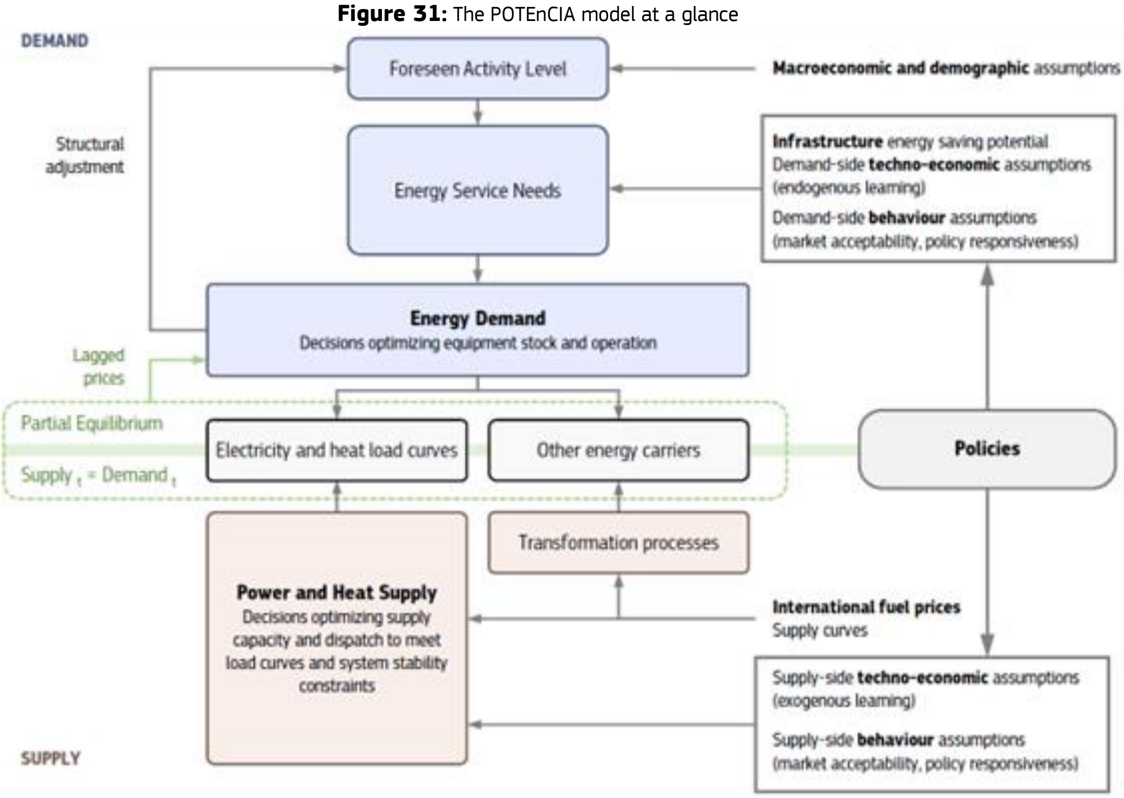
AN 3.1.1 Model Overview

The Policy Oriented Tool for Energy and Climate Change Impact Assessment (POTEnCIA) is an energy system simulation model designed to compare alternative pathways for the EU energy system, covering energy supply and all energy demand sectors (industry, buildings, transport, and agriculture). Developed in-house by the European Commission's Joint Research Centre (JRC) to support EU policy analysis, POTEnCIA allows for the joint evaluation of technology-focused policies, combined with policies addressing the decision-making of energy users. To this end:

- By simulating decision-making under imperfect foresight at a high level of techno-economic detail, POTEnCIA realistically captures the adoption and operation of new energy technologies under different policy regimes;
- By combining yearly time steps for demand-side planning and investment with hourly resolution for the power sector, POTEnCIA provides high temporal detail to suitably assess rapid structural changes in the EU's energy system;
- By tracking yearly capital stock vintages for energy supply and demand, POTEnCIA accurately represents the age and performance of installed energy equipment, and enables the assessment of path dependencies, retrofitting or retirement strategies, and stranded asset risks.

The core modelling approach of POTEnCIA (Figure 31; detailed in Mantzos et al., 2017, 2019) focuses on the economically-driven operation of energy markets and corresponding supply-demand interactions, based on a recursive dynamic partial equilibrium method. As such, for each sector of energy supply and demand, this approach assumes a representative agent seeking to maximize its benefit or minimize its cost under constraints such as available technologies and fuels, behavioural preferences, and climate policies.

Figure 31: The POTEnCIA model at a glance



Source: JRC adapted from (Mantzos et al., 2019)

This core modelling approach is implemented individually for each EU Member State to capture differences in macroeconomic and energy system structures, technology assumptions, and resource constraints. The national model implementation is supported by spatially-explicit analyses to realistically define renewable energy potentials and infrastructure costs for hydrogen and CO_2 transport. Typical model output is provided in annual time steps over a horizon of 2000-2070; historical data (2000-2021) are calibrated to Eurostat and other official EU statistics to provide accurate initial conditions, using an updated version of the JRC Integrated Database of the European Energy System (JRC-IDEES; Rózsai et al., 2024).

AN 3.1.2 POTEnCIA CETO 2024 Scenario

The technology projections provided by the POTEnCIA model are obtained under a climate neutrality scenario aligned with the broad GHG reduction objectives of the European Green Deal. As such, this scenario reduces net EU GHG emissions by 55% by 2030 and 90% by 2040, both compared to 1990, and reaches net zero EU emissions by 2050. To model suitably the uptake of different technologies under this decarbonisation trajectory, the scenario includes a representation at EU level of general climate and energy policies such as emissions pricing under the Emissions Trading System, as well as key policy instruments that have a crucial impact on the uptake of specific technologies. For instance, the 2030 energy consumption and renewable energy shares reflect the targets of the EU's Renewable Energy Directive and of the Energy Efficiency Directive. Similarly, the adoption of alternative powertrains and fuels in transport is consistent with the updated CO_2 emission standards in road transport and with the targets of the ReFuelEU Aviation and FuelEU Maritime regulations. A more detailed description of the *POTEnCIA CETO 2024 Scenario* will be available in the forthcoming report (Neuwahl et al., 2024).

AN 3.2 POLES-JRC model

AN 3.2.1 Model Overview

POLES-JRC (Prospective Outlook for the Long-term Energy System) is a global energy model well suited to evaluate the evolution of energy demand and supply in the main world economies with a representation of international energy markets. It is a simulation model that follows a recursive dynamic partial equilibrium method. POLES-JRC is hosted at the JRC and was designed to assess global and national climate and energy policies.

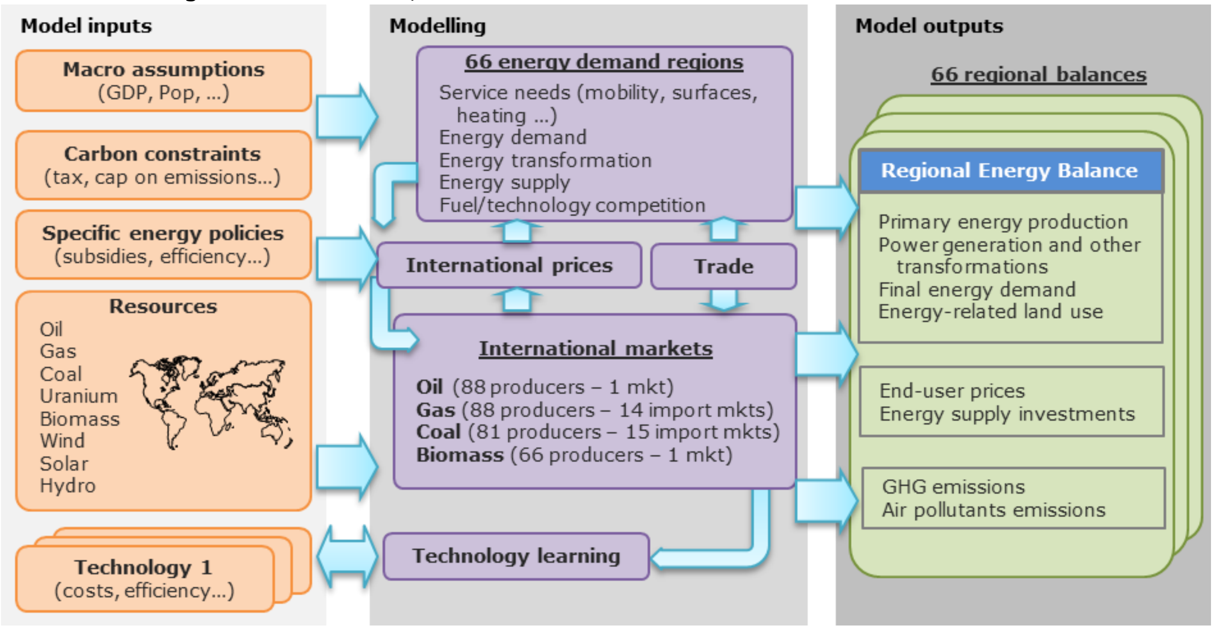
POLES-JRC covers the entire energy system, from primary supply (fossil fuels, renewables) to transformation (power, biofuels, hydrogen and hydrogen-derived fuels such as synfuels) and final sectoral demand (industry, buildings, transport). International markets and prices of energy fuels are calculated endogenously. Its high level of regional detail (66 countries & regions covering the world with full energy balances, including all detailed OECD and G20 countries) and sectoral description allows assessing a wide range of energy and climate policies in all regions within a consistent global frame: access to energy resources, taxation policy, energy efficiency, technological preferences, etc. POLES-JRC operates on a yearly basis up to 2100 and is updated yearly with recent information.

The POLES-JRC model applied for the CETO project is specifically enhanced and modified to capture learning effects of clean energy technologies.

POLES-JRC results are published within the series of yearly publications "Global Climate and Energy Outlooks" – GECO. The GECO reports along with detailed country energy and GHG balances and an on-line visualisation interface can be found at: https://joint-research-centre.ec.europa.eu/scientific-activities-z/geco_en

A detailed documentation of the POLES-JRC model is provided in (Després et al., 2018).

Figure 32: Schematic representation of the POLES-JRC model architecture.



Source: POLES-JRC model

AN 3.2.2 POLES-JRC Model description

Power system

The power system considers all relevant power generating technologies including fossil, nuclear and renewable power technologies. Each technology is modelled based on its current capacities and techno-economic characteristics. The evolution of cost and efficiencies are modelled through technology learning.

With regard to the power technologies covered by CETO, the model includes solar power (utility-scale and residential PV, concentrated solar power), wind power (on-shore and off-shore), hydropower and ocean power. Moreover, clean thermal power technologies are taken into account with steam turbines fuelled by biomass, biomass gasification, CCS power technologies and geothermal power. Furthermore, electricity storage technologies such as pumped hydropower storage and batteries are also included.

For solar and wind power, variable generation is considered by representative days with hourly profiles. For all renewables, regional resource potentials are considered.

Electricity demand

Electricity demand is calculated for all sectors taking into account hourly fluctuations through the use of representative days. Clean energy technologies using electricity consist of heat pumps (heating and cooling), batteries and fuel cells in transport, and electrolysers.

Power system operation and planning

Power system operation allocates generation by technology to each hour of representative days, ensuring that supplying and storage technologies meet overall demand, including grid imports and exports. Capacity planning considers the existing power mix, the expected evolution of electricity demand as well as the techno-economic characeristics of the power technologies.

Hydrogen

POLES-JRC takes into account several hydrogen production routes: (i) low temperature electrolysers using power from dedicated solar. wind and nuclear plants as well as from the grid, (ii) steam reforming of natural gas (with and without CCS), (iii) gasification of coal and biomass (with and without CCS), (iv) pyrolysis of gas and biomass as well as (v) high temperature electrolysis using nuclear power.

Hydrogen is used as fuel in all sectors including industry, transport, power generation and as well as feedstock for the production of synfuels (gaseous and liquid synfuels) and ammonia. Moroever, hydrogen trade is modelled, considering hydrogen transport with various means (pipeline, ship, truck) and forms (pressurised, liquid, converted into ammonia).

Bioenergy

POLES-JRC receives information on land use and agriculture through a soft-coupling with the GLOBIOM-G4M model (IIASA, 2024). This approach allows to model bioenergy demand and supply of biomass adequately by taking into account biomass-for-energy potential, production cost and reactivity to carbon pricing.
Biomass is used for power generation, hydrogen production and for the production of 1st and 2nd generation of liquid biofuels.

Carbon Capture Utilization and Storage (CCUS)

POLES-JRC uses CCUS technologies in:

- Power generation: advanced coal using CCS, coal and biomass gasification with CCS, and gas combined cycle with CCS.
- Hydrogen production: Steam reforming with CCS, coal and biomass gasification with CCS, and gas and biomass pyrolysis.
- Direct air capture (DAC) where the CO_2 is either stored or used for the production of synfuels (gaseous or liquid).
- Steel and cement production in the industrial sector.
- Second generation biofuels production.

The deployment of CCS technologies considers region-specific geological storage potentials.

Endogenous technology learning

The POLES-JRC model was enhanced to capture effects of learning of clean energy technologies. To capture these effects, a one-factor learning-by-doing (LBD) approach was applied to technologies and technology sub-components, aiming at endogenising the evolution of technology costs.
POLES-JRC considers historical statistics and assumptions on the evolution of cost and capacities of energy technologies until the most recent year available (this report: 2022/2023). Based on the year and a capacities threshold, the model switches from the default time series to the endogeneous modelling with the one-factor LBD approach. Within the LBD, the learning rate represents the percentage change of the cost of energy technology based on a doubling of the capacity of the energy technology.
This generic approach is applied on a component level to capture spillover effects as well. For instance, a gasifier unit is used as component for several power generating technologies (e.g. integrated gasification combined cycle, IGCC) as well as for several hydrogen production technologies (e.g. gasification of coal and biomass). Therefore, the component-based LBD approach allows to model spillover effects not only across technologies, but also across sectors. Also, it allows to estimate costs for emerging technologies for which historical experience does not yet exist.
Moreover, for each component a floor cost is specified which marks the minimum for the component's investment cost and serves as limitation for the cost reduction by endogenous learning. Cost reductions by learning in POLES-JRC slow down when the investment cost approaches the floor cost.
The described method above applies not only for the overnight investment cost of energy technologies, but as well for operation and maintenance (OM) costs, which also decrease as technologies improve, and for efficiencies. In the model, OM costs diminish synchronously to the decrease of total investment cost of the technology. The efficiency of renewables is implicitly taken into account in the investment cost learning and the considered renewable potentials. For most technologies the efficiencies are endogenously modelled.

AN 3.2.3 Global CETO 2°C scenario 2024

The global scenario data presented in the CETO technology reports 2024 refers to a 2°C scenario modelled by the POLES-JRC model in a modified and enhanced version to address the specific issues relevant for the CETO project.
The *Global CETO 2°C scenario 2024* and its specific POLESJRC model configuration is described in detail in the forthcoming report "*Impacts of enhanced learning for clean energy technologies on global energy system scenario*" (Schmitz et al., 2024).
The *Global CETO 2°C scenario 2024* is designed to limit global temperature increase to 2°C at the end of the century. It is driven by a single global carbon price for all regions that reduces emissions sufficiently so as to limit global warming to 2°C. This scenario is therefore a stylised representation of a pathway to the temperature targets. This scenario does not consider financial transfers between countries to implement mitigation measures. This is a simplified representation of an ideal case where strong international cooperation results in concerted effort to reduce emissions globally; it is not meant to replicate the result of announced targets and pledges, which differ greatly in ambition across countries.
As a starting point, for all regions, it considers already legislated energy and climate policies (as of June 2023), but climate policy pledges and targets formulated in Nationally Determined Contributions (NDCs) and Long-Term Strategies (LTSs) are not explicitly taken into account. In particular, the EU Fit for 55 and RePowerEU packages are included in the policy setup for the EU. Announced emissions targets for 2040 and 2050 for the EU are not considered.
The *Global CETO 2°C scenario 2024* differs fundamentally from the *Global CETO 2°C scenario 2023* used in the CETO technology reports in 2023 in various aspects[1]:

- The version of the POLES-JRC model used for the Global CETO 2°C scenario has been further enhanced and modified to capture effects of endogenous learning of clean energy technologies and, furthermore, several technology representations were further detailed, e.g. DAC (composition of renewable technologies, batteries and DAC unit), fuel conversion technologies (for hydrogen transport) and batteries in transport.
- The techno-economic parameters have been thoroughly revised and updated taking into account the expertise of the authors of the CETO technology reports.

As a result, major scenario differences occur in the *Global CETO 2°C scenario 2024* regarding DAC, synfuels, CCS power technologies, wind power and ocean power.

AN 3.3 Distinctions for the CETO 2024 Scenarios - POLES-JRC vs. POTEnCIA

The results of both models are driven by national as well as international techno-economic assumptions, fuel costs, as well as policy incentives such as carbon prices. However, on one side these two JRC energy system models differ in scope and level of detail, on the other side the definitions of the POTEnCIA and POLES-JRC scenarios presented in this document follow distinct logics, leading to different scenario results:

- The *Global CETO 2°C scenario 2024* (POLES-JRC) scenario is driven by a global carbon price trajectory to limit global warming to 2°C, where enacted climate policies are modelled, but long-term climate policy pledges and targets are not explicitly considered. Scenario results are presented for the global total until 2100.
- The *POTEnCIA CETO 2024 scenario* is a decarbonisation scenario that follows a trajectory for EU27's net GHG emissions aligned with the general objectives of the European Climate Law (ECL) taking into consideration many sector-specific pieces of legislation. Scenario results are presented for the EU27 until 2050.

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