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OFFSHORE WIND ENERGY POTENTIAL IN EUROPE: A FORECAST OF INSTALLED CAPACITIES AND COSTS

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Abstract. Offshore wind installation targets of EU Member States were considered. The analysis of the national plans showed that EU target can be exceeded, provided the appropriate resources are committed: offshore space, capital and supply chain. Spatial plans were analyzed and the need for the number of installed turbines was determined. The capital needs to cover the costs of investment outlays were analyzed. A projection for the number of wind turbines installed in Europe up to 2030 was presented. The analysis identified how the resources committed to the targets will contribute to: the generation of electricity, the reduction in greenhouse gas emissions and contribution to improving Europe's energy independence.

Keywords: decarbonization, energy, energy transformation, European Union, Green Deal, maritime spatial plan, offshore wind.

Introduction

Offshore wind energy is one element of the energy transition in Europe (EC, 2019). The development of this form of energy production has been ongoing for 20 years, dictated primarily by the demand for access to cheap renewable energy. Already in 2009, the European Parliament and the Council of the European Union (EU) adopted Directive 2009/28/EC, which set a target of a minimum 20% share of renewable energy consumption by 2020 (EP, 2008). By signing the Paris Agreement in 2016, the EU committed to increase the share of renewable energy to 32% by 2030 and reduce greenhouse gas emissions (UN, 2015). However, after 2022, when the European energy industry was shaken by the disruption of energy supplies, EU Member States (MS) changed their approach to energy (Sturm, 2022). Even greater importance has been given to the European energy transition, which, in addition to its mission to reduce greenhouse gas emissions, also carries the possibility of increasing European energy independence (Kuzemko et al., 2022). According to the EU's Green Deal policy, decarbonization is one of the primary goals of the Energy Transition. Other goals set out in the Green Deal concern rebuilding economic potential after the COVID pandemic and ensuring the competitiveness of European industry, based on green technologies (EC, 2019). The outbreak of the energy crisis in Europe exposed its dependence on Russian fossil fuels. In response to energy supply constraints and price volatility, the European Commission prepared the REPowerEU program, which aims to make Europe less dependent on Russian fossil fuel imports while increasing the importance of renewable energy sources (EC, 2022; Lonergan et al., 2022).

As a result of the disruption to the existing European energy structure, the offshore wind installation targets set by individual EU MS have changed. Many countries have decided to enlarge their plans for installing offshore wind farms. This has resulted in challenges that need to be addressed in order to successfully meet the targets for offshore wind farm installations.

There are valuable investment-specific multi-criteria assessment studies in the literature that assess the development potential of a given offshore wind farm project based on a number of factors (Ziemba, 2022). There are also sustainability indices that allow the assessment of progress towards achieving sustainable development in relation to policies, regions or nations (Ziemba et al., 2022). To the author's knowledge, there is a lack of up-to-date research about how to place the European offshore wind development plans in the broad context of the post-war energy transition in Europe, i.e., within a framework of spatial, financials and manufacturing aspects. This article analyzes the direction of offshore wind energy development in Europe, taking into account selected resources needed to meet the objectives of offshore wind farm installations: the marine space allocated for energy development, according to the maritime spatial plans; capital to cover necessary expenditures; and supply chains able to deliver components in a timely manner and at acceptable prices.

The development of offshore wind energy is one of the elements that increases the pressure on the marine ecosystem. In order to manage maritime space in a sustainable and efficient way, the EU has adopted a directive on the need to plan maritime space taking into account the many activities taking place at sea, including the development of renewable energy sources (EU, 2014). Efforts to plan appropriately for the use of marine space for activities that may be mutually exclusive cannot completely eliminate trade-offs (Püts et al., 2023), so access to marine space is a condition for offshore wind energy development. Spatial plans adopted by EU MS provide the basis for the offshore wind farm development process and allow the potential for electricity generation to be estimated.

Figure 1 presents the two sides of the offshore wind farm process: the resources required for the investment and the expected outcomes resulting from the construction of an offshore wind farm.

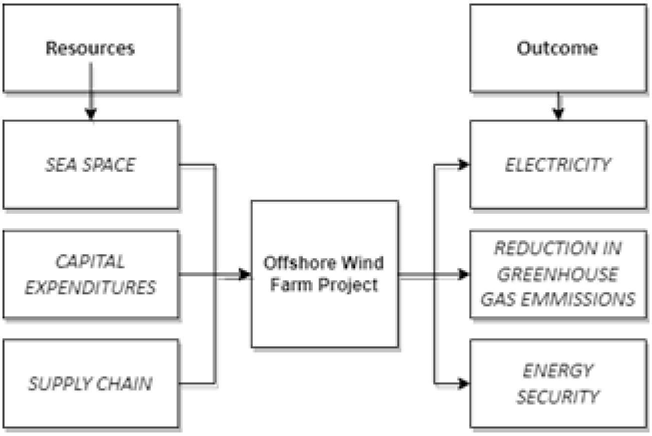

Figure 1. Selected resources required for offshore wind farms and expected investment outcomes

The parameters investigated were attempted to be selected in such a way as to present a maximally objective and up-to-date picture of the current state of offshore wind energy development in Europe, based on available data and information. It should be acknowledged that an undoubted research difficulty is the attempt to juxtapose the historical data available on the market, with planned development of the sector. Analysis of data on existing wind farms is used to prepare technical assumptions (distance from land, depth of foundation, type of foundation) for future projects in individual EU MS. The purpose of this article is to assess the resources for future wind farm development and to forecast its impacts that will materialize before 2030. However, the offshore wind sector is subject to dynamic changes that are caused by a number of factors, such as changes in technology, developments in the supply chain, economic changes, and other developments. The medium-term forecast up to 2030 coincides with EU targets and country-specific declarations for the realization of wind farm installations. At the same time, there is enough data on the expected dynamics of change in this period to make realistic assumptions and, based on these, to come up with a forecast based on concrete numbers.

This paper therefore seeks to identify the most important aspects of offshore wind development in the EU and the UK that can be analyzed in a measurable way and, based on the data collected, to determine the potential for installing the assumed generation capacity within a given timeframe. The paper takes into consideration the required commitment of capital and supply chain that will be needed to meet the targets, the availability of maritime space, and the possible obstacles that may cause difficulties in the implementation of current European energy policy.

The research in this paper is guided by two scientific questions, that delimit the scope of the analysis:

1. What resources are required to meet the goals of installing offshore wind power in Europe by 2030, and how are they to be measured?
2. How to measure the importance of offshore wind energy for the European energy transition up to 2030?

Chapter one presents the current importance and status of offshore wind energy development. The assumptions and calculation methods used, including projections, are presented in the methodology chapter. The results of the analyses and data compilation are presented next, with emphasis on the data on the assumed installed capacity and the amount of energy produced per year, and the expected results in terms of greenhouse gas emissions reduction are computed. In the chapter presenting the results, data on the ability to meet demand for offshore wind farm components (turbines) against planned demand up to 2030 is presented. The final part contains a discussion and proposal on the conclusions that can be drawn from the analyzed data.

Current role of offshore wind energy and potential for development

Currently, EU MS and United Kingdom (UK) have a total of around 32 GW of installed offshore wind farm capacity provided by approximately 6,300 turbines. The European leader in offshore wind farm development in Europe has for years been the UK, which has 13.7 GW of installed wind farm capacity provided by more than 2,700 operating turbines. The 11 EU MS that have managed to start generating electricity from offshore wind farms have 3,549 turbines with a total capacity of around 18 GW.

The EU target for the installation of offshore wind farms is currently set at 60 GW by 2030 and 300 GW by 2050 (EC, 2020). The EU identifies the capacity to install offshore wind farms as crucial to achieving the targets set in the European Green Deal. In order to accelerate the development of this energy sector, initiatives dedicated to two seas have been set up: the North Seas Energy Cooperation (NSEC) and the Baltic Energy Interconnection Plan (BEMIP). Individual EU countries set their own targets for the installation of offshore wind farms, which in total exceed the common EU target. Table 1 shows the targets of individual EU MS and UK that still seems to play an important role in achieving the final outcome of the European energy transformation and climate neutrality.

Table 1. Current status of offshore wind energy in EU MS and UK and adopted installation target by 2030

Country	Number of turbines installed (units) at the end of 2022	Actual installed capacity (GW) at the end of 2022	Planned capacity target by 2030 (GW)
Belgium	399	2.23	5.8
Denmark	648	2.47	12.9
Finland	11	0.04	2.0
France	81	0.48	5.2
Germany	1,556	8.11	30.0
Ireland	7	0.03	7.0
Italy	10	0.03	0.9
Netherlands	739	4.53	21.0
Portugal	3	0.03	9.0
Spain	1	0.05	3.0
Sweden	80	0.19	4.0
Poland	0	0.00	5.9
Lithuania	0	0.00	1.4
Latvia	0	0.00	0.4
Estonia	0	0.00	1.2
Romania	0	0.00	0.5
Greece	0	0.00	2.0
Total at national level of EU Member States	3,549	18.18	111.2
European Union	**3,549**	**18.18**	**60.0**
United Kingdom	2,766	13.70	50.0

Source: modified after Díaz and Guedes Soares (2020); Musial et al. (2022).

After the outbreak of war in Ukraine, in August 2022, eight EU Baltic Sea countries signed a joint declaration in Marienborg to install 20 GW of capacity in the Baltic Sea by 2030 (EU BSG, 2022). The associated countries have also declared a plan, based on the NSEC initiative, to install 76 GW of capacity by 2030 and 260 GW by 2050 (NSEC, 2022). Of the NSEC countries, Belgium, Denmark, Germany and the Netherlands may be the leaders in offshore wind development, having announced a plan to install 150 GW of capacity by 2050 (ED, 2022). The assumed targets for offshore wind farm installations announced by the three European agreements, independently of the target set by the European Commission, are summarised in Table 2.

The presented targets for the installation of offshore wind farms in EU MS, in addition to access to offshore space, also require supply chain capacity to access the products and services needed to meet the growing installation targets. While interest in the supply chain for renewables has been the subject of research for years (Wee et al., 2012), the study of the supply chain for offshore wind farms, does not appear to have been widely undertaken in the literature (Poulsen & Lema, 2017). This issue has received attention in recent years, due to the rapidly increasing installation pipelines of offshore wind farms, which require access to components at a specific time in order to effectively manage the supply chain (Irawan et al., 2018). One indicator for the supply chain is the number of wind turbines planned for installation by 2030, in order to estimate the scale of demand that developers with projects in Europe will submit in the coming years.

Table 2. Installation targets of offshore wind energy joint transnational agreements

Transnational Agreement	Signatory States	Actual installed capacity (GW) at the end of 2022	Planned capacity target 2030 (GW)	Planned capacity target 2050 (GW)
The Marienborg Declaration signed by BEMIP Members	Poland, Germany, Denmark, Sweden, Finland, Lithuania, Latvia, Estonia	2.6	20	–
The Esbjerg Declaration	Belgium, Denmark, Germany, the Netherlands	15.2	65	150
North Seas Energy Cooperation	Belgium, Denmark, Germany, Netherlands, France, Ireland, Luxembourg, Norway	15.8	76	260
European Union	**European Commission**	**18.18**	**60**	**300**

Source: EU BSG (2022); EC (2020); ED (2022); NSEC (2022).

Methods

The aim of this paper is to provide answers to the research questions posed, namely: 1. What resources are required to meet the goals of installing offshore wind power in Europe by 2030, and how are they to be measured? 2. How to measure the importance of offshore wind energy for the European energy transition up to 2030?

In order to find possible answers, appropriate research methods and data on offshore wind energy development in Europe were selected. Data on existing wind farms as well as individual governments' plans for offshore wind farm development over a specific timeframe, expressed in terms of so-called offshore wind farm installation targets, were used. The source of information on existing wind farms was the database from the 4C Offshore portal (4C Offshore, 2023). As the individual EU countries create their own policies for offshore wind farm development, so-called interim targets were used, whereby common target dates were set in order to be able to make projections for reduction in greenhouse gas emissions and the offshore spaces needed to be developed to meet the targets.

The possibility to develop offshore wind farms requires the availability of a significant amount of offshore space. As offshore wind energy grows, the average value of offshore space and the installed capacity of a single wind farm increases (Bilgili & Alphan, 2022). The selection of the offshore spaces that will enable the allocation of offshore wind farms lies within the scope of the maritime spatial plans prepared by individual countries (Zaucha et al., 2020a). The selection of space for the development of offshore wind farms is crucial in terms of the attractiveness of realizing investments in a given area, due to distance from the shore, windiness, water depth, distance from the installation port and service port (Przedrzymirska et al., 2021). When designating areas for the development of offshore wind farms, planners must take into account the need to limit other economic activities, such as fishing and other social and economic activity accompanying the addition of a new dimension to the maritime space (Ciołek et al., 2018; Zaucha, 2018). The preparation of maritime spatial plans requires taking into account multiple — often conflicting — interests and finding solutions that will most effectively realize them mutually (Zaucha et al., 2020b). The efficiency resulting from the construction of offshore wind farms in offshore spaces can be measured by the relation of the designated space to the expected renewable energy production, which influences decarbonization and increased energy security.

The maritime spatial plans of EU MS were analyzed. According to the analysis, the value of marine space designated for offshore wind farm development in the EU is 55,816 km^2. Table 3 presents the value of areas designated for offshore wind energy development together with the share of the given space form in the total value of the maritime spatial development plan in the exclusive economic zone of the country.

The countries' maritime spatial plans, which determine what space will be allocated for offshore energy development, were also analyzed. The maritime spaces designated for offshore wind energy development were reviewed on a European scale. The table does not include the offshore areas designated for offshore wind farm development in countries that have not yet adopted an offshore spatial plan.

Table 3. Areas designated for offshore wind power development

Country	**Area designated for offshore wind farm development (km^2)**	**Offshore exclusive economic zone allocation for construction of offshore wind farms (%)**
Belgium	519	15
Denmark	11,000	10
Finland	3,500	4.3
France	12,000	2.3–3.5
Germany	8,400	15
Ireland	1,000	0.2
Italy	No applicable maritime spatial development plan	–
Netherlands	3,400	5.9
Portugal	3,203	–
Spain	5,000	0.46
Sweden	1,400	1
Poland	3,600	12
Lithuania	644	9.4
Latvia	300	1
Estonia	1,850	5
Romania	No applicable maritime spatial development plan	–
Greece	No applicable maritime spatial development plan	–
European Union	**55,816**	

Source: EC (2023b).

In order to determine the potential assumed efficiency of offshore utilization, 87 European existing or planned offshore wind projects were analyzed. The analyzed projects were connected to the grid after 2019 or are planned to be connected to the grid before 2030. Consequently, projects with a total planned connection capacity of 113,913 MW, which have been or are planned to be built over an area of 19,728 km^2, were screened. The projects vary significantly in terms of the expected efficiency of installing offshore wind farm capacity in space; from 1.2 MW/km^2 (lowest space factor) to 18.8 MW/km^2 (highest space factor). This analysis covers the timeframe up to 2030 and therefore also applies to projects at an early stage of development, including potential installed capacity, in line with the set targets of the MS. On the basis of the analyzed data on project assumptions, the possibility of installing an average of 5.77 MW of capacity per 1 km^2 of offshore space in European marine waters was assumed. The maritime spatial plans of EU countries that have published such plans have also been analyzed.

The capital expenditure required for the construction of offshore wind farms was determined on the basis of the selected technology, using the offshore wind farm construction cost allocation model prepared by the UK Department for Business, Energy and Industrial Strategy (Freeman & Blanch, 2021). Different capital expenditures were assumed depending on the chosen foundation technology. The analysis covers projects using different types of foundations: bottom-fixed and floating. Fixed foundation technology (monopiles) was adopted as typical for wind farms installed in Europe by 2030 (Díaz & Guedes Soares, 2020), with the exception of: France, Portugal, Italy, Greece and Spain, which are focusing on the development of floating offshore wind. The following parameters were assumed for wind farms installed with monopiles in water depth up to 25 meters: distance from operations and maintenance port: 40 km; average wind speed at 100 meters above water level: 9.4 m/s and CAPEX is assumed €1992 per installed MW. When the wind farm is installed on water depths between 25 and 60 meters, the foundation technology might be monopile or jacket and the CAPEX is assumed as €2126 per installed MW.

The feasibility of floating offshore wind technology in Europe by 2030 was also taken into consideration. It was assumed that 100% of the planned installed capacity for France, Portugal, Spain, Greece and Italy will be using semi-submersible technology by 2030 and UK will add another 1.2 GW. This assumption is based on the countries offshore wind development strategy and their natural conditions, primarily water depth. This could result in 20,713 MW of new installed floating offshore wind in Europe by 2030. Average parameters for floating wind technology were assumed as following: water depth: 60 meters and above; distance from O&M port: 40 km; average wind speed at 100 meters above water level: 9.7 m/s.

Table 4. Assumptions for determining the amount of capital expenditure (CAPEX) depending on the technology adopted

Assumptions	**Bottom-fixed (Monopile)**	**Bottom-fixed (Monopile or Jacket)**	**Semi-submersible (Floating)**
Water depth	up to 25 m	between 25 and 60 m	above 60 m
Distance from O&M port	40 km	40 km	40 km
Turbine size	18 MW	18 MW	18 MW
CAPEX breakdown: (€000s/MW)			
Project development	96	98	134
Turbine	925	925	947
Tower	81	81	155
Support structure	203	254	715
Array cables	26	26	31
Installation	149	209	97
Transmission supply and installation	379	391	442
Construction phase insurance	43	46	58
Construction contingency	91	97	123
SUM	**1,992**	**2,126**	**2,702**

Source: own calculation based on information from Innovation Impact on Levelized Cost of Energy Model (Freeman & Blanch, 2021).

On the basis of the adopted technological assumptions, the amount of investment necessary to bear the costs of construction of offshore wind power plants was determined, with a breakdown into individual components. The development of floating offshore wind technology was supposed to occur mainly in France, Portugal, Spain, Italy and Greece (water depth of more than 60 metres). In the other countries, the predominance of the use of monopiles or jackets to attach wind towers the seabed was presumed. Table 4 presents the financial data used for estimation of the construction costs of offshore wind power plants.

The increase in installation targets for offshore wind farms requires supply chains to adapt to meet new requirements. The number of turbines installed has been considered as one of the indicators relevant to shaping the supply chain for offshore wind in the EU and the UK. In order to estimate the demand for the number of turbines installed in Europe, a forecast of the growth in the generation capacity of a single turbine was executed (Bilgili & Alphan, 2022). An increase in the value of the installed capacity of a single turbine also implies a higher generation potential per km^2 of marine space (Fig. 2). Projections of installed turbine capacity were based on contracts concluded by offshore wind farm developers with turbine manufacturers and announcements by developers regarding the assumed installed turbine capacity.

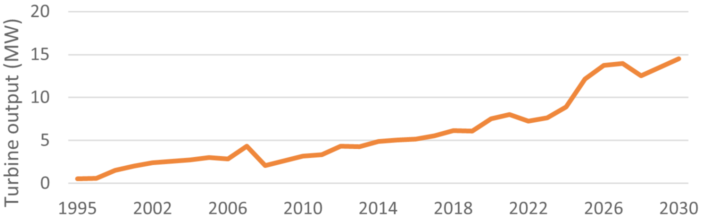

Figure 2. Average installed capacity per turbine in European offshore wind farms (EU and UK)
Source: modified after Bilgili and Alphan (2022).

Energy production from offshore wind farms depends on factors such as nominal power, hub height, rotor diameter, and windiness (Arrambide et al., 2019). Limitations in turbine availability (due to maintenance and breakdowns) and losses at different stages of energy transmission affect the energy actually delivered to the system. Table 5 presents the assumptions used to calculate the power generated from offshore wind farms installed in Europe. They are based on the information from the Innovation Impact on Levelized Cost of Energy Model (Freeman & Blanch, 2021).

Table 5. Assumptions made for the calculation of actual delivered electricity from offshore wind farms

Gross energy production	**4,906 (MWh/MW/year)**
Gross load factor	56%
Wind farm availability	95.6%
Aerodynamic array losses	6.1%
Electrical array losses	1.0%
Blockage effect	1.0%
Other losses	1.9%
Net load factor	48.3%

Source: Levelized Cost of Energy Model (Freeman & Blanch, 2021).

According to an assumed net load factor of 48.3%, 4,234 MWh is generated annually from every 1 GW of installed capacity of offshore wind farms.

Based on data on planned offshore wind farm installations, an analysis was made of the potential to reduce carbon emissions by changing the energy generation technology. The analysis was carried out in one of three possible scenarios depending on the original source of energy production to be replaced by offshore electricity generation. Data was taken from available studies, and emissions were assumed to be 16 gCO_2/kWhe for an offshore wind farm over its entire operating phase (including material generation and construction, operations and decommissioning phases) (Kaldellis & Apostolou, 2017). Assumptions for the value of carbon emission reductions are presented in the case of moving away from coal-fired, gas-fired and nuclear generation. Figure 3 shows the lifecycle carbon footprint for the compared power generation technologies: coal fired and natural gas-fired, nuclear, and offshore wind. According to the assumed values, offshore wind is the least carbon-intensive source of power generation among those analyzed, second only to onshore wind (Kaldellis & Apostolou, 2017).

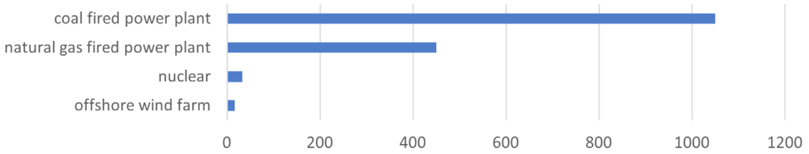

Figure 3. Comparison of the emissivity of electricity by generation source
Source: modified after Kaldellis and Apostolou (2017).

In line with the assumed difference in carbon intensity, a reduction greenhouse gas emissions was calculated in the case of replacement of electricity generation by offshore wind farms. In the case of replacement of electricity generation by offshore wind farms, a reduction of 4.38 Mt CO_2 per year was assumed for each gigawatt of installed capacity, which is a greater reduction than the International Energy Agency's figure of 3.5 Mt CO_2 per year (IEA, 2020). Similarly, based on the assumptions made, a reduction of 1.84 Mt CO_2 per year was calculated for the replacement of gas-fired power plants and 0.07 Mt CO_2 per year for the replacement of nuclear power plants. In order to obtain the results of the reductions in greenhouse gas emissions in the EU resulting from the installation of the assumed offshore wind farm capacities, a source substitution structure was assumed for the period 2019–2021, with the reduction in energy production coming most from gas-fired power plants (50%), nuclear power plants (35%) and, to the least extent, coal-fired power plants (15%) (Moore et al., 2022).

To determine the share of offshore wind energy in the EU energy mix, an increase in energy demand in the EU of 1% per year was assumed. According to Eurostat, electricity production in the 27 EU countries was 2.911 TWh in 2021 (Eurostat, 2023b). An average increase in energy production between 2022 and 2030 of 1% per year was assumed.

The construction of offshore wind farms makes it possible to achieve the energy transition and to reduce the carbon footprint of electricity generation in Europe. The construction of offshore wind farms requires a commitment of resources in the form of financial outlays and the designation of offshore space for the construction of offshore wind farms, as well as the capacity of the supply chain to ensure the availability of components for offshore wind farm installations (Freeman et al., 2019).

An area of 55,816 km^2 earmarked for offshore wind development could allow up to 323 GW of installed capacity to be realised, which would allow the EU target of installing 300 GW of offshore wind farms by 2050 to be surpassed. The designation of such areas for offshore wind energy development may therefore provide a rationale for assuming that the installation target for offshore wind energy in Europe might be surpassed as well. This is also indicated by the declarations of individual MS. The countries of the North Seas Energy Cooperation group have made a commitment to installing a total of 260 GW of offshore wind capacity by 2050, which is almost 87% of the EU target (EC, 2020; NSEC, 2022). Full utilization of the available offshore space requires a number of conditions to be met, among them: availability of capital, a supply chain capable of responding to market demand, available infrastructure, and many others.

To calculate the capital expenditure required to meet the installation targets for offshore wind turbines in each country, the capacity installation targets declared by each country were adopted. The cost of the capital expenditure was assumed in accordance with the assumptions presented in the methodology chapter. The capital expenditure was deemed to be €1992/MW installed capacity for bottom-fixed turbines in water depth up to 25 metres; €2126/MW in water depth between 25 and 60 metres, and 2702 €/MW capital expenditure for floating offshore-wind turbines (above 60 metres water depth). Based on the offshore wind auctions and water depths, the installation of floating-type turbines was assumed for France, Portugal, Spain, Italy, Greece and partly in UK. The amounts of capital expenditure (CAPEX) to meet the targets for installing offshore wind farms by 2030 are shown in Table 6.

Table 6. Projected investment in offshore wind farm projects by country

Country/Area	Planned capacity yet to be installed in order to meet the 2030 target (MW)	Forecasted installation cost (€ per MW) based on the technology adopted	Capital expenditure required to develop planned capacity in order to meet the 2030 target (€ billion)
Belgium	3,574	1,992	7.12
Denmark	10,427	1,992	20.77
Finland	1,956	2,031	3.97
France	4,718	2,702	12.75
Germany	21,890	2,031	44.46
Ireland	6,975	2,031	14.17
Italy	870	2,702	2.35
Netherlands	16,473	1,992	32.81
Portugal	8,975	2,702	24.25
Spain	2,950	2,702	7.97
Sweden	3,809	2,031	7.74
Poland	5,900	2,031	11.98
Lithuania	1,400	2,031	2.84
Latvia	400	2,031	0.81
Estonia	1,200	2,031	2.44
Romania	500	1,992	1.00
Greece	2,000	2,702	5.40
SUM for EU MS	94,017	-	202.83
United Kingdom	36,300	2,031 – bottom fixed 2,702 – floating offshore wind	97.28

Source: own calculations based on country declarations on the installation target for offshore wind energy and Innovation Impact on Levelised Cost of Energy Model (Freeman & Blanch, 2021).

On the basis of the assumptions made, the total investment for the realization of offshore wind farms was estimated to be up to €202.83 billion to meet the installation targets of individual EU MS. The UK's capital expenditure could reach the level of €97.28 billion. In the scenario of the most dynamic growth in installed capacity in Europe (EU and UK), the total investment in offshore wind farm construction could amount to €300 billion by 2030, in order to meet the stated targets of installing offshore wind capacity. The source of funding for offshore wind farm projects developed in Europe is private capital, which finances the project at different stages depending on the nature of the investment instrument. At the initial stage of a project, the development work typically is covered by the developer and then financed by private investors depending on their risk exposure strategy. Apace with the development of offshore wind technology, the value of the investment in a single project is increasing despite a reduction of Levelized Cost of Electricity (LCOE) indicator due to an increase in the average installed capacity per project (Rubio-Domingo & Linares, 2021; Shields et al., 2021a). There has also been a decline in expected returns on offshore wind farm investments over the past decade, due to the maturity of the sector and better risk identification. Depending on the stage of investment in a project, expected rates of return can range from 5% internal rate of return for projects in the operations phase, to 25% internal rate of return for projects in the early development phase, prior to permitting (Guillet, 2022).

Realizing such a rapid increase in the value of installed offshore wind capacity, however, requires not only capital investment, but also a prepared supply chain that is able to meet market demand (Poulsen & Lema, 2017). European offshore wind farms are dominated by turbines manufactured by three manufacturers: Siemens Gamesa, Vestas and General Electric. Historically, a maximum of around 500-600 turbines per year have been installed in Europe. In order to meet the installation targets, around 9,830 turbines will need to be installed between 2023 and 2030, most of which might be installed after 2027 due to the early stage of development of wind farm projects that plan to be online by 2030. This implies a dynamic, exponential increase in demand for turbines, wind towers, access to port facilities' services and installation vessels and crews, cables and all the components required to install offshore wind farms. As a result of the analysis of the installation plans of individual EU countries and the UK, and assumptions on the increase in the value of a single turbine's capacity, a forecast for the number of installed turbines in Europe has been prepared (Fig. 4). The available data shows approximately 6,300 in operation in Europe at the end of 2022. According to the forecast, a total of 16,130 turbines could be in operation at the end of 2030.

Achieving the planned capacity targets for offshore wind farms in Europe requires the installation of an additional 9,830 turbines between 2023 and 2030. However, this implies a significant development of the supply chain in Europe (Poulsen & Lema, 2017). Due to the relatively early stage of most European projects that are expected to contribute to the 2030 installation scenario, the installation of most turbines will fall between 2028 and 2030, a period that coincides with a very busy period of offshore wind development also outside Europe, including in the United States (US). The management of the European supply chain has its own characteristics because, despite expressing common targets through the regions, individual countries pursue their own policies to support the offshore wind industry and are responsible for preparing installation plans, auctioning space for wind farm development and adapting infrastructure. Like the US and the UK, the EU needs a common vision for offshore wind development to ensure that installation targets can be met and that the energy transition can be achieved. The US and UK are developing offshore wind with extensive use of the local supply chain (Allan et al., 2020; Shields et al., 2021b). The EU has put forward the Green Deal Industrial Plan for the Net-Zero Age as its response to the global supply chain situation for the renewables sector (EC, 2023a). One of the targets of the program is to mobilize a large pool of national and EU funds through the Recovery and Resilience Facility, Horizon Europe and the Just Transition Fund, among others (EC, 2023a). The current production capacity of offshore wind farm turbines in Europe is around 9.5 GW per year, and could reach 11.5 – from 2024, thanks to the work of the new turbine factory (Hutchinson & Zhao, 2023). The development of local supply chains can significantly contribute to the installation targets of offshore wind farms, but in the context of the assumed timeframe, the current stage of industry readiness may not be sufficient. Figure 5 shows the annual value of new offshore wind installations in Europe versus the capacity of European turbine manufacturing plants. The graph shows a possible lack of access to European-made turbines from 2027 if investments in increased turbine manufacturing capacity are not undertaken.

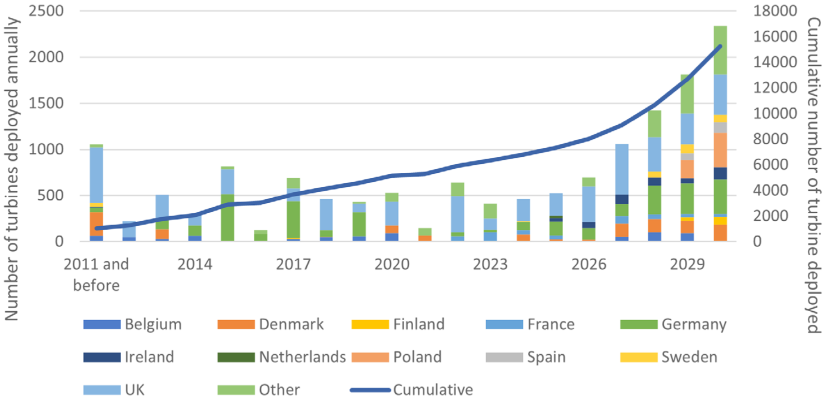

Figure 4. Forecasted number of offshore wind turbines deployed in Europe
Source: 4C Offshore (14.02.2023).

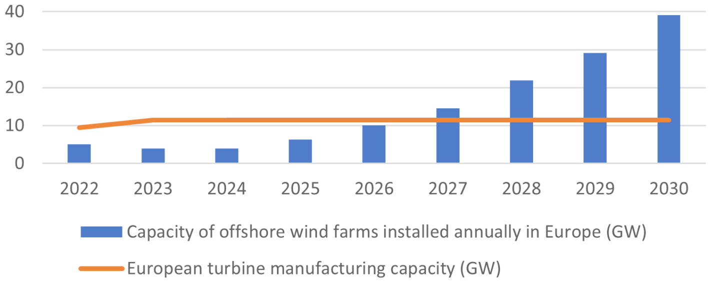

Figure 5. Annual installation of offshore wind turbines in Europe between 2022 and 2030 in relation to supply chain capacity
Source: annual new installation targets stated by EU MS (Hutchinson & Zhao, 2023).

Offshore wind farm developers have to use the principle of economic efficiency in their investment and supplier selection decisions, which does not always mean choosing a local supplier as the best option (van der Loos et al., 2022). One of the prerequisites for the development of an industrial base for realizing the energy transition with offshore wind energy is a long-term and credible plan for the development of this sector, which will allow private investors to commit resources to undertake capital expenditure. A significant investment risk for the offshore wind industry is the variability in component demand that results from overlapping investment plans of different offshore wind projects, while at the same time the need to maintain generation capacity during periods of reduced activity and market interest. The above considerations also apply to the necessary port infrastructure, installation vessels and personnel to cope with both installation ambitions and technological advances that require the adaptation of vessels and technical infrastructure.

Currently, the EU's energy mix is based primarily on the combustion of fossil fuels (coal and gas) and the production of energy by nuclear power plants. Of renewable energy, which accounts for almost 46% of EU energy production, wind and hydro are the most important (Eurostat, 2023a). Among wind power, onshore wind is dominant, but, with ambitious installation targets, the importance of offshore wind could increase in the coming years. Based on the assumptions made about the potential for offshore wind energy production in Europe, the annual value of electricity production in the EU was calculated. In 2021, the value of electricity generated by offshore wind farms will only allow 3.5% of the EU's energy needs to be met. The enormous potential of offshore wind farms to reduce the need for imported energy resources will make it possible to produce around 457 TWh of electricity from offshore wind farms by 2030, provided the targets are met (Table 7). This implies the possibility to increase the importance of offshore wind energy to around 14.4% of the EU energy mix.

Table 7. Electricity production from offshore wind farms installed in the EU

Year	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Offshore wind generation (TWh)	66.7	78.5	86.7	99.6	118.6	148.4	219.6	321.2	457.1

Source: own calculations based on: EU MS installation targets.

In order to estimate the generation potential for one square kilometer of offshore space, the possible electricity production from a theoretical 5.77 MW turbine installed under European conditions was calculated. Based on the assumptions made, the potential to generate 24,430 MWh of electricity on an annual basis was calculated from each kilometer of offshore wind space where offshore wind farms are located. The indicated value refers to new wind power plants with the high efficiency and effectiveness assumed for offshore wind farms installed after 2022. The projected value can serve as an element of the evaluation of spatial rents resulting from the use of space for a given type of activity and thus allow for the inclusion of indicators related to sustainable electricity generation in the management of marine space (Gilek et al., 2021).

Another indicator is the possibility of reducing carbon dioxide emissions due to the transition from energy production based on the current energy mix to the replacement of conventional sources of electricity generation by offshore wind farms. Based on the assumptions made, the annual and cumulative reduction in greenhouse gas emissions due to the replacement of power stations (according to the adopted methodology) by offshore wind farms was calculated. The annual reduction in carbon dioxide emissions in the EU, resulting from the installation of offshore wind farms, amounted to approximately 36.6 Mt in 2022, and could be as much as 184.6 Mt in 2030. The cumulative reduction in greenhouse gas emissions, due to the installation of 115 GW of offshore wind power, could amount to 886.7 Mt.

The expected value of reduction in greenhouse gas emissions from the construction of an offshore wind farm in an area of one square kilometer is 9,235 tons per year, for the assumptions made (Fig. 6).

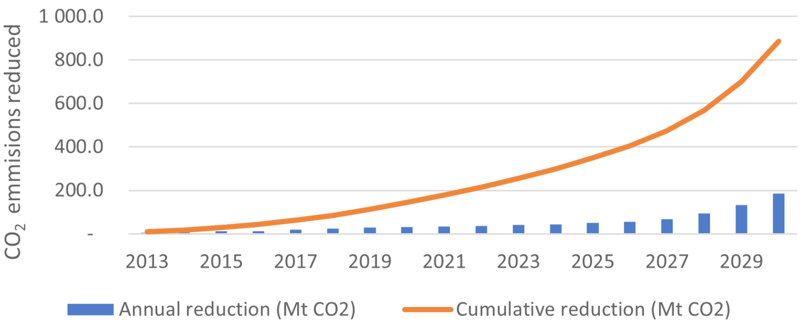

Figure 6. Reduction in carbon dioxide emissions in Europe due to the installation of offshore wind farms, under the assumed scenario of installing new plants by 2030
Source: own calculations based on: EU MS installation targets (Kaldellis & Apostolou, 2017).

Discussion and conclusion

The calculations made show the potential of offshore wind energy to meet the targets set in the European Green Deal and REPowerEU strategy. European countries undertook a significant increase in the installation dynamics of offshore wind farms, following energy crisis in Europe. However, it should be borne in mind that such a significant acceleration of the energy transition based on offshore resources must not violate planning processes for marine spaces.

Most EU countries have already adopted Maritime Spatial Plans that provide for the allocation of significant marine areas for offshore energy development. At the same time, increasing the efficiency of space use, thanks to technological advances including the rapid increase in the size of a single turbine installed at sea, will allow countries to make even better use of marine space for energy purposes. On many occasions, it may turn out that the generation potential of specific offshore areas is higher than the planners had assumed.

Many of Europe's offshore wind farm projects are currently in the early stages of development, which requires going through a process of permitting, environmental impact assessment and environmental clearance. This multi-year process is important as it allows potential conflicts of interest to be identified and managed at an early stage and allows the work started at the spatial planning stage to continue. The identification of a given marine space as a space with potential for offshore energy development also determines the possibility of developing the local economy and community, changing its character and carrying both potential benefits and costs (Laskowicz, 2021). Adequate management of the marine space at the stage of its inclusion in the spatial development plan and then through continued dialogue between different interest groups is important for the feasibility of offshore wind farm projects, with an appropriate level of public acceptance (Lamy et al., 2020). The changes brought about by offshore energy transformation requires working with local communities and local economic actors to increase public acceptance of the changes (Haraldsson et al., 2020). Suitable communication and community education can serve to engage communities in offshore energy development (Ciołek et al., 2018) and transform the local economy, which in coastal areas is currently focused on tourism and fishing (Szejgiec-Kolenda et al., 2018). Some of the elements that influence perceptions of offshore wind energy development are distance from the shore, environmental impact, landscape pollution (Gee & Burkhard, 2010; Sonnberger & Ruddat, 2017). Stakeholders can expect solutions to mitigate the negative impacts of offshore wind development (Johansen & Emborg, 2018). Some of the potential economic benefits may be subject to distribution with stakeholders through, the involvement of local communities and businesses in the supply chain for the project, which results in job creation and economic benefits (Chen et al., 2015; Weig & Schultz-zehden, 2019).

It may be important for a sound planning process to be able to use measurable indicators to quantify the consequences of decisions in terms of giving space a specific character. The development of offshore wind energy translates into concrete changes in social, environmental, economic, energy and climate terms. This article presents a proposal for measuring indicators that can be used to shape offshore space and climate policy. Through historical data and assumptions, values for electricity production and carbon emission reductions in the EU are presented both holistically and universally per square kilometer of maritime space. Using these indicators, maritime space planners can enter numerical values for these values into decision-making models with greater precision.

In addition to providing adequate marine space suitable for offshore energy development, it is necessary to create a supply chain capable of responding to the demand expressed by the EU's climate policy targets. The projections presented provide an indication of the demand for turbines over time to 2030. While turbines are an important component in determining the amount of investment in the overall project, there are a number of elements that need to be integrated into the supply chain to enable the ambitious targets to be met. One of the identified bottlenecks relates to grid connections and availability of specialized installation vessels (Gatzert & Kosub, 2016). Further challenges will arise during the maintenance and operations phase of offshore wind farms, due to the need for sufficient trained personnel and crew transfer vessels (Ren et al., 2021).

However, it should be borne in mind that the indicators analyzed in this article only cover a slice of the reality shaped by offshore wind energy development. The analysis of the necessary resources and potential effects for the construction of offshore wind farms can be extended to include numerous indicators, including employment, impact on economic development, geographical location of costs and benefits, environmental impact, parameterization of conflicts of interest, and others. There are also studies on the impact of changing the nature of marine and coastal areas on values beyond measurable indicators, related to cultural or even emotional impacts, among others (Zaucha & Pardus, 2019). These aspects can further research on indicators describing offshore wind development.

Faced with an energy crisis in Europe, EU countries have resorted to a consistent climate policy, aiming to accelerate the energy transition based on renewable energy sources. Offshore wind energy is an excellent addition to the EU's energy mix, which today in terms of renewables is mainly focused on onshore wind and hydro. Technological developments, greater cost efficiency (per LCOE) and increased production capacity of offshore wind farms make it an attractive form of energy generation for EU countries. By using green hydrogen production with electricity generated from offshore wind farms, it is possible to eliminate variability in energy access. One potential solution for providing continued access to low-carbon energy is the production of hydrogen through electrolyzers working with large-scale floating offshore wind projects (Ibrahim et al., 2022).

The research shows the potential for offshore wind farms to also work with other forms of power generation, such as floating solar photovoltaic (López et al., 2020) and tidal turbines (Nasab et al., 2020). There are also many multi-use options for offshore wind turbine installations, such as aquaculture (van den Burg et al., 2017; van den Burg et al., 2020), tourism (Glasson et al., 2022) and recreational fishing (Hooper et al., 2017). Additional opportunities for offshore energy to coexist with other activities can positively influence the efficiency of marine space use (Przedrzymirska et al., 2021). Individual countries independently create policies for the management of multiple marine activities in offshore windfarm areas, which affects the availability of marine areas for fishing, between other activities (Schupp et al., 2021). With the development of offshore wind turbine technology and the possibility of using floating offshore wind turbines, new sea spaces can be utilized for the production of renewable energy. This will further increase the importance of offshore wind energy in building energy security in Europe.

This article presents calculations of spatial and capital resources for the implementation of EU climate policy targets that are given independent shape by the individual countries of the European Community. The development of the energy transition in different countries points to certain factors that cause some countries to adapt renewable energy generation better than others (Ćetković & Buzogány, 2016). Among European countries, the leader in offshore wind development is the UK, which, based on an offshore wind support scheme and the promotion of local content, has created an efficient supply chain for offshore wind (Higgins & Foley, 2014). Decarbonization of the energy system in Europe is a long-term process and the announcement of installation targets for offshore wind turbines in individual countries is only the first step towards achieving it (Victoria et al., 2020). EU MS have not been dynamically developing offshore energy production over the past few years, although the example of the UK shows that it has been possible to create the conditions for the development of this sector. The current dynamic changes in installation plans and the adoption of offshore spatial plans, juxtaposed with the possibilities of installing turbines in these spaces, show that there is a very high potential for energy production in European offshore areas. Offshore wind energy has for years been seen as a potential source of low-carbon electricity that can be cost-effective and have a positive impact on energy security (Esteban et al., 2011). However, it was only the energy crisis in Europe, that led to significant increases in national offshore wind installation targets. The timing of the installation targets set by European countries overlap with each other and with the dynamic development in the US and Asia. Through the loss of the last few years in offshore wind development and the supply chain for the sector, it can be very challenging for Europe to reach the installation targets set, proving that energy and climate policies should be planned for the long term (Victoria et al., 2020).

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