Economic Aspects of Marine Spatial Planning: The Case of Offshore Wind Farms in Poland

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Abstract

Spatial rent (annuity) makes it possible to estimate the economic value resulting from the use of space for a given type of activity. This article provides calculations of spatial rent in regard to offshore wind energy development and proposes a data-driven approach for optimizing spatial management strategies, ultimately contributing to more informed decision-making processes in marine spatial management. It analyses seven projects that could be developed in the Polish part of the Baltic Sea as part of Poland's energy transition. The article employs a robust methodology that integrates technoeconomic analysis and financial forecasting to calculate spatial rent by discounting net cash flows. The calculations are carried out for two windiness scenarios, with the results of the weighted average annual energy production ranging from 38.02 GWh/km^2 to 40.56 GWh/km^2. Such energy production could yield an annual spatial rent of 10.72 million €/km^2 to 13.30 million €/km^2.

Keywords

offshore wind, spatial rent, green deal, energy transformation

Introduction

The European Union (EU)'s energy policy is one of the pillars of the entire community and is integral to shaping the social and economic development of the continent. For decades, the EU has consistently pursued a plan to decarbonize the energy sector, aiming to reduce electricity generation from coal and other fossil-fuel-fired power plants in favour of sustainable renewable energy. The contributions of individual EU countries have been planned by setting specific targets for reducing carbon dioxide emissions and increasing the production of energy from renewable sources. In pursuing their aims, EU countries have simultaneously been leading the way in reducing energy dependence on fossil fuels, including fossil fuels from Russia. However, as a result of the military conflict in Ukraine in February 2022, European countries faced the new challenge of having to immediately address energy supply constraints and energy price fluctuations.

In Poland, the milestones for developing offshore wind energy as part of the energy transition were the establishment of an offshore spatial development plan (*Regulation of the Council of Ministers of April 14, 2021 on the Adoption of the Spatial Development Plan of Internal Sea Waters, Territorial Sea and Exclusive Economic Zone in the Scale 1:200 000*, 2021) and the passing of a special act to promote offshore wind energy (*The Act on Promoting Electricity Generation by Offshore Wind Farms*, 2020), guaranteeing that developers offtake energy at a certain price. These two documents provide the foundation for determining the economic viability of a project in relation to the area of offshore space required for its implementation. Although the development of offshore wind energy in Poland was planned even before Poland's accession to the EU, adjusting legislative and economic frameworks was necessary (Beurskens & De Noord, 2003; Stryjecki, 2009). Economic assessment is an essential part of the analysis of the investment process for renewable energy sources, as it provides the grounds for justifying the action in a free market economy. Investors need to receive a return on the capital investment that is adequate to compensate the risks incurred (Dopierała et al., 2022). Investors are thus incentivized to make investments, ensuring that the energy transition targets set by countries at the local and EU/international levels are met. In 2020, the EU set, as part of its renewable energy strategy, a target for offshore wind energy development of 60 GW by 2030 and 300 GW by 2050 (European Commission, 2020a). However, in

2022, with the outbreak of war in Ukraine, individual EU countries reacted strongly and decided to increase the targets for offshore wind installations (North Sea Governments, 2022; NSEC, 2022). The development of this form of renewable energy production, in addition to the possibility of curbing carbon dioxide emissions, is also an opportunity for Poland and Europe to reduce their dependence on imports of energy resources and to improve their energy security.

The surge of interest in offshore wind farm investment in Europe has also drawn attention to the aspect of marine space utilization. The maritime spatial development plan adopted by the Polish government in 2021 is meant to enable the development of offshore energy in designated areas; specifically, 2,310.81 km^2 are designated where offshore wind energy development is permitted (*Regulation of the Council of Ministers of April 14, 2021 on the Adoption of the Spatial Development Plan of Internal Sea Waters, Territorial Sea and Exclusive Economic Zone in the Scale 1:200 000*, 2021). These areas represent 7.6% of the total area covered by the Polish Maritime Spatial Plan. An integral part of maritime governance is the management of conflicts of interest, which, with the emergence of new maritime activities and increased use of marine space, may require trade-offs (Zaucha, 2019).

This work investigates a specific dimension of energy transition, namely offshore wind development in Poland. A certain challenge for undertaking a study in this area is the early stage of said development in Poland: At the time of preparing this article, none of the proposed projects have started offshore construction. However, it should be kept in mind that spatial planning, which determines the feasibility of investment and energy transition by identifying space for development, takes place at an early stage, where the range of available data on specific projects is limited and information gaps exist (Zaucha, 2018). This study assessed the economic value of building offshore wind farms by taking into account spatial considerations. Critical elements of the decision-making process regarding the siting of wind farms in the Polish coastal zone and the electricity they generate have already been analysed (Ziemba, 2022). Offshore wind farms are key to meeting the EU's renewable energy development targets set by the Green Deal (European Commission, 2020a). However, a comprehensive economic, legal, and environmental framework is necessary for their realization (Adamiec, 2023). To mitigate financial risks, various support mechanisms can be used, such as contracts for difference, feed-in tariffs, tax policies, and subsidies, among others (DeCastro et al., 2019). Further, spatial planning can determine the economic value resulting from, among other things, the use of specific marine areas (Zaucha et al., 2020).

This study aimed to provide a tool for enhancing the spatial planning process through the consideration of the specific economic value of the sea space allocated to renewable energy, namely offshore wind energy (OWE) spatial rent[1] (annuity), which is mainly derived from OWE financial benefits. Similar attempts have been made in the literature for determining the economic value of other maritime activities, such as fishing, for which a contribution margin has been estimated (Psuty et al., 2021). The need to develop economic tools for more accurate decision-making in marine spatial planning development has been identified by various researchers (Psuty et al., 2021; Surís-Regueiro et al., 2021; World Bank, 2022; Zaucha et al., 2020).

Theory

The sustainable use of marine spaces remains the subject of many scientific and practical studies (Gilek et al., 2021), which have concluded that their use is conditioned by the preservation of the natural capacity of marine resources to reproduce and the possibility of the coexistence of a wide range of human activities that do not conflict with each other and with the natural marine environment (Morf et al., 2019; Turski et al., 2018). The sustainable use of marine spaces is one of the key challenges facing modern maritime spatial planning in the face of the increased intensity of activities carried out on the seas (Nash et al., 2020).

Each of the sea areas that make up the EU maritime economy has distinct characteristics. The seas that make up the EU maritime basins are divided into Northern Waters (Atlantic Ocean, North

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[1] The term 'spatial rent' is used in this paper instead of the concept of 'annuity' to follow the original terminology proposed by Ricardo (Ricardo, 1821).

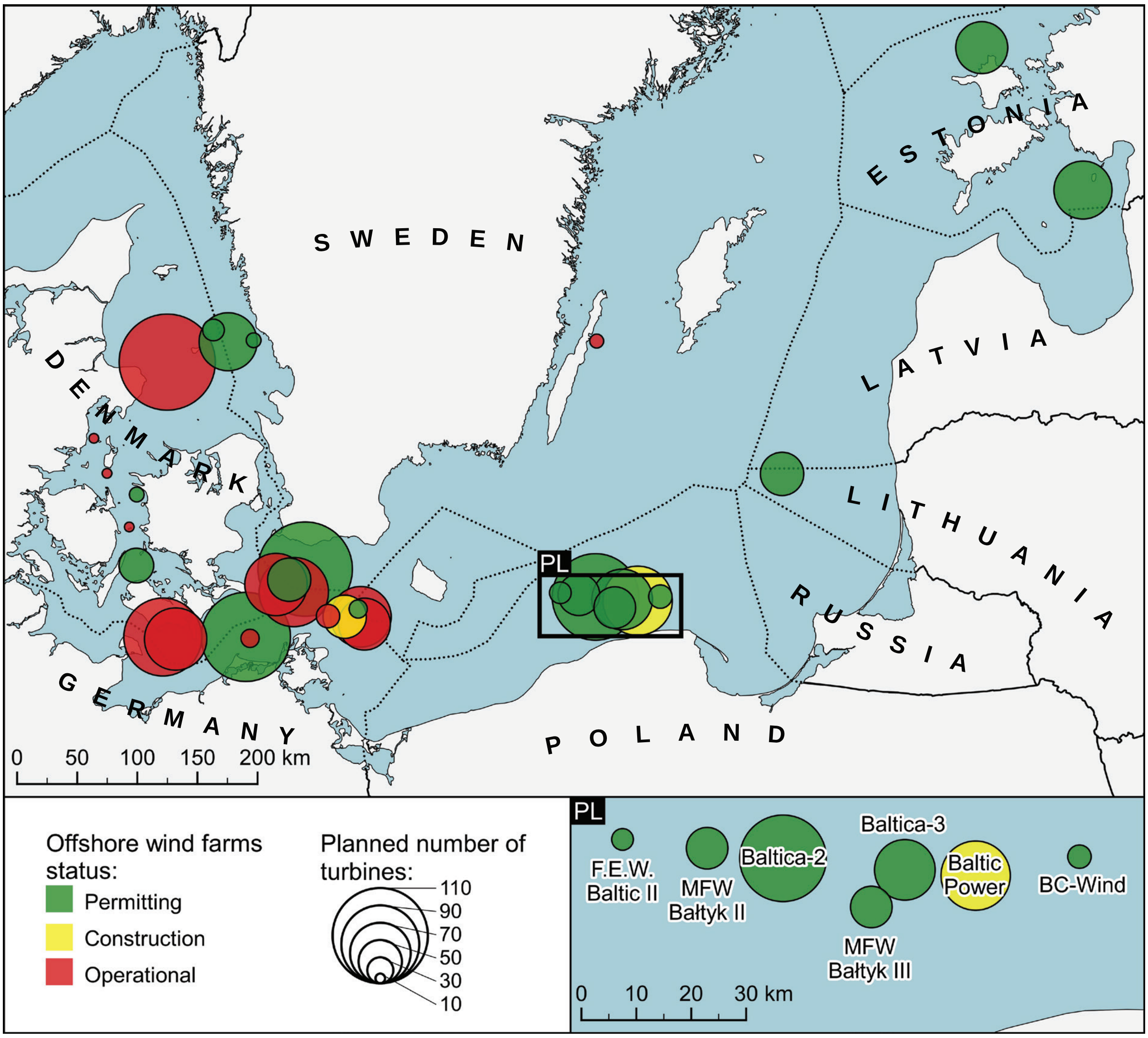
Sea, Baltic Sea) and the Mediterranean (Mediterranean, West Mediterranean, Adriatic-Ionian Sea, East Mediterranean, Black Sea). Each of these basins represents huge potential for the installation of offshore wind turbines for the production of renewable electricity, but this sector of the maritime economy currently represents a small fraction of the added value generated. Coastal tourism represents the largest sector of the EU maritime economy, both in terms of gross value added and employment (European Commission, 2020b). Previous studies on the sectoral development of the EU's sea basins have revealed the potential for increasing the efficiency of spatial development through multiple use, but they have not made use of specific calculations of financial indicators. Using OWE as an example, this article proposes a solution for comparing the economic benefits of implementing a specific activity in marine areas (Przedrzymirska et al., 2021). Table 1 presents the current marine energy potential and its technical installation potential. Not all countries developing OWE in the listed maritime areas are part of the EU, as the leader in offshore wind development in the North Sea is the United Kingdom.

Table 1. Utilization of offshore wind potential in European waters in relation to estimated technical capacity

Sea Basin	Current installed offshore wind capacity [GW]	Installation target [GW]	Total technical potential for offshore wind installation [GW]
North Sea	27.9	150 in 2050	1948
Mediterranean Sea	0.1	-	1,646.2
Black Sea	0	-	453
Baltic Sea	3.32	19.6 in 2030	93.5
Atlantic Ocean	2	-	-

Sources: Hahmann et al. (2023), European Commission (2019), Staschus et al. (2020), The World Bank Data Catalog (Retrieved from: www.datacatalog.worldbank.org)

While the construction of offshore wind farms is part of the EU's energy strategy, the significant impact of such projects on the entire 'blue economy' sector should not be overlooked (European Commission, 2023). The complexity of this sector means that assessing its individual components is not straightforward and that the sector needs to be considered holistically. To do this, it is necessary to obtain the right data to enable effective decision-making and impact monitoring (Burgess et al., 2018). The need for a socioeconomic assessment is part of the trend towards the quantification of the phenomenon that is captured by the term blue economy. Individual studies have examined selected geographical areas and specific activities in the maritime sector (Fernández-Macho et al., 2015; Kwiatkowski & Zaucha, 2023; Mogila et al., 2021; Psuty et al., 2021). There have been also some attempts to estimate the benefits of maritime spatial plans. For instance, Surís-Regueiro et al. (2021) proposed a methodology for estimating the total (induced and indirect) economic effects—specifically, for the blue economy—related to maritime spatial plans by making use of counterfactual scenarios for the planned marine areas (Surís-Regueiro et al., 2021). Offshore wind development is of vital importance for the European blue economy, as new investments in offshore renewable energy can contribute to job creation and improve energy security, thereby enhancing the resilience of the European economy (IRENA, 2017, 2020). The development of OWE necessitates the implementation of effective decisions regarding the allocation of new marine spaces to facilitate the advancement of new investments (European Commission, 2018). However, to date, no universal method has been devised for the quantification of the economic benefits of the development of a particular maritime activity in relation to the space it occupies. This poses a major challenge for maritime spatial planning, which can be based on subjective judgements and captured by well-organized marine stakeholders. The approach proposed in this paper can contribute to building a tool for maritime spatial planning decision-makers by providing for a clear assessment of the economic impact of planning decisions. In response to the need to develop a universal method for determining spatial rent, a method for calculating the spatial rent resulting from the use of marine space in the Polish Baltic Sea zone for the development of OWE is proposed herein.



Map 1. Location of offshore wind farms in the Southern Baltic Sea

Source: Map created by Krystian Puzdrakiewicz based on data provided by the author, 2024.

Spatial rent can shape spatial development and influence the desire to maximize the efficiency of resource allocation. Positive rent motivates sea users to allocate certain resources to a given area. In the long run, activities with higher rents can be expected to displace activities with lower rents. Consequently, the ability to tally and compare the rents resulting from different activities may make it possible to predict conflict dynamics and space use processes. In the Baltic Sea, the development of OWE displaces fishermen's access to the fishing areas and also reduces the availability of shipping routes due to the size of the expected installations (Zaucha et al., 2020). The amount of the expected rent varies depending on the factors that determine the efficiency of the space used for a given activity; in the case of offshore wind farms, these are mainly windiness, water depth, distance from land, and distance from port.

The Baltic Sea has the potential to make a significant contribution to the EU's energy policy goals within a few years. As shown in Table 1, the Baltic Sea could reach an installed capacity of almost 20 GW by 2030 (EU Baltic Sea Governments, 2022), of which 5.9 GW would be wind farms installed in the Polish Baltic Sea zone. Map 1 shows the location of existing and planned offshore wind farm projects in the Baltic.

Meeting the target of installing almost 20 GW of capacity in the Baltic Sea before the end of this decade means that the number of sited turbines must be doubled from the current 720 to around 1,500 turbines in 2030. In addition to the installation of the turbines, the construction of offshore wind farms requires a cable connection between the towers and the transmission station and the laying of submarine cables for the export of energy to land. The pace and size of investment are not without impact on the Baltic Sea ecosystem and have certain consequences, both positive and negative (Galparsoro et al., 2022). The development of offshore wind farms takes place in successive stages, which are characterized by various environmental, social, and economic impacts. The external effects of an offshore wind farm at different stages are taken into account at an early stage of marine spatial planning (Bailey et al., 2014).

The impact of offshore wind farm development on the environment should be considered in light of the phase of the investment cycle and technology (Mauricio Hernandez et al., 2021). Particularly intense local effects occur during the construction and decommissioning phases due to the noise and vibrations associated with offshore activities (Galparsoro et al., 2022). Research indicates the presence of both positive and negative aspects of offshore wind farm development. Among the negative environmental aspects, birds whose migration corridors intersect with the locations of wind farms may come under particular pressure (Adamiec, 2020; Snyder & Kaiser, 2009). However, upon observing fish species, researchers have noted that certain ones derive benefits from the effects of artificial reefs (Hooper & Austen, 2014). The structures of wind farms may also influence potential social conflicts including fishing activity and landscape disturbances, which are especially significant concerns for coastal areas focused on tourism (Biniek, 2021; Voltaire et al., 2017).

While the benefits stemming from the energy security and low carbon footprint of electricity production associated with renewable sources are widespread, the potential negative social and environmental effects are primarily observed locally. Developers of offshore wind farms are required to prepare an Environmental Impact Assessment (EIA) document in order to apply for necessary permits (Adamiec, 2023). The EIAs for Polish investments anticipate minimal negative environmental impact, and the plans for locating individual farms are designed to mitigate potential threats, such as by preserving migratory corridors for birds (Bednarska et al., 2017). The actual impacts of the planned investments centred in the Baltic Sea environment and potential conflicts are challenging to estimate due to the lack of existing installations (Biniek, 2017).

Material and methods

A spatial rent is a monetary expression of the benefits derived from the use of a given space (Zaucha et al., 2020). Determining the value of spatial rent allows an objective estimation of the economic benefits provided by a given economic activity in a given area (Zaucha, 2019). Therefore, in order to estimate the spatial rent for the offshore wind farms planned in the Polish Baltic Sea zone, it is necessary to estimate the financial values of the investment. Based on the available knowledge on modelling the costs and financial flows resulting from offshore wind farm operation, a financial model was developed for seven Polish projects, covered by a support mechanism guaranteeing a minimum price for energy consumption (Judge et al., 2019; Kaiser & Snyder, 2013; Castro-Santos et al., 2018). A challenge for the determination of the spatial rent of the planned project is the lack of accurate data on the costs of the implementation of the various stages of an offshore wind farm. In this study, seven projects with a total installed capacity of 5.9 GW were analysed. All projects are expected to be connected to the national grid by 2028, according to the developers' plan. Table 2 shows the projects analysed along with their basic technical characteristics.

Table 2. Offshore wind farm projects

Name of project	Developer	Planned generation capacity (MW)	Assumed number of turbines	Offshore wind farm area (km^2)	Distance from shore (km)
Baltic Power	PKN ORLEN, Northland Power	1,200	80	131	39
Baltica 3	PGE, Ørsted	1,045	70	131	25
Baltica 2	PGE, Ørsted	1,498	100	189	30

Table 1. – cont.

Name of project	Developer	Planned generation capacity (MW)	Assumed number of turbines	Offshore wind farm area (km^2)	Distance from shore (km)
Bałtyk III	Polenergia, Equinor	720	48	116	23
Bałtyk II	Polenergia, Equinor	720	48	121	37
BC-Wind	Ocean Winds	399	27	91	23
F.E.W. Baltic II	RWE	350	25	41	46
TOTAL	-	5,932	398	820	-

Source: own elaboration, based on developers' plans.

The technical assumptions adopted in the model can have a significant impact on offshore wind energy production and consequently affect the financial performance of the projects analysed (Monforti & Gonzalez-Aparicio, 2017; Mora et al., 2019). To calculate the spatial rent, assumptions were made regarding: technical solutions of offshore wind farms, construction and operating costs, production capacity and revenues generated from the sale of electricity. Recent years have been characterized by high dynamics of technical development of offshore wind energy, including a significant increase in the capacity of a single turbine (WindEurope Business Intelligence, 2022). The capacity of a single turbine was assumed to be 15 MW, according to the first tenders awarded by developers with projects in Poland. In order to estimate the possible spatial rent depending on wind power, spatial rent calculations were adopted based on two different average wind power scenarios for the projects analysed. On the basis of wind measurement data, wind speeds of 9.5 m/s were assumed for Scenario 1 and 10.5 m/s for Scenario 2 (Boniecka et al., 2016) due to the installation of the turbines at a height of approximately 150 m. The capacity factor was assumed to be 60% in Scenario 1 and 64% in Scenario 2, respectively (Valpy et al., 2017; Vestas Wind Systems A/S, 2023). The calculation methodology used in this document is based on certain simplifications and assumptions, including the determination of the capacity factor. This parameter is derived from technical specifications provided by turbine manufacturers. Research by Sobotka et al. (2019) analysed the actual performance of a 400-MW offshore wind farm and revealed a lower capacity factor for 8-MW turbines. This means that actual energy production and the resulting revenue may differ from the values assumed in the model, particularly due to differences in geographic conditions at different sites. The amount of energy produced is subject to regional variations due to wind conditions in different offshore areas (Boniecka et al., 2016). In addition, different technical solutions may be employed to account for various factors such as water depth, soil conditions, and other site-specific conditions (Ziemba, 2022). These considerations emphasize the complexity of predicting wind energy production in different environments. If current trends continue, the construction cost of offshore wind farms will decrease in the coming years (Rubio-Domingo & Linares, 2021). For the projects analysed, the investment cost for the construction of an offshore wind farm was assumed to range from 2,292 €/kW to 2,736 €/kW and 33.7 €/kW in annual operating expenditures (IRENA, 2022). A 25-year wind farm lifespan and decommissioning costs of 211 €/kW were assumed (Judge et al., 2019). The projects analysed were subject to a support mechanism, which consists of guaranteeing a fixed minimum energy offtake (€68 per MWh) in order to reduce market risk (*The Act on Promoting Electricity Generation by Offshore Wind Farms*, 2020). In this way, investors can plan for the revenue generated by the projects. Assumptions were made according to available sources and studies by other authors (Rubio-Domingo & Linares, 2021; Ziemba, 2022). A weighted average cost of capital of 7.6% was used, higher than in Germany, the Netherlands, or Denmark (Rubio-Domingo & Linares, 2021). The model also assumed a government concession fee of PLN 23,000 (€4,845). Because of different financing models for offshore wind farm investments, equal shares of debt capital and equity were assumed (Lam & Law, 2018).

Calculations were made in Excel using formulas that recalculate the financial parameters of each of the seven projects analysed. Certain technical and financial assumptions were made, as shown in Table 3.

Table 3. Assumptions adopted for calculation of spatial rent for offshore wind farm projects located in Poland

Category of assumption	Parameter	Assumption made
Technical	Wind speed—SCENARIO 1	9.5 m/s
Technical	Wind speed—SCENARIO 2	10.5 m/s
Technical	Turbine size	15 MW
Technical	Capacity factor—SCENARIO 1	60%
Technical	Capacity factor—SCENARIO 2	64%
Technical	COD year	2027/2028
Technical	Operations and maintenance lifetime	25 years
Financial	CAPEX per kW	€2,292–€2,735
Financial	OPEX yearly per kW	€33.7
Financial	Decommissioning per kW	€211
Financial	CfD Rate/MWh	€68 (EURPLN = 4.70)
Financial	Inflation rate estimation	2.5%
Financial	Weighted average cost of capital	7.6%
Financial	Concession fee	€4,945 (EURPLN = 4.70)
Financial	Discount rate	6.0%
Financial	Share of equity and debt	50% equity, 50% debt

Source: Rubio-Domingo and Linares (2021); Ziemba (2022).

The development of offshore wind energy in Europe, mainly in the United Kingdom but also in other countries, including the Baltic Sea Basin, provides data for estimating the cost of generating 1 kWh of energy from offshore wind farms and the value of energy production from a 1 km^2 offshore wind farm (Boniecka et al., 2016). These estimated data may constitute a significant supplement to the existing studies on the determinants of spatial development of maritime areas, both Polish and European, which, to the author's knowledge, have not performed economic analysis as an element of the study of conditions.

However, estimating the external costs resulting from the construction of offshore wind farms remains a difficulty (Ladenburg & Lutzeyer, 2012). The decision to allocate certain marine spaces for a particular activity may result in other activities having to be abandoned. In the case of offshore wind farm development, one of the potential external costs may be a reduction in the ability to develop fisheries in wind farm areas (Hooper & Austen, 2014; Stelzenmüller et al., 2016). Apart from the impact on fisheries, the development of offshore wind farms in the Baltic Sea may affect tourism, which is an important part of the economy of coastal regions. The construction of offshore wind farms may affect the attractiveness of tourist regions due to the industrialization of the landscape (Biniek, 2021; Voltaire et al., 2017). Table 4 presents an analysis of the potential benefits and threats resulting from the construction of offshore wind farms in the Baltic Sea (Laskowicz, 2021).

Table 4. Externalities arising from offshore wind farm development at different stages

Life stage of an offshore wind farm	Activity	External costs
Development	Survey of areas for the construction of offshore wind farms	Increased intensity of maritime space exploration; possible conflicts with fishing industry
Construction	Transport and installation of offshore wind farm components	Possible risk to marine mammals and fish from noise pollution

Table 4. – cont.

Life stage of an offshore wind farm	Activity	External costs
Construction and operation	The need to maintain safety zones during construction and operation	Restricted access to fishing grounds
Operation	Rotor blade movement	Threat to birds
Construction and operation	Industrialization of the landscape	Threat to tourism and cultural identity of coastal residents
Development, construction, and operation	Adaptation of port infrastructure	Capital expenditure required to adapt port infrastructure; adaptation of significant land areas required
Operation	Operation and maintenance of farms during operation	Necessary maintenance of infrastructure related to transmission provision, including cables and transformer stations; risk of accidents and spills of hazardous substances
Decommissioning	Removal of offshore wind farm features and restoration of the natural environment	Risk to fish and marine mammals from demolition work; risk of disturbance to wildlife habitats

Source: own elaboration.

The benefits and risks listed are not always possible to include in an economic calculation due to the lack of a methodology to estimate the costs or profits arising from phenomena that co-occur in the different phases of an offshore wind farm. This study estimated the spatial rent resulting from the possibility of building offshore wind farms in marine areas, and the purpose of presenting the calculations for the spatial rent resulting from the construction of offshore wind farms is to provide an economic rationale for decisions regarding the management of marine space.

Results

Results were obtained for two different scenarios, varying in terms of the efficiency of the wind turbines. The operating efficiency of wind turbines depends on a number of factors, including the location of the turbines and the technical efficiency of the equipment, but a key factor is the wind (Ziemba, 2022). Table 5 presents the financial outlay required to achieve the assumed generation capacity and the expected values of electricity production from the assumed projects. Also presented is the value of the electricity generated from the use of 1 km^2 of offshore space dedicated to the construction of an offshore wind farm and the unit cost of electricity generation.

Table 5. Electricity production of Polish offshore wind farm projects by 2028 under two production efficiency scenarios

Capacity factor	Name of project	Planned generation capacity (MW)	CAPEX m (€)	Annual energy production (GWh)	Area (km^2)	Annual energy production per km^2 (GWh/km^2)
60%	Baltic II	350	802	1,840	41	44.87
	Baltic Power	1,200	3,163	6,307	131	48.15
	Baltica 2	1,498	4,099	7,874	189	41.66
	Baltica 3	1,045	2,859	5,493	131	41.93
	Baltic II	720	1,650	3,784	121	31.28
	Baltic III	720	1,650	3,784	116	32.62
	BC WIND	399	915	2,097	91	23.05
	Total for Scenario 1	5,932	15,138	31,179	820	Weighted average: 38.02

Table 5. – cont.

Capacity factor	Name of project	Planned generation capacity (MW)	CAPEX m (€)	Annual energy production (GWh)	Area (km²)	Annual energy production per km² (GWh/km²)
64%	Baltic II	350	802	1,962	41	47.86
	Baltic Power	1,200	3,163	6,728	131	51.36
	Baltica 2	1,498	4,099	8,398	189	44.44
	Baltica 3	1,045	2,859	5,859	131	44.72
	Baltic II	720	1,650	4,037	121	33.36
	Baltic III	720	1,650	4,037	116	34.80
	BC WIND	399	915	2,237	91	24.58
	Total for Scenario 2	5,932	15,138	33,257	820	Weighted average: 40.56

Source: own study based on prepared financial model and assumptions shown in Methodology section.

The capital expenditure for the construction of the seven projects analysed according to the model will amount to €15,138 million. Turbines with a total generating capacity of 5,932 MW will be installed over an area of 820 km^2, which will generate between 31,179 GWh and 33,257 GWh of electricity annually, depending on the actual windiness. The average annual electricity production from 1 km^2 of sea space will range from 38.02 GWh/km^2 to 40.56 GWh/km^2.

The level of energy consumption in Poland has been more or less constant for more than a decade. In 2010, the level of energy consumption was about 150 TWh, and in 2021 the value will exceed 174 TWh (Polish National Grid, 2022). The construction of seven offshore wind farm projects with an installed capacity of 5.9 GW could translate into production of between 31 TWh and over 33 TWh per year. The expected year for this phase of offshore wind development to reach full capacity is 2028. This means that in 2030, when a demand of 198.8 TWh is projected (Polish National Grid, 2020), offshore wind could meet around 16.5% of the national electricity demand. Table 6 presents the financial indicators together with an estimate of the spatial rent for offshore wind projects.

Table 6. Results of financial model for offshore wind farms with estimation of spatial rent

Capacity factor	Name of project	Planned generation capacity (MW)	Total discounted net cash flows (million €)	Total undiscounted net cash flows (million €)	IRR (%)	Spatial rent based on discounted net cash flows (€ million/km²)
60%	Baltic II	350	614	2,539	11.67	14.97
	Baltic Power	1,200	1,649	8,089	9.88	12.93
	Baltica 2	1,498	1,920	9,874	9.43	10.16
	Baltica 3	1,045	1,339	6,888	9.43	10.22
	Baltic II	720	1,262	5,223	11.67	10.43
	Baltic III	720	1,262	5,223	11.67	10.88
	BC WIND	399	700	2,895	11.67	7.69
	Total for Scenario 1	5,932	8,790	40,732	-	Weighted average: 10.72
64%	Baltic II	350	734	2,824	12.65	17.91
	Baltic Power	1,200	2,131	9,066	10.79	16.27
	Baltica 2	1,498	2,466	11,093	10.32	13.05
	Baltica 3	1,045	1,720	7,739	10.32	13.13
	Baltic II	720	1,510	5,809	12.65	12.48
	Baltic III	720	1,510	5,809	12.65	13.02
	BC WIND	399	837	3,219	12.65	9.20
	Total for Scenario 2	5,932	10,908	45,559	-	Weighted average: 13.30

Source: own study based on prepared financial model and assumptions shown in Methodology section.

Through the data analysis, the financial efficiency of the individual projects was determined and compared with the data on the maritime space used for the project. The prepared model demonstrated the high financial profitability of the planned projects, with the internal rate of return ranging from 9.43% to as high as 12.65%. The spatial rent resulting from the construction of offshore wind farms in the Polish Baltic Sea zone was calculated, and depending on the analysed project and the adopted wind scenario (rate of capacity factor), the expected spatial rents were found to range from 7.69 to 17.91 million €/km^2. The weighted average spatial rent was found to be €10.72 million/km^2 in Scenario 1 and €13.30 million/km^2 in Scenario 2.

Conclusion and policy implications

For the model, this study assumed a relatively high capacity factor, which contributed significantly to the high expected spatial rent values based on discounted net cash flows. Discounted net cash flows are essential due to the long operating life of offshore wind farms and the need to account for changes in capital value over time. As a result of installing offshore wind farms with a capacity of 5.9 GW in an area of 820 km^2, the potential to generate 31–33 TWh of energy per year was assumed. Such energy production, assuming the guaranteed energy prices in the differential mechanism, would allow for high rates of return and space rents that are not achievable for other marine activities. Research on the economic value of marine space use has been conducted by Psuty et al. (2021) for the fisheries sector and by Czermański et al. (2024) for the shipping sector. Studies on the economic viability of marine space use differ in methodology, so a direct comparison of spatial rent results is not possible; nevertheless, previous work provides a basis for assessing the economic efficiency of the activities conducted. Based on differences in the expected spatial rents depending on the type of activity, decisions on marine spatial management and guidelines for mitigating potential conflicts of interest arising from the displacement of more profitable activities by those generating lower spatial rents can be made.

The development of offshore renewable energy requires significant capital investment and extensive marine space utilization. The deployment of offshore wind farms has local and global environmental and social impacts, with most of the adverse effects concentrated locally. However, quantifying such externalities within an economic modelling framework is challenging due to the lack of reliable data on the specific impacts, some of which are inherently subjective and lack quantifiable parameters for description. Another crucial aspect in managing the decision-making process regarding the development of activities in specific areas is the need to mitigate potential conflicts of interest arising from other functions. Alternative uses of space must be integrated into the economic calculus governing decisions on spatial functions, as such alternatives are a fundamental component in the overall assessment of the economic viability of an activity.

An important element of offshore development decisions, especially in the context of offshore renewable energy, is the time dimension of the decision. Due to the high financial costs of building an offshore wind farm, projects with a long lifecycle are likely to have a payback period of 25 to 30 years. After this period, developers, depending on the approvals obtained, may decide to extend the life of the project in question for a further period by, for example, using new turbines embedded in the existing space. In practice, this means that the decision to authorize the construction of offshore wind farms has a large temporal impact, as an investment in infrastructure that constitutes some kind of interference with the environment will remain in the offshore space for at least 30 years, and once the infrastructure is built, it is in practice impossible to change the use of the space.

Some of the parameters that influence the economic evaluation of an offshore wind farm project are shown in Table 3. There are nine effects listed that can be analysed from an economic perspective, and attempts have been made to do so in scientific studies (Aitken, 2010; Lamy et al., 2020; Laskowicz, 2021; Smythe et al., 2020; Varela-Vázquez & Sánchez-Carreira, 2017). To date, however, no integrated tool has been proposed to provide for comprehensive economic assessment of a project. The proposed tool, which aligns the economic benefits of offshore wind farms with the marine spatial area, represents a step towards making planning decisions based on economic data. Financial models prepared by developers take into account only the financial aspect of the investment, are undertaken by the investor, and are based on an analysis of a narrow slice of reality, which has a direct impact on financial flows for the investor. In practice, various types of costs may not be included in the economic calculation and are borne by other users of the neighbouring space or entities excluded from the use of the space intended for OWE development. The calculations conducted in this study also do not fully cover all elements. Due to numerous limitations, only selected data were analysed, whose quantification and incorporation into the model were feasible. Numerous external costs were not valued for the purposes of this study, but they may impact both the profitability of the investment itself and the assessment of the justification for maintaining such high spatial rents generated by offshore wind farms. Certain external costs, such as potential negative impacts on the environment or landscape or economic changes in coastal municipalities, may influence the economic assessment of marine spatial utilization (Dorrell & Lee, 2020; Zaucha, 2018). Thus, further work on OWE spatial rent should focus on internalizing the aforesaid external costs and benefits. The literature on this is vast but still hardly conclusive (Kwiatkowski & Zaucha, 2023; Laskowicz, 2021).

The overintensive use of marine space for energy can cause social conflicts (Alexander et al., 2013). Considering the economic conditions of a project already at the space planning stage can help identify potential conflicts of interest and estimate their economic value. The use of spatial rents can therefore help manage, avoid, or mitigate potential conflict altogether. It is necessary to consider the justification for imposing an obligation on developers of offshore wind farms to prepare, in addition to EIA documents, an analysis of the investment's impact on potential socioeconomic conflicts and possible mitigation measures, including potential compensation for specific interest groups, such as for the fishing industry due to the loss of opportunity to exploit fisheries (Hooper & Austen, 2014). The calculation of opportunity costs can provide a basis for dialogue between the various parties to a conflict and rationalize the interests of both parties. Relying on reliable and credible data can also provide a starting point for further economic calculations, which would be applied at the stage of developing the legal and institutional framework for OWE. Incorporating spatial rent calculations can enrich the comprehensive evaluation of investment profitability, particularly regarding government-granted energy offtake price guarantees. In addition, it is essential to recognize that the construction of offshore wind farms yields various benefits, the distribution of which should be accounted for in studies addressing the economic dimensions of marine space utilization (Allan et al., 2020; Connolly, 2020).

The seven wind farm projects analysed in this article located in Poland have a minimum offtake price mechanism granted, but in Europe, projects are increasingly being developed on a so-called ‘zero-subsidy’ basis—that is, on fully commercial terms. Individual countries extract various contributions, including royalties, taxes and other outlays, from offshore wind farm developers as a condition for the permission to use the space and develop projects. Some of the contributions are intended as a kind of compensation for the distribution of benefits resulting from the construction of offshore wind farms and are directed to a precisely defined group of recipients—for instance, through the direct mechanism of opportunities for business participation in the project for residents and entities of coastal regions or through funding for environmental protection in a given area (Adamiec, 2023; Gorroño-Albizu et al., 2019).

The elements of compensation for possible losses resulting from OWE development vary from country to country, including within the EU. Some of them are mandatory in character and are precisely calculated by the organizer of the tender for access to sites for the construction of offshore wind farms, while at other times, developers take it upon themselves to establish relationships with specific interest groups. Developers actively pursue substantial support for the implementation of OWE projects, recognizing that proceeding with an investment amidst unresolved conflicts of interest could severely hamper or, in severe cases, entirely derail project development. Therefore, developers are prepared to incur the cost of managing the distribution of economic benefits by committing resources and capital in order to build or maintain public acceptance at key points.

On the one hand, the implementation of the goals established in the Green Deal policy brings benefits to society as a whole through access to secure renewable energy and offers the possibility of independence from fossil fuels; on the other hand, it brings some challenges. Basing decisions on the use of marine space for the implementation of the energy goals set out in the Green Deal can contribute to more efficient management of marine space and, as a result, measurably help to achieve the energy goals, especially in regard to the construction of OWE, which is an important element of the Polish and EU energy strategies.

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