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Optimization of offshore wind farm locations using GIS-based tools

Optymalizacja lokalizacji morskich farm wiatrowych z wykorzystaniem narzędzi GIS

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ABSTRACT

The use of wind energy to generate electricity is becoming more and more popular. Wind farms are located onshore and, in recent years, offshore. The aim of this study was to determine the technical potential of the Polish Exclusive Economic Zone and to identify potential areas for offshore wind development. The first part of the study presents a theoretical introduction to the use of wind energy. Technologies and experiences of European and world countries were presented. Then, in the practical part, a multi-criteria analysis of offshore wind farm locations was discussed. Criteria determining the location of offshore wind farms were selected and criterion weights were determined using the AHP method. Calculations were performed using QGIS and Excel software. A map was created for each constraint and then the data was combined to obtain the final value. In this way, the suitability of the area for offshore wind energy was verified.

STRESZCZENIE

Wykorzystanie energii wiatru do produkcji energii elektrycznej staje się coraz bardziej popularne. Farmy wiatrowe są lokalizowane na lądzie, a w ostatnich latach także na morzu. Celem pracy było określenie technicznego potencjału Polskiej Wyłącznej Strefy Ekonomicznej oraz wskazanie obszarów perspektywicznych dla morskiej energetyki wiatrowej. W pierwszej części przedstawiono teoretyczne wprowadzenie do zagadnień związanych z wykorzystaniem energii wiatru. Przedstawiono stosowane technologie oraz doświadczenia krajów Europy i świata. Następnie, w części praktycznej omówiono przeprowadzoną wielokryterialną analizę lokalizacji morskich farm wiatrowych. Wybrano kryteria warunkujące lokalizację morskich farm wiatrowych i przy wykorzystaniu metody AHP określono hierarchię ważności. Obliczenia przeprowadzono przy użyciu programu QGIS oraz Excel. Dla każdego ograniczenia stworzono mapę, a następnie połączono dane, by uzyskać ostateczną wartość. W ten sposób zweryfikowano przydatność obszaru dla celów morskiej energetyki wiatrowej.

ABBREVIATIONS

PEP2040	The Energy Policy of Poland until 2040
RES	Renewable energy source
GIS	Geographic Information System
SODAR	Sound Detection and Ranging
LIDAR	Light Detection and Ranging
SAR	Synthetic aperture radars
OWF	Offshore wind farm
EEZ	Exclusive Economic Zone
VAWT	Vertical Axis Wind Turbine
HAWT	Horizontal Axis Wind Turbine
WTG	Wind Turbine Generator
BoP	Balance of Plant
HVAC	High voltage alternating current
HVDC	High voltage direct current
RCP	Reactive power compensation platform
VSC	Voltage Source Converter
OSS	Offshore substation
ESMAP	Energy Sector Management Assistance Program
PSEW	Polskie Stowarzyszenie Energetyki Wiatrowej (Polish Wind Energy Association)
PSZW	Pozwolenie na wznoszenie sztucznych wysp (location permit)
CfD	Contract for difference
COD	Commercial operational date
MCDM	Multi-criteria decision-making method
AHP	Analytical Hierarchy Process

1. INTRODUCTION

In order to meet the natinal and European targets, countries like Poland have to implement an adequate strategy that takes into account the air quality, energy transition, and overall well-being of the citizens. The transformation cannot be performed without the significant role of renewables. Numerous documents, such as the Kyoto Protocol, the Paris Agreement, the European Green Deal, or "Fit for 55", address the matter. The main objectives of Europe's climate and energy policy until 2030 include a reduction in greenhouse gas emissions by at least 40% compared to 1990, a share of RES in total energy consumption of at least 32%, and an improvement in the energy efficiency by at least 32.5% [1]. The Energy Policy of Poland until 2040 (PEP2040) issued by the Ministry of Climate and Environment is an example of a document on a national level. It describes the strategy of an energy transition and introduces three pillars: I - Fair transition, II - Zero-emission energy system, and III - Good air quality, which are the basis for the development of specific goals [2].

Currently, solar and wind systems are developing most rapidly, and further growth is predicted. Due to the optimization of used components, and the application of technical innovations, the energy transition takes place. Every year, the number of clean energy sources increases, and in the global energy mix, conventional energy is replaced. Every method of producing electrical energy has its drawbacks, however, renewable energy sources neither emit pollutants nor use depletable assets. Despite the intermittency of wind or solar technologies, a well-balanced energy system should remain stable. The application of energy storage, reduced electricity consumption, increased efficiency, and finally the right location of solar or wind farms are key to avoiding blackouts and stabilizing the grid. As a consequence, wind and solar projects that are currently being developed require former multicriterial location selection. Technical, economic, social and political factors as well as specific constraints dependent on the RES type are among the parameters that should be taken into consideration.

One of the most dynamically growing markets is offshore wind, especially in Europe. In 2021 3,3 GW were added, and the overall capacity of offshore wind farms in Europe reached 28,3 GW. There are predictions that by 2030 only the United Kingdom will own 40 GW, while all of the European countries are expected to have up to 135 GW of offshore wind power [3]. There are numerous reasons for an expansion of that size. First of all, wind turbines allow clean energy production due to the usage of renewable sources. Both onshore and offshore technologies are characterized by technical maturity and their environmental impact is not significant if the necessary precautions have been taken. However, offshore wind technology has some advantages over the onshore one. The quality of the wind resources is more convenient and stable in the sea. This results in the possibility of installing higher turbines with bigger rotor diameters that have a capacity of up to 15 MW/turbine [4], [5]. Further comparison between onshore and offshore as well as a detailed description of the technology is presented in *3.1. Wind energy technologies.*

The first step while developing a new wind project should be the selection of an optimal location. This could be performed using supportive tools to assess the energy potential of the area. To do this, it is necessary to process the meteorological data, especially wind parameters such as velocity, direction, and power. There are numerous papers describing different approaches to resource assessment. The examples are the resource estimation model and Geographical Information System (GIS). Data collection is a former step, and the methods are on-site measurements, weather station networks, and numerical climate models. Typically, the measurements in offshore regions are performed using different types of buoys (met buoys or moored buoys, depending on the water depth). Examples of remote sensing measurements are SODAR and LIDAR. Another possible option is to employ satellite data and combine it with the surface wind recording data accumulated using devices like scatterometers, altimeters, passive microwave remote sensors, and synthetic aperture radars (SAR). The raw data is then inserted into the mathematical model to create data sets. The next step is to employ an estimation model or Geographical Information System (GIS) approach. The objective is to investigate which parameters would affect offshore wind farm locations [6].

2. AIM AND SCOPE OF THE THESIS

2.1. AIM AND OBJECTIVES OF THE RESEARCH

The thesis aims to investigate the factors that determine offshore wind farm location and to incorporate these constraints into a model to develop a complex tool that would allow multi-criteria analysis. The assessment of the offshore wind turbines' potential will be performed with the usage of the QGIS software. During the analysis, only the part of the Baltic Sea would be considered, the Exclusive Economic Zone of Poland. The details of the criteria method will be described in the following chapters. As a result of the investigation, the optimal sites for offshore wind farm development would be proposed.

The main objectives of the thesis are:

- To assess the potential for offshore wind farms in the Polish part of the Baltic Sea using a multi-criteria model developed with the use of QGIS software.
- To propose optimal sites for offshore wind farm locations.

2.2. RESEARCH QUESTIONS

Questions to be answered by the analysis are:

- What are the key aspects that should be considered while deciding on the offshore wind farm location?
- Which spatial data sets are crucial to determine the optimal offshore wind farm locations using QGIS software?
- What are the suitable sites for offshore wind farm development in the Polish part of the Baltic Sea other than those proposed in the Act [7]?
- What is the technical potential of offshore wind in the Baltic Sea?

3. ELECTRICAL ENERGY PRODUCTION USING WIND-BASED SOURCES

3.1. WIND ENERGY TECHNOLOGIES

3.1.1. ONSHORE WIND TECHNOLOGIES

The use of wind energy has been known to mankind for centuries. An example of making use of wind is to propel boats along the rivers and seas, which people implemented as early as 5000 BC near the Nile River. Another use could be simple wind-powered water pumps and irrigation systems in China. Later on in the Middle East, the first windmills were created and used to grind grain. Eventually, wind energy technology was brought to Europe and America, where more ideas on how to use wind were proposed. In the Netherlands, wind was used for land drainage purposes, American colonists on the other hand implemented windmills to grind grain, pump water, and cut wood at sawmills. The first attempt to construct a machine that could convert wind energy into electricity took place in Denmark at the end of the 19th century. This was followed by a gradual development of small wind-electric generators at the turn of the century in both Europe and the United States. Later, the interest in the technology decreased due to common electrification. The breakthrough came with the energy crisis of the 1970s. The oil shortage entailed the interest in generating electrical energy with the use of renewable energy sources, such as wind energy [8].

The development of wind turbines concerns the size and capacity. Before the 1990s, the power did not exceed a few hundred kW, and currently, turbines installed onshore are in the 1 MW to 8,5 MW range. There are numerous reasons for onshore wind development. Patel and Beik have listed the following:

- High-strength fibre composites for constructing large, low-cost blades;
- Falling prices of the power electronics associated with wind power systems;
- Variable-speed operation of electrical generators to capture maximum energy;
- Improved plant operation, pushing the availability up to 95%;
- Economies of scale as the turbines and plants are getting larger in size;
- Accumulated field experience (the learning curve effect) improves the capacity factor by over 50% [9].

The abovementioned contribute to a decline in the cost of generating energy. Wind energy has become a cheaper option than coal, oil, nuclear, and most natural gas-fired plants. Furthermore, it is a non-polluting technology, it is scalable, and different options are available on the market. There are two basic types of modern wind turbines based on the axis of rotation: VAWT (Vertical Axis Wind Turbine) and HAWT (Horizontal Axis Wind Turbine). The technologies differ in construction, size, operating range, and noise generation. The table below compares the two technologies with regard to size, rated power, operating range, and noise generation. It also shows the most popular variants and typical applications.

Table 3.1 Comparison of VAWT and HAWT technologies

	VAWT	**HAWT**
Size	small size, possibility to locate in places inaccessible to HAWT	Significant size, tower heights even over 100 m, located in areas with good wind conditions
Nominal power	less than 50 kW	several MW
Operating range (wind velocity)	starting operation at low wind speeds of a few m/s, stable operation at several m/s	approx. 4-30 m/s
Noise generated	no noise generated	approx. 40-55 dB
Most popular variants	• Savonius turbine • Darrieus turbine • H-Rotor turbine	three-bladed turbine
Application	domestic installations	commercial power plants

source: compiled from [10], [11]

3.1.2. OFFSHORE WIND TECHNOLOGIES

The previously mentioned categories (VAWT and HAWT) were proposed according to the axis of rotation. Another possible way to classify wind energy technologies is by taking into account the localisation of the system: onshore wind and offshore wind. The history of offshore wind began in the 1990s when the first turbines were installed in Danish territorial waters. The interest in offshore was due to the better wind conditions. In general, offshore winds are stronger and more stable when compared to onshore. Since the middle of the 2000s, a growth in offshore project development has been observed [12]. The details are presented in the following chapter (*3.2. Wind energy development*). In the beginning, wind farms were located only a few kilometres from the shore, at a favourable water depths (less than 20 m). With the advancement of technology, more localisations have been considered. New wind farms are being located further and deeper. This occurs for the following reasons: not sufficient sites, visual constraints, more stable and higher wind conditions, and progress in floating technology. On the other hand, the challenges regarding offshore wind farms are the optimal offshore wind farm array, cabling to connect wind turbines to facilities and land stations, and integration of power from offshore farms into the onshore power grid [12]. The main elements that form an offshore wind farm are often referred to as WTG (Wind Turbine Generators) and BoP (Balance of Plant). The latter term concerns foundations, cables (internal and exporting), offshore substations, onshore stations, and other components [13].

Foundations

Offshore wind turbines do not differ much in terms of construction from onshore ones. However, there are additional components that are indispensable in that kind of project. First of all, turbines are usually bigger and require a suitable foundation. Among the most popular ones, one should list monopile, jacket, and gravity base. The table below presents the details regarding these technologies, such as water depth, construction, dimensions, design, fabrication, and installation. Other examples of fixed-bottom technologies are tripod and triple. Furthermore, floating technology is promising and continues to grow. Currently developed systems are spar-buoy, semi-submersible, and tension log platform

(TLP) [13], [14]. Figure 3.2 presents the comparison among the different foundation types.

Table 3.2 Most popular offshore wind foundations and their characteristics

	Monopile	**Jacket**	**Gravity base**
Water depth	typically 10 - 30 m (in the future, possibility to extend up to 60 m)	typically 40 - 60 m	most often less than 20 m
Construction	a steel tube, typically with a cone at the upper end, formed from cylinders approximately 2 - 3 m high	four metal piles that are linked together thanks to a lattice that provides strength and stability to the whole structure	foundation made entirely or partly of concrete with ballast to stabilise the structure
Dimensions	• diameter approx. 4 - 9 m • wall thickness approx. 60 - 100 mm • length approx. 40 - 80 m • weight up to about 700 t	• weight up to 2,000 t. • lattice connections with a contour at the bottom from several to several tens of metres	• weight up to 1,000 t • dimensions of the base vary from 15×15 m to 20×20 m
Fabrication	combining cylinders approx. 2 - 3 m long that have different thicknesses	complicated with a large number of nodal welded connections, requires a lot of space	the concrete part can either be made in situ or from prefabricated elements
Installation	once the pile is embedded in the installation frame, it is driven into the soil of the seabed using a special installation hammer, requires the use of a jack-up vessel with a suitable crane and hammer	installation of piles is easier compared to monopiles due to the smaller size of the piles, the lattice frame is then placed over the piles and connected using cement	two types of installation can be distinguished: craneless (the structure is towed to the installation site and filled with ballast, resulting in an immersion) and with the use of a crane (the structure is transported to the installation site on board of the vessel and positioned on the seabed by crane)

source: compiled from [13], [14]

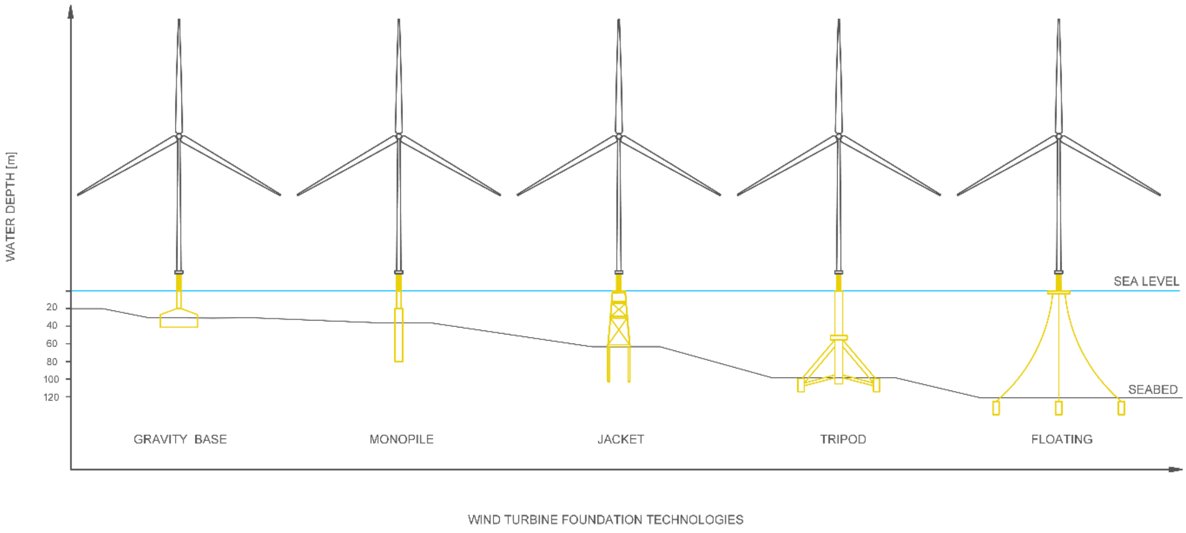

Figure 3.1 Comparison of different foundation types

source: own elaboration, based on [15]

Cables

In general, there are two possibilities for the electrical power transmission from the turbines: high voltage alternating current (HVAC) and high voltage direct current (HVDC). The voltages for AC connections could have the value 220 kV, 275 kV, and 400 kV, while for DC connections even up to 525 kV. Historically, the former option has been more popular and is more suitable for shorter export cable routes. Among the advantages are easy protection system design and the use of transformers to change between different voltage levels. On the other hand, many dynamic and transient electromagnetic problems have occurred due to the combination of high-capacitance submarine cables and seawater. As a result, the active power transmission capacity is reduced. The latter technology, HVDC, is mostly used in projects located further from the shore. HVAC transmission topology is formed by the following elements: an offshore substation that increases the offshore voltage level to the transmission voltage level, three-core HVAC submarine transmission cables, reactive compensation units on both ends (offshore and onshore), and an onshore substation. Furthermore, HVAC transmission can be realised in two different ways: with or without the marine reactive power compensation platform (RCP). HVDC transmission topology consists of an offshore substation that increases the voltage level to the level of the transmission line, AC/DC rectifier, AC and DC filters, DC filtering reactance, DC cables, DC/AC converter, and an onshore substation. The transmission using HVDC is considered more advanced and requires an additional component – VSC (Voltage Source Converter) that converts power from AC to DC [13], [14]. Figure 3.2 and Figure 3.3 present a comparison of the two systems.

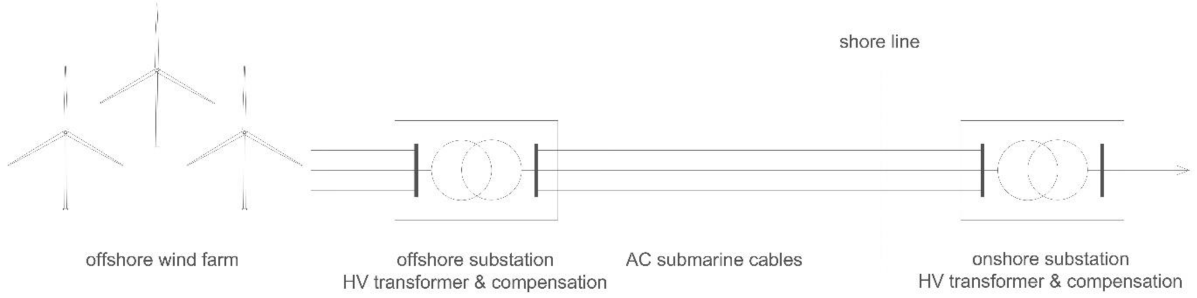

Figure 3.2 Offshore wind power plant HVAC transmission system
source: own elaboration, based on [14]

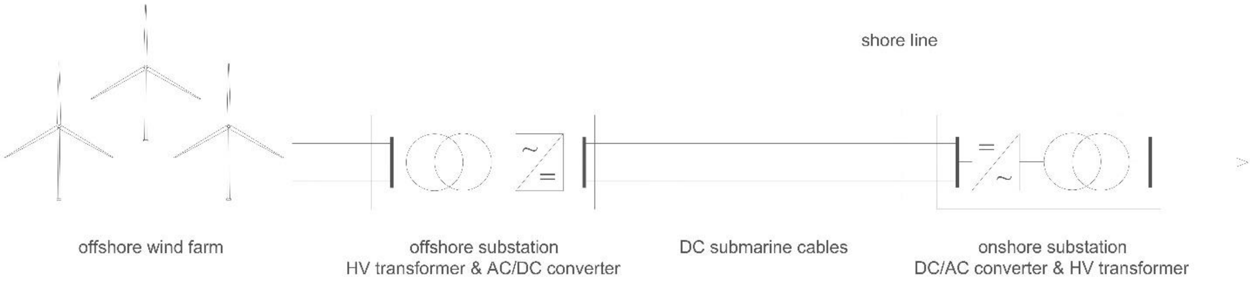

Figure 3.3 Offshore wind power plant HVDC transmission system
source: own elaboration, based on [14]

Offshore substations (OSS)

All turbines are connected through internal cables to an offshore substation where energy is transmitted. Later on, received energy is raised to the high voltage required by the export cables. Every substation is equipped with the set of devices necessary for safe and efficient voltage conversion. In addition, there are other elements such as a backup diesel generator, control and monitoring system, fire protection system, and others. Offshore substations are usually placed on monopile or jacket foundations. Depending on the used technology - HVAC or HVDC, different platforms are needed. For HVAC solutions two main types are usually applied, the classic marine substation, which is a single substation for an entire offshore wind farm, or a much smaller modular OSS that supplies only one export cable. Using one substation results in a more complex installation process due to its dimensions and weight. However, this kind of platform can satisfy the needs of an entire offshore wind farm because it can be equipped with more than one transformer and export cable connection. On the contrary, lighter and smaller modular OSS are suitable for smaller projects but also for bigger ones when several substations are considered. They require smaller foundations and contain one transformer that supplies one export cable. For HVDC technology, usually a single OSS is applied. What differentiates this approach from the previous ones is the usage of an AC/DC converter [13]. Table 3.4 presents the comparison of different types of offshore substations.

Table 3.3 OSS comparison

Substation type	Technology	Dimensions [m]	Weight [t]
single substation	HVAC	80×60×40	4 000
modular substation	HVAC	40×35×35	2 500
single substation	HVDC	70×60×40	12 000 - 18 000

source: compiled from [13], [16]

Onshore substations

The remaining component of an offshore wind farm infrastructure, an onshore substation, is a building equipped with transformers located close to the shore. The aim of the station is to change the voltage from the level of export cables to the level allowed in the grid. In addition to transformers, there are such components as high-voltage busbars, compensation reactors, or harmonic filters. Furthermore, HVDC technology requires a converter to change power from DC to AC. All of the equipment ensures the quality of the energy and provides output signals through measurement and control devices. In the vicinity of the substation, there should be a grid operator’s station or a connection point to an existing power line where the energy would be transmitted. As a result, the energy produced by the offshore wind farm reaches end users [13].

Wind farm size

Commercial offshore wind farms usually consist of more than a few turbines. The number of turbines is associated primarily with the available area and chosen technology (size of the turbine). The derivative of the mentioned factors is spacing among the turbines. The distance should be sufficient to minimise the aerodynamic losses and so-called wake effect [17]. The extraction of the energy from the wind by the turbine causes the difference between wind speed values upstream and downstream. Wind leaving the turbine is turbulent and its speed decreases. The wake of the turbine is this downstream wind that eventually returns to free stream conditions. When the distance is not satisfactory, the downwind turbine is shadowed by the turbine that produces the wake. As a consequence, wind speed is reduced, so energy production is lower, and wind is more turbulent which potentially increases the dynamic mechanical loading on downwind turbines. In order to avoid the outcome of the wake effect, the appropriate spacing is required. An example proposed by [18] is to maintain 500 m - 1000 m among turbines. Other sources suggest relating the distance to the rotor diameter of the proposed turbines (D). The optimal stream-wise spacing has been found within 10 - 15 D [19]–[21].

3.2. WIND ENERGY DEVELOPMENT

3.2.1. OFFSHORE WIND IN THE WORLD

In 2019 the Energy Sector Management Assistance Program (ESMAP) published a report identifying four subsets which describe the potential of offshore wind development. The technical potential is considered to have the widest range, determined by water depth and wind speed. It is then followed by locational potential, economic potential, and actual deployment, of which each successive one covers a smaller range. The final realistic potential results are only a fraction of the total technical potential. The report [22] analysed eight countries (Brazil, India, Morocco, Philippines, South Africa, Sri Lanka, Turkey, and Vietnam) in terms of technical potential for fixed and floating offshore wind. The total estimated potential proposed by the authors was almost 3,1 TW. Moreover, further studies show that 115 countries in the world accumulate the technically extractable offshore wind potential of 71 TW, of which only 20 TW is suitable for fixed offshore wind turbines [23].

More than thirty years have passed since the last decade of the 20th century when the first offshore projects were established. By the end of 2022, total offshore wind capacity reached 64,3 GW, and new capacities of 8,8 GW were fed into the grid [24]. The chart below (Figure 3.4) presents the distribution of offshore wind installations worldwide. 49% of all offshore installations belong to China and 22% to the United Kingdom. Germany owns 13% and both Denmark and the Netherlands 4%. The remaining value of 9% stands for the capacities of other countries, mostly European ones such as Belgium and France but also Vietnam, Japan, South Korea, Taiwan, and the USA [24].

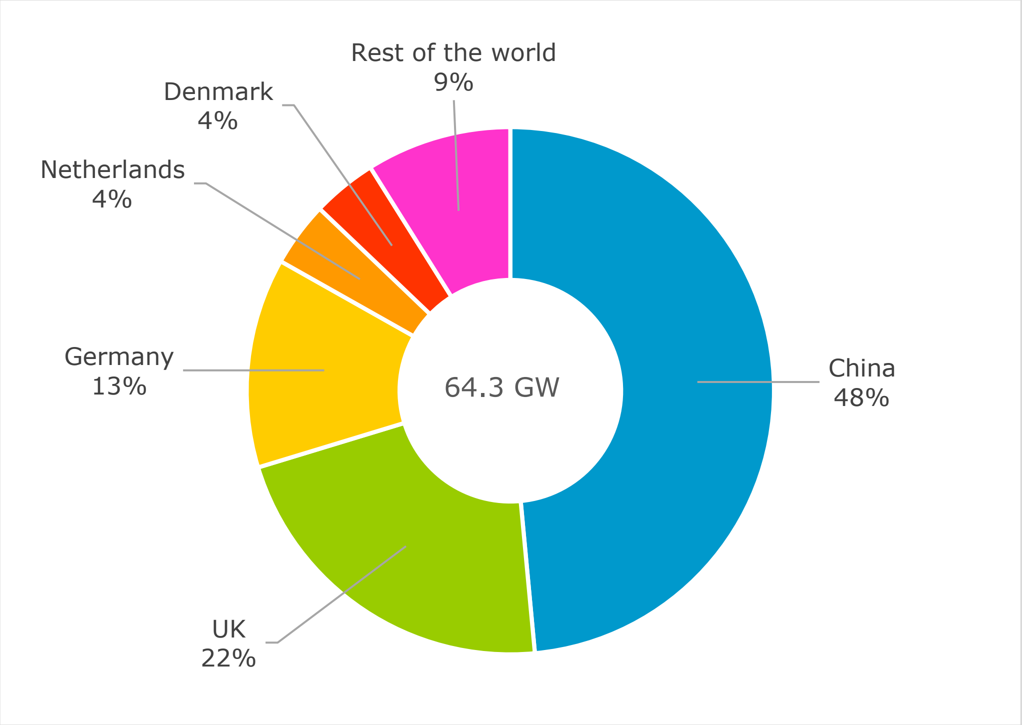

Figure 3.4 Offshore wind power distribution in the world

source: compiled from [24]

The most successful year for offshore wind so far was 2021, when 21 GW were commissioned [24]. To put this into perspective, in 2022 the total installed wind capacity, both onshore and offshore, was 909 GW, then rising to 1 TW in June of 2023 [25]. There are fewer offshore than onshore projects, however, the offshore industry is growing dynamically. The statistics regarding new commissions reflect on the matter. Between 2010 and 2014, around +1 GW of new power was fed into the grid every year. In the following years, the values increased gradually, reaching +8,8 GW in 2022 and even +21 GW in 2021. This results in an increment in the total installed capacity. In 2010 it was around 3 GW, and in 2022 64,3 GW already. Both the total installed capacity and the development of new installations show an upward trend as illustrated in Figure 3.5. Additionally, more and more countries are declaring the development of new offshore projects. Especially in the Pacific region, North America and Europe [24].

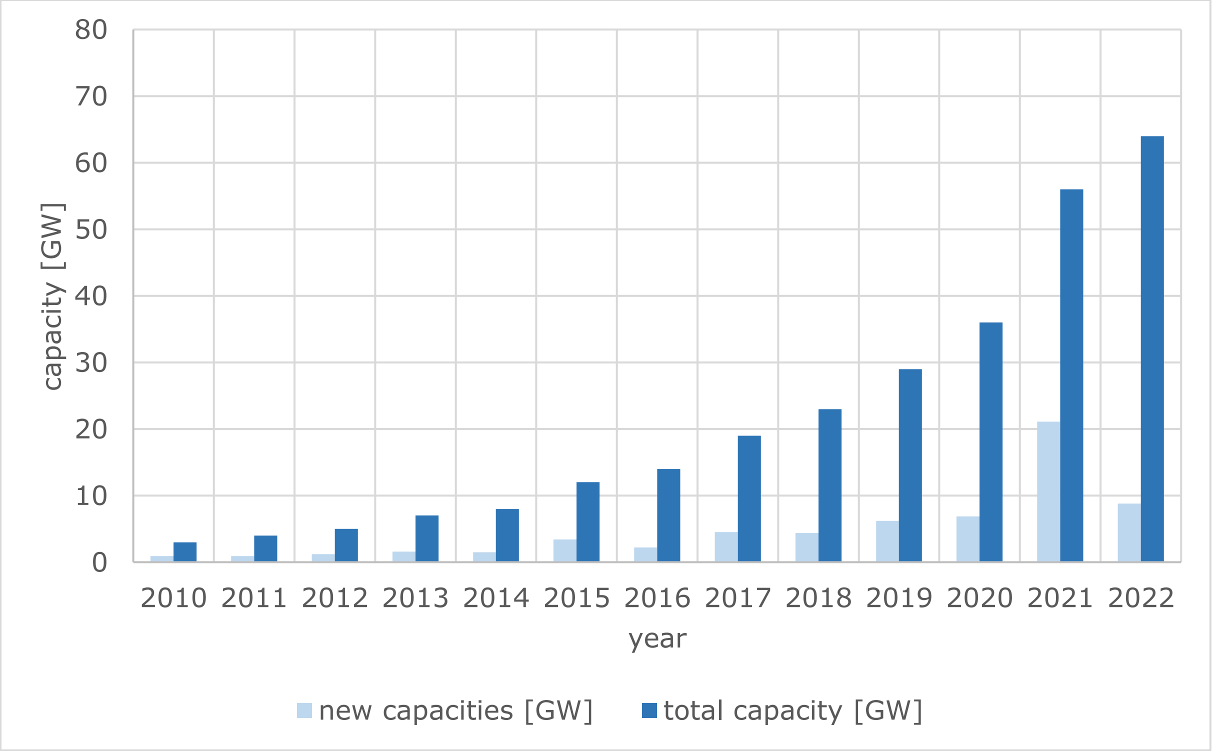

Figure 3.5 New commissions and total capacity of offshore wind in the world in the years 2010 – 2022

source: compiled from [24]

China

Without a doubt, the biggest market for offshore wind is China which owns 49% of the total installed capacity. By the end of 2022, total power reached 31,4 GW [24]. The development is a result of favourable wind conditions, long coastal lines, and the need to transform the energy mix by replacing coal sources with renewables. Offshore wind farms are located in the waters of the Yellow Sea, East China Sea, and South China Sea as well. The most promising regions for further development are near power-intensive provinces like Guangdong and Jiangsu [26]. According to [27] in 2022 there were 73 offshore wind farm projects distributed along the entire coastline, 35 of which were completed while 38 were under construction. One of the biggest offshore wind farms is CGN Shanwei Jiazi I located in the South China Sea, Guangdong where the installed capacity reaches 503,1 MW. The OWF is formed with 78 turbines and there is one offshore platform [28].

Asia-Pacific (APAC)

Not only is the offshore wind industry growing in China but there are also numerous installations in other countries in the Asia-Pacific (APAC) region. For example, Taiwan reported 1175 MW of new offshore wind installations in 2022. The total installed capacity in this country is 1412 MW. Similarly, Vietnam has offshore wind farms with a capacity of 874 MW, and South Korea with that of 142 MW. Both countries did not feed into the grid any new installations in 2022. Another mature Asian market, Japan has already installed 136 MW, 84 MW of which were commissioned in 2022. The total capacity of offshore wind farms in the Asia-Pacific region excluding China equals 2,564 GW. By 2027, Taiwan aims to add 6,9 GW, South Korea 2,3 GW, Vietnam 2,2 GW, and Japan 0,9 GW [24].

USA

In North America currently only the USA has fully commissioned offshore wind projects. The total capacity is 42 MW, and in 2023 grid connection of the first industrial-scale offshore wind project is expected. However, in the next five years, commissions of 15 GW have been predicted. That would result in the USA being the third biggest market after China and the UK with regard to the new capacities [24].

3.2.2. OFFSHORE WIND IN EUROPE

Historically, the first offshore projects were developed in Europe. The continent remains a large market for offshore wind that grows systematically. By the end of 2022, offshore wind projects in 13 countries contributed to the total installed capacity of 30,267 GW. 126 wind farms consist of 5954 turbines. Nevertheless, over 80% of the installed capacity belongs to three countries: the UK, Germany, and the Netherlands. That is the reason why 79% of all turbines are located in the North Sea. Fewer projects are also situated in the Irish Sea and the Baltic Sea [29]. The chart below (Figure 3.6) presents the distribution of offshore wind installations in Europe. As mentioned, three countries, the UK, Germany, and the Netherlands dominate and own respectively 46%, 26,6%, and 9,3% of all installed capacities.

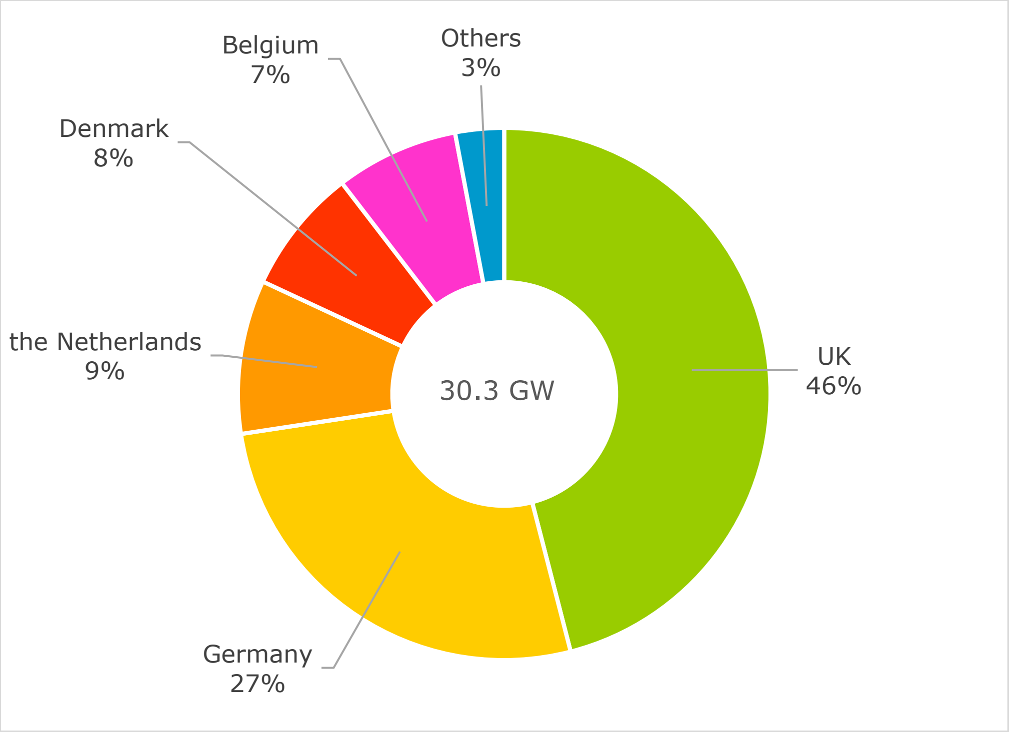

Figure 3.6 Offshore wind power distribution in Europe
source: compiled from [24]

In 2022 2,46 GW were commissioned in Europe (UK, France, the Netherlands, Germany, Norway, and Italy). The value is the lowest since 2016. The best year in terms of new additions was 2019 when 3,7 GW were fed into the grid. As chart below presents (Figure 3.7), each year new projects are developed. Since 2015 the total installed power has tripled and should continue to increase. The average size of the offshore wind farm has doubled since 2016 and is now over 800 MW. Almost half of the total installed capacity in 2022 belongs to the UK (1179 MW) [29], [30].

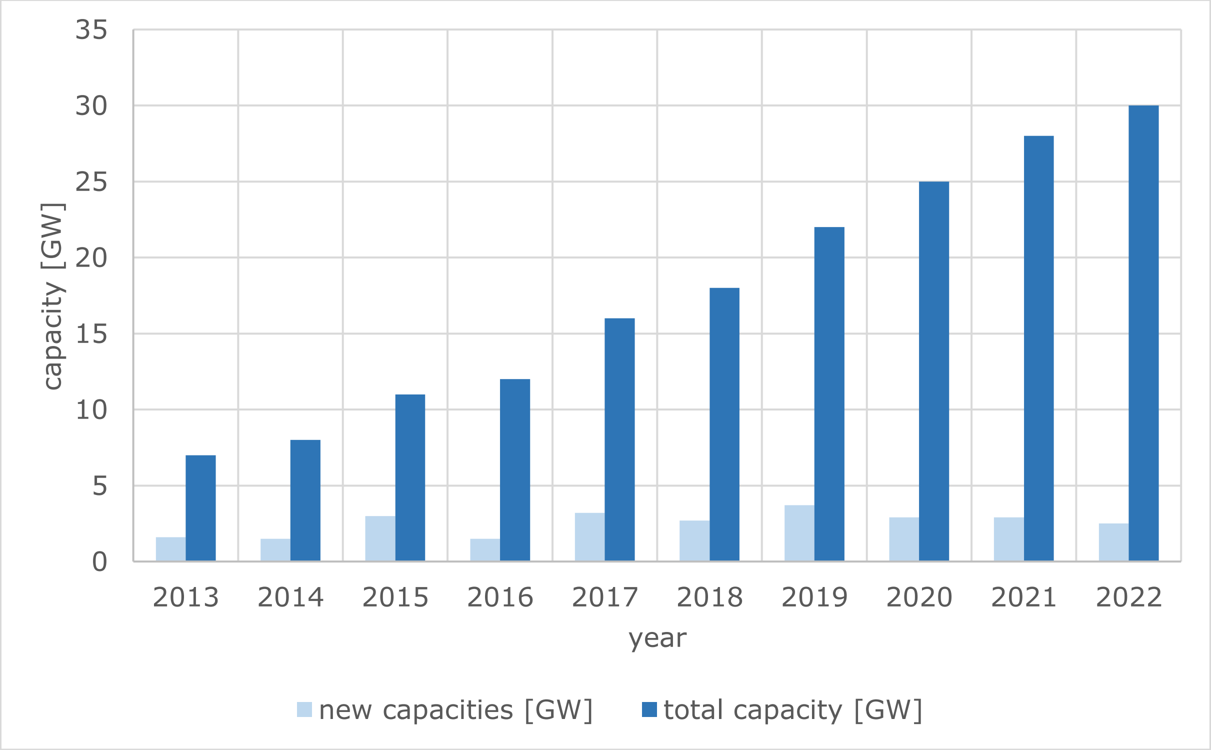

Figure 3.7 New commissions and total capacity of offshore wind in Europe in years 2013 – 2022

source: compiled from [24]

UK

The largest market in Europe is the UK which owns 46% of all installed capacities. The UK has 45 grid-connected offshore wind farms with a total capacity of 13,9 GW [29]. The world's largest operational offshore wind farm, Hornsea 2 (1,386 GW) belongs to the UK as well. It consists of 165 8 MW turbines and can provide power to over 1,4 million homes [31]. Currently another large project, Dogger Bank Wind Farm, which consists of three phases is under development. Once fully commissioned, it will have a capacity of 3,6 GW and will be the world's largest offshore wind farm. Dogger Bank will be located between 125 and 290 km off the east coast of Yorkshire, on an isolated sandbank [32]. Most UK projects are concentrated in the North Sea due to the excellent wind conditions, but there are wind farms located in the Irish Sea as well [33]. There are plans to install 12,7 GW until 2027 and reach 50 GW by 2030. Additionally, they intend to have 5 GW of floating offshore projects by 2030. To accomplish these ambitious goals, they reduced the time needed to voice consent for the new farms from 4 years to 1 year [29].

Germany

The second largest market in terms of installed capacity is Germany which owns 26,6% corresponding to 8,1 GW (30 wind farms). In 2022, they added a capacity of 387 MW. Germany aims to have connected 30 GW of power by 2030, and in the next five years, there are plans to feed 6,4 GW into the grid [29]. Germany owns offshore projects located in the North Sea and in the Baltic Sea [33]. Offshore wind farm Kaskasi is a recently commissioned project that is composed of 38 turbines of 9 MW each, contributing to the total capacity of 342 MW. The offshore wind farm is located 35 km from Heligoland in the German part of the North Sea. What differentiates this farm from others is the use of recyclable wind turbine blades [34].

Netherlands

The Netherlands contributes to 9,3% of the total capacity installed in Europe. By the end of 2022, they owned 2,8 GW distributed among 10 farms. In the following five years, the Netherlands plans to commission 4,3 GW, and by 2030 they aspire to have 21,5 GW [29]. One of the largest ongoing projects is a Hollandse Kust Zuid, composed of four parcels. The site is located 18 km from the shore, between the Zandvoort and The Hague. The advantages of the locations are suitable seabed, favourable weather conditions, appropriate depth of water, and the proximity of the port. Hollandse Kust Zuid will be the first offshore wind farm developed without any government subsidy. The total capacity of four farms will be 1520 MW, and turbines of 11 MW will be used [33], [35].

3.2.3. OFFSHORE WIND IN POLAND

In the Baltic Sea, mean wind speed values are around 8-10 m/s at the height of 100 m. Moreover, the higher values are in the southern part, in the Polish territory [36]. According to the [37] the most frequent wind direction in Polish maritime areas is from west to east. More specifically, the authors mention the western sector of the wind rose (between 255° to 285°), and that it concerns 17% of the wind rose. Additionally, the report indicates that the average wind speed is 10 m/s at 100 m and 10,46 m/s at 150 m. The distribution of the hours per year, determined by the wind speed intervals at 150 m is presented in Table 3.4.

Table 3.4 Wind speed distribution in the Polish part of the Baltic Sea

Wind speed [m/s]	<4	4-8	8-12	12-25	>25
The frequency of hours per year	7,8%	25,5%	31,1%	35,2%	0,4%

source: compiled from [37]

According to Wind Europe, today there is over 30 GW of offshore wind power installed in European waters. The capacity of projects realised in the Baltic Sea is around 2,8 GW [29]. By 2030, total capacity could increase up to 11 GW or even 14 GW. There are predictions that by 2050, in the Baltic Sea, there will be 85 GW of offshore wind installed. As a result, the Baltic Sea would be the second-largest basin for offshore wind in Europe, after the North Sea [38]. The offshore wind technical potential of the Polish part of the Baltic Sea (EEZ) is estimated to be 116 GW according to [23]. The total value of the mentioned potential is then divided to be suitable for fixed (60 GW) and for floating (56 GW) technologies. Nevertheless, the realistic potential is much smaller, according to PEP2040 11 GW [2], and 33 GW based on the PSEW report [39].

The act [7] *Ustawa o promowaniu wytwarzania energii elektrycznej w morskich farmach wiatrowych* defines the available locations for offshore wind farms projects. The areas are listed in two appendixes, which are often referred to as areas from the first or second phase. Additionally, the regulation [40] *Rozporządzenie w sprawie przyjęcia planu zagospodarowania przestrzennego morskich wód wewnętrznych, morza terytorialnego i wyłącznej strefy ekonomicznej w skali 1:200 000* determines the possible uses of the exclusive economic zone (EEZ) where offshore wind projects could be developed. Projects that are currently under development have a total capacity of around 8,4 GW. Moreover, projects with a total capacity of 5,9 GW have received support in the contract for difference (CfD) formula.

The most advanced projects are described below, and the details are listed in Table 3.5. All of them obtained the location permit that is called PSZW (*Pozwolenie na wznoszenie sztucznych wysp*), some of them also received an environmental decision, a grid-connection agreement or other required permits. The areas from the second appendix have been submitted for consideration by investors, and then the submitted applications were revised by the Ministry of Infrastructure. By mid-2023, all of the proceedings were concluded. Five areas were granted to the PGE Group (total planned capacity 3,9 GW), five locations were awarded to the Orlen Group (total planned capacity 5,2 GW), and one site remained excluded due to proximity to the NATO site [41].

Highly-developed projects are called Baltic Power, Baltica I, Baltica II, Baltica III, BC-WIND, F.E.W. Baltic II, MFW Bałtyk I, MFW Bałtyk II, and MFW Bałtyk III. Figure 3.8 presents the location of these OWF as well as areas proposed during the second phase.

Baltic Power

Baltic Power is the project developed by PKN Orlen and Northland Power as a joint venture. The total capacity of the wind farm is planned to be 1,2 GW. Once completed, Baltic Power is going to be one of the biggest offshore wind farms in the world. There are plans to install 76 turbines in total, each of 15 MW capacity, more than 200 m in height, and 43 000 m^2 of rotor area. A world-class leader in wind energy - Vestas was selected as a supplier [5]. The Baltic Power wind farm will be located 23 km from the coast near Łeba. The chain of supply is expected to include a high percentage of Polish vendors. The construction work will begin in 2024, whereas the start of operation is scheduled for 2026. Baltic Power has already obtained the location permit, the environmental decision for the farm and the grid-connection infrastructure, the grid connection agreement, a contract for difference (CfD), and has secured contracts for the production, transport, and installation of all most significant elements. Moreover, it is the first offshore project that has received the building permit for the onshore part. The next step will be obtaining the same permit for the offshore part [42].

Baltica 1, Baltica 2, Baltica 3

The largest electricity provider in Poland, PGE - Polish Energy Group has three ongoing projects named Baltica 1, Baltica 2, and Baltica 3. Two of them (Baltica 2 and Baltica 3) are developed with a Danish partner in the form of a joint venture (50%-50%). Ørsted, the owner of the world's biggest wind farm in operation - Hornsea 2, is a global leader in the offshore wind industry [43]. The joined capacity of Baltica 2 and Baltica 3 in is expected to be up to 2,5 GW, while the capacity of Baltica 1 is planned to be 1 GW. As it has been recently declared, Siemens Gamesa will provide wind turbines for the Baltica 2 project, each with 14 MW capacity. Projects that are developed with a partner have an earlier commercial operational date (COD), probably due to the location, and a closer distance from land. Both projects have obtained location permits, environmental decisions for the offshore part, the grid connection agreement, a contract for difference (CfD), and environmental decisions for connection infrastructure. The next part will be obtaining the building permit. On the other hand, Baltica I has received the location permit, and the grid-connection agreement [44], [45].

BC-Wind

BC-Wind is a project developed by Ocean Winds. The company was created as a joint venture between two global leaders ENGIE, and EDPR. Project BC-Wind has two parts B-Wind and C-Wind, that together are expected to have 0,399 MW. The total number of turbines will be 31 with a nominal power of no less than 13 MW. The project has already obtained a location decision, the grid connection agreement, a contract for difference (CfD), and the environmental decision for the offshore part. Ocean Winds considers two types of foundation, monopile, or jacket. The farm will be located approximately 23 km from the shore and will cover an area of 90,94 km^2. According to the schedule, BC-Wind farm should start producing energy in 2028 [46].

F.E.W. Baltic II

RWE, a world-class leader in offshore wind energy, owns and operates a total of 3,3 GW of offshore wind projects in Europe. The company currently develops the 1,4 GW Sofia Offshore Wind Farm – one of the largest projects in the world, that will be located 195 km from the coast [47]. In the Polish part of the Baltic Sea, RWE is developing a project with a planned capacity of 0,350 GW with the help of Polish and German experts. An offshore wind farm called F.E.W. Baltic II will be located approximately 55 km from the shore, with a grid landing point near Ustka and a grid connection point near Słupsk. The average water depth in the proposed location is 42 m. F.E.W. Baltic II will cover an area of 41 km^2. Apart from the location permit, RWE has already obtained the contract for difference (CfD) and the environmental decision. Moreover, the geophysical and geotechnical surveys have been completed. Siemens Gamesa has been chosen to provide 25 turbines with a capacity of 14 MW each [48].

MFW Bałtyk I, MFW Bałtyk II, MFW Bałtyk III

Poleneria together with a partner – Equinor is currently working on three projects called MFW Bałtyk I, MFW Bałtyk II, and MFW Bałtyk III. Two of them, MFW Bałtyk II and MFW Bałtyk III will be located about 40 and 27 km from the port of Łeba. The combined capacity is supposed to be 1,44 GW. For MFW Bałtyk II, investors have received the location permit, the environmental decision, the grid-connection agreement, and a contract for difference (CfD). For MFW Bałtyk III, the location permit, the environmental decision for both the farm and the transmission infrastructure, the grid-connection agreement, and the permit establishing the location and conditions for maintaining offshore cables in marine areas. The third project, MFW Bałtyk I is currently in its earlier phase and once completed, will have 1,56 GW capacity. It will be situated 81 km from the shore, on the border of the Polish exclusive economic zone, and will cover an area of 128,5 km^2. MFW Bałtyk I has already obtained a location permit and has submitted the application for the environmental decision [49]–[51].

Table 3.5 Currently developed offshore wind projects in Poland

Name of the project	Investor	Capacity [GW]	Distance to the land [km]	Area [km²]	Commercial operational date (COD)
Baltic Power	PKN Orlen, Northland Power Inc.	1,2	23	130	2026
Baltica 1	PGE	1	80	108	after 2030
Baltica 2	PGE, Ørsted	1,5	40	190	2027
Baltica 3		1,05	25	130	2026
BC-Wind	Ocean Winds	0,399	23	90,94	2028
F.E.W. Baltic II	RWE	0,35	50	41	2026
MFW Bałtyk I	Equinor, Polenergia	1,56	80	128,53	after 2030
MFW Bałtyk II		0,72	37	122	2028
MFW Bałtyk III		0,72	22	119,52	2028

source: compiled from [42], [44]–[46], [48]–[51]

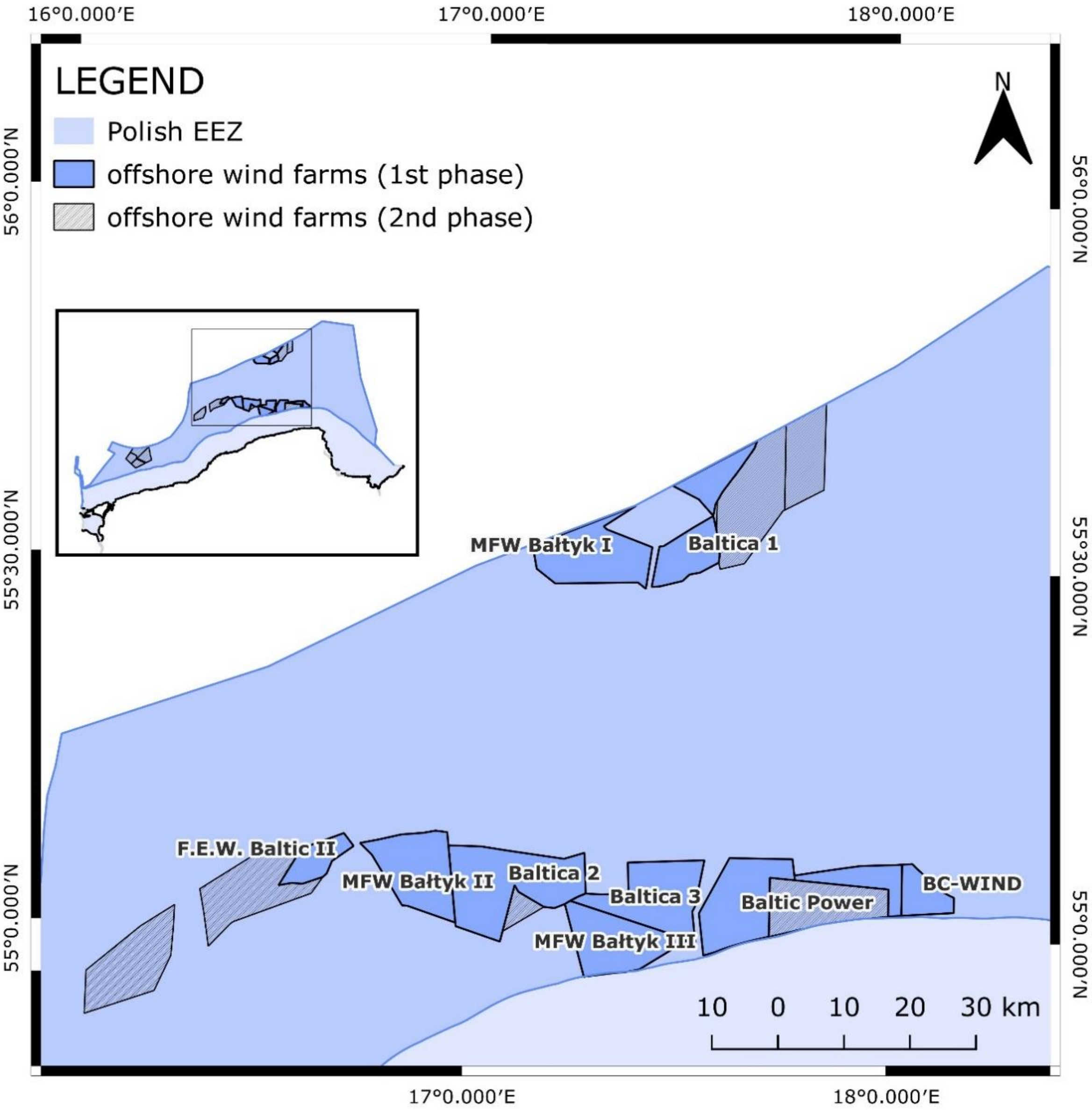

Figure 3.8 Currently developed offshore wind projects in Poland

source: own elaboration

4. OPTIMIZATION OF OFFSHORE WIND FARM LOCATIONS

4.1. CONSTRAINTS

The implementation of different locational restrictions for offshore wind farms depends primarily on the specifics of the area. The constraints for the Chinese coast are not necessarily the same as for the UK. For example, [52] indicates the need to maintain a distance from seismic fault lines, which is specific to the Turkish coast and will not apply to the North Sea, for example. Nevertheless, some restrictions apply to the majority of areas predisposed to offshore wind energy like wind energy potential or water depth.

For the purpose of optimisation, the restrictions should be identified and then formulated as constraints. The following step would be to assign the possible and/or required outcome. For example, the wind speed should be maximised while conservation areas and bird migratory routes should be excluded [52].

[53] have divided the constraints into three types of limitation factors: technical, regulatory, and economical. Similarly, Kim et al. have classified the criteria for offshore wind farm site selection using four categories: energy resources and profitability, conservation area and view protection, human activities, marine environment, and marine ecology. Each of the above-mentioned categories includes additional subpoints (criteria) that identify the detailed parameters [54]. Criteria proposed in different papers can be easily assigned to the four categories. The examples are described and interpreted below.

4.1.1. ENERGY RESOURCES AND PROFITABILITY

Among the constraints that could be assigned to the category *energy resources and profitability* are aspects regarding wind energy potential and water depth. In general, wind energy potential is considered a determining factor for offshore wind farm location, and its value should be maximised [52]. The minimum wind speed that is perceived as suitable for offshore energy use is around 6,5 m/s at a height of 100 m [52]. Another way in which the wind potential can be determined is by calculating the wind power density. An annual power density of approximately 200 W/m^2 is accepted as a suitable value for offshore wind energy purposes [54]. The water depth constraint determines the possibility of OWF development in fixed or floating technology. There is no universal foundation type, and various technologies are applied depending on water depth as well as the consistency of the seabed. In shallow waters (below 30 m) monopile foundations are most commonly used, and where the sea is deeper (30-60 m), jacket foundations are usually applied. Floating technology is promising for deep waters above 60 m [55]. To summarise, the constraint of the water depth might be formulated as less or equal to 100 m with the objective of minimising the value [52]. Moreover, distance to the coast determines for example cabling, transportation of the turbines, substations, and other necessary equipment that influences the cost. Additionally, the offshore and onshore grid infrastructure should be considered, cables that already exist reduce the cost significantly. Similarly, the existing onshore substation infrastructure.

4.1.2. CONSERVATION AREA AND VIEW PROTECTION

As a continuance, *conservation areas and view protection* should be analysed. The constraints assigned to that category are usually excluded from the offshore wind development. Among them are seabird conservation areas. Wind turbines can pose a threat to birds flying nearby. Despite the use of safeguards in the form of motion detectors, sensors, acoustic signals, etc., the problem has not yet been fully eliminated. For this reason, offshore wind farms are usually not located in protected bird habitat areas, [56] suggests a buffer of 3-5 km. Another example of a constraint is the natural environment conservation area. Areas such as Natura 2000, which were established to protect plant and animal species, usually cannot be used for other purposes, including OWFs. For example, [57] introduces the following buffers: 1 km for a near-shore scenario and 2 km for a far-shore scenario. Other protected areas are taken into account as well [52], [54], [57]. Additionally, coastal landscapes should be considered. Revised papers offer a buffer from land to protect the marine view of 2 km [54] or even 8-16 km [56]. The distance from various types of conservation areas should therefore be maximised.

4.1.3. HUMAN ACTIVITIES

Human activities other than offshore wind farms include fishing areas, harbour developments, shipping routes, anchorages, shipwrecks, submarine cables and pipelines, oil and gas infrastructure, existing wind farms, military units, and marine leisure activities [52], [54]–[57]. In this category, as a rule, the buffers are proposed. For example, for anchorages and fishing areas [57] proposes a 1-2 km buffer while [52] suggests a 1 km buffer from shipwrecks and offshore petroleum and natural gas wells, and at least 750 m buffer from subsea communication cables and subsea pipelines. The distance maintained from densely used shipping routes should be at least 1 km according to [52]. The buffer is applied in order to decrease the risk of a collision with the infrastructure.

4.1.4. MARINE ENVIRONMENT AND MARINE ECOLOGY

Last but not least, there are constraints from the category of *marine environment and marine ecology*. [54] analysed marine water quality and excluded areas with 1st-grade dissolved oxygen (7,5 mg/l). Similarly, they disregarded areas with increased activity of marine benthos and marine mammals. As it has been mentioned, offshore wind farms have an influence on birds. OWF can affect birds in terms of collision risk, short-term and long-term habitat loss, barriers to movement, and disconnection of ecological units [58]. To prevent and reduce the damages, numerous papers exclude and/or apply a buffer from birds' migratory routes [52], [54], [56].

4.2. LITERATURE REVIEW

The table on the next page (Table 4.1) presents the approaches described in articles regarding the topic, as well as the selection criteria and received results. The solutions concern the method of criteria selection and then data implementation into the GIS software.

Table 4.1. Offshore wind farm location selection in different sources

Author	Title	Region	Approach	Selection decision	Results
Kim T. et al. [54]	Offshore wind farm site selection study around Jeju Island, South Korea	Jeju Island, South Korea	Four scenarios that focus on different criteria	• equally weighted method • each subsequent scenario considered a wider set of selection criteria	to receive optimal sites, all of the criteria should be reviewed
Cavazzi S., Dutton A.G. [55]	An Offshore Wind Energy Geographic Information System (OWE-GIS) for assessment of the UK's offshore wind energy potential	UK-REZ (UK Renewable Energy Zone)	The entire UK-REZ was divided into grid squares of 10 km × 10 km, and then exclusions have been applied. The LCOE formula was calculated. Additionally, the model's sensitivity was tested	• equally weighted method • data collection, application of exclusions, estimation of energy yield and cost • investigation of the model's sensitivity	maximum offshore wind energy potential and economically accessible potential taking into account all of the constraints
Hong L., Möller B. [56]	Offshore wind energy potential in China: Under technical, spatial and economic constraints	EEZ of China	The boundary of the study is the EEZ of China, and the spatial resolution is 1 km2. The study presents: a GIS-based energy output model, GIS-based cost model, GIS-based marine spatial planning	• use of technical, spatial and economic constraints • assumption of the number of wind farms, turbines, installed capacity • use of the power curves from WindPRO software to assess the energy production and annual energy output per area	the technical, spatial, and economic potential of offshore wind was assessed, and compared with the energy demand of the coastal region
Möller B. et al. [57]	Evaluation of offshore wind resources by scale of development	EEZ of Denmark	The Danish EEZ area was divided into uniform cells of 1 km^2 size, the wind energy potential was calculated using a WAsP/KAMM model. Two scenarios were considered: near shore and far shore.	• assumptions related to non-spatial parameters and cost components • spatial parameters implemented into GIS and the SCREAM model built • the cumulative available wind power and its marginal production costs modelled taking into account: available areas, power production potential, and the associated power production costs.	comparison of the near- and far-shore scenarios considering annual power production [TWh], gross area consumption [km2], installed capacity [MW]
Chaouachi A. et al. [53]	Multi-criteria selection of offshore wind farms: Case study for the Baltic States	EEZ of Lithuania, Latvia, and Estonia - Baltic Sea	identification of the candidate sites using a predefined set of GIS layers, then the introduction of the AHP, corresponding calculation methods, and comparison methodology	• multi-criteria selection approach made using the Analytic Hierarchy Process (AHP) • implementation of the methodology as a case study in the 2020 time horizon	the ranking of the best location for all three Baltic States, histograms of wind distribution and the power generation duration in the top sites for every country

4.3. GIS APPROACH

The first attempts to use geographical layers occurred in 1854. British physicist John Snow discovered a correlation between cases of cholera and the presence of water lines. However, the actual concept of GIS was introduced in the 1960s by Dr. Roger Tomlinson. The first works concerned the storage, collation, and analysis of land use data in Canada. Nowadays, GIS is a type of software that enables the handling of spatial data, that is, information about the location of features or phenomena on the Earth's surface. It includes both the functionality of a conventional database management system and a computerised mapping system. In GIS software, there are two types of data for each object: attribute data (statistics, text, image, etc.) and spatial data (features, objects, and related phenomena). Moreover, the data can be a Vector that stores discrete features (point, line, polygon) or a Raster data that represents a continuous surface. GIS software is implemented with the following objectives: to improve the efficiency of the decision-making processes and planning, to provide efficient means for data distribution and handling, to eradicate duplicated data, to integrate information from many sources, to analyse the queries involving geographical reference data for generation of new information, to update data quickly and at the minimum cost. Examples of software include QGIS, ArcGIS, and MapInfo [59].

Nearly all significant aspects regarding offshore wind farms can be assessed using GIS software. Among them Cavazzi and Dutton have placed: development costs dependent on water depth, distance from the nearest port or grid connection point, the potential energy production dependent on annual average wind speed, potential array losses, turbine availability, operation and maintenance costs, and financial parameters [55]. GIS as an analytical site modelling tool, supports the preliminary selection of new turbine sites. In order to achieve that, numerous conditions and limitations must be taken into account. However, usually not all of the constraints are equally important. For that reason, weighted restrictions could be implemented using for example Analytic Hierarchy Process (AHP) [52], [53].

The exemplary process of site selection using GIS software and AHP could be formulated as follows [53]:

A. Perquisite data processing
    1. GIS data collection
    2. Define a granularity level of sites
B. Pre-selection phase
    1. Define pre-selection criteria
    2. GIS layers mapping of sites characteristics
    3. Pre-selection of sites
C. Sites evaluation and ranking
    1. Define selection objectives and sub-objectives (criterion)
    2. Criterion evaluation for site selection
    3. Pairwise comparison
    4. Weight determination
    5. Calculate the final score index per site
    6. AHP-based sites ranking

5. METHODOLOGY DESCRIPTION

5.1. USED SOFTWARE

QGIS

QGIS is an example of geo-information software. It uses an open-source Geographic Information System (GIS) licensed under the General Public License (GNU). This software allows users to manage geographic data, create their own data, visualise, edit, and perform spatial analysis, or compose maps. Vector, raster, and database formats can be processed using QGIS [60]. GIS as an analytical site modelling tool supports the preliminary selection of new turbine sites. Using the QGIS software the optimal locations were proposed while taking into account the appropriate constraints in the form of layers.

MS EXCEL

Microsoft Excel spreadsheet is a widely known tool for calculations of any kind. The software has multiple mathematical functions and accessible database support. Additionally, it allows a presentation of the processed data in the form of graphs and other figures [61].

5.2. PROPOSED FRAMEWORK

The study concerns the Polish part of the Baltic Sea, more specifically the Exclusive Economic Zone of Poland. The area under analysis is presented below (Figure 5.1). In order to find optimal locations for offshore wind farms, a model in QGIS was developed. Before developing the model, solutions proposed in articles and publications were reviewed. This led to a preliminary selection of location factors on which the feasibility of siting offshore wind farms depends. Then, the availability of source data was verified, and in this way, the final constraints were selected. These are described in detail in subsection *5.3. Criteria selection*. The data was obtained from different sources and in vector or raster format. The individual layers containing the constraints were imported into QGIS software and their properties were adjusted. To receive the final layers tools like buffer, cut, aggregate, and others were used. At the same time, the importance of each constraint was assessed, and the pairwise matrix was created using the Analytic Hierarchy Process (AHP). As a result, weights were assigned to each constraint. The process is broadly described in the subsection *5.4. Analytic Hierarchy Process*. In QGIS software, data from all layers was then aggregated into one grid layer of a 1 km x 1 km spatial resolution. Similarly, areas where offshore wind farms cannot be located, were rejected, and the excluded areas were combined. The sites with the best properties were selected to show the wind farm location suitability.

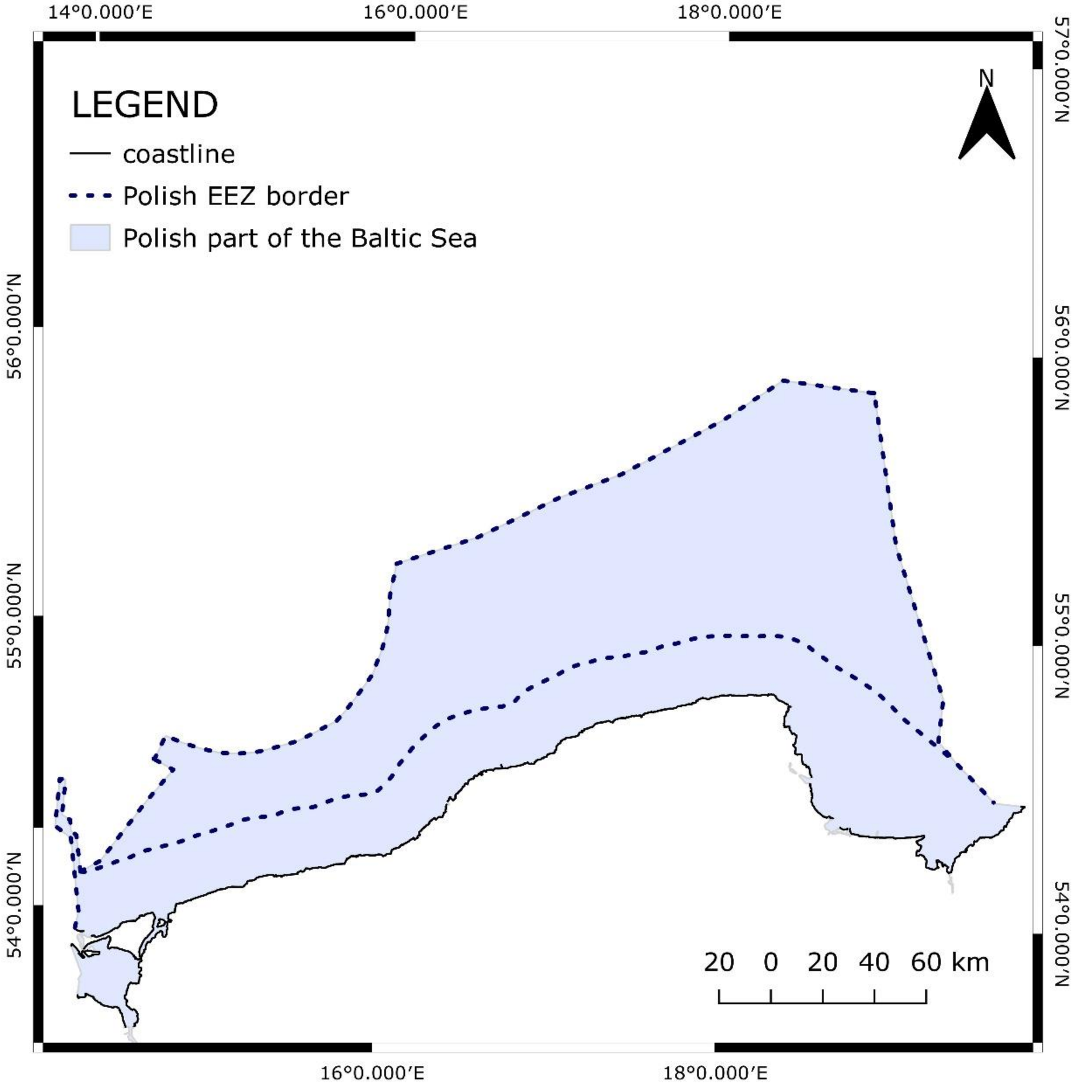

Figure 5.1 Area under investigation – EEZ of Poland

source: own elaboration

5.3. CRITERIA SELECTION

The literature mentions different criteria that can help with the site assessment process. Four categories could be applied regarding all of the constraints: *Energy resources and profitability*, *Conservation area and view protection*, *Human activities*, and *Marine environment and marine ecology*. Various sources provide the data that could be later processed using QGIS software. For the constraints described below the data was obtained from the following sources [36], [62], [63]. However, not all of the data was stored in vector format, which is more suitable for the analysis. Some layers were available only in raster format and in low quality. For that reason, the values could not be very precise. Moreover, not all of the data could be collected. For example, data about bird migratory routes or some of the human activities like military units or anchorages is not considered in the study. Table 5.1 contains the final nine constraints assigned to four categories and the source of raw data implemented to QGIS software.

Table 5.1 Proposed criteria with sources

Category	Criteria	Data source
Energy resource and profitability	wind velocity	Global wind atlas [36]
	water depth	Global wind atlas [36]
Marine environment and marine ecology	distance from nature conservation areas (Natura2000)	SIPAM [62]
Human activities	distance from submarine cables and gas pipelines	SIPAM [62]
	distance from shipping routes	EMODnet [63]
	fishing areas	EMODnet [63]
	distance from shipwrecks	SIPAM [62]
Conservation area and view protection	distance from coast	SIPAM [62]
	EEZ area	SIPAM [62]

5.3.1. WIND VELOCITY

Wind velocity that corresponds with wind energy potential is considered the determining constraint. The speed of the wind is directly related to the energy potential of the site. The minimal suitable value proposed by [52] is 6,5 m/s. Nevertheless, for the Polish part of the Baltic Sea typical values are around 9 m/s. Data about wind velocity was obtained from the Global Wind Atlas for the Polish Exclusive Economic Zone (EEZ). The implemented data concerns the wind speed at a height of 100 m. For this criterion, the objective is to maximise the value.

5.3.2. WATER DEPTH

Water depth is also one of the decisive factors when selecting a location for an offshore wind farm. The depth, as well as the type of seabed, influences the choice of foundation technology for wind turbines (monopile, jacket, gravity base, or floating). The bathymetric data was obtained from the Global Wind Atlas. The depth of the water should not exceed 100 m [52]. The objective proposed for that constraint is to minimise the value.

5.3.3. DISTANCE FROM NATURE CONSERVATION AREAS (NATURA2000)

Due to environmental constraints, some areas need to be excluded completely from the study. Data about nature conservation areas protected by the Natura 2000 programme were provided by the SIPAM database. [56] suggested at least a 5 km buffer from protected areas. The objective regarding this constraint is to maintain at least a 5 km distance from the protected area and to maximise the distance.

5.3.4. DISTANCE FROM SUBMARINE CABLES AND GAS PIPELINES

In order to prevent collision with infrastructure like submarine cables and gas pipelines, the appropriate distance should be maintained. Submarine cables and pipeline data was provided by the SIPAM database. The buffer should not be less than 1 km [52], and these locations should be excluded. The objective of this constraint is to maximise the distance.

5.3.5. DISTANCE FROM SHIPPING ROUTES

One of the uses of the sea is shipping. The Baltic Sea is navigated by cargo ships as well as passenger or military vessels. EMODnet provides data on the most frequent shipping routes for the EEZ. The distance from the shipping routes should not be less than 1 km according to [52] with the objective to maximise.

5.3.6. FISHING AREAS

Fishing could be difficult in the vicinity of offshore wind farms therefore, this constraint is also considered in the selection. Data on fishing intensity in the EEZ was obtained from the EMODnet database. From the concerned areas, a buffer of 1 km was proposed by [57] with the objective to maximise.

5.3.7. DISTANCE FROM SHIPWRECKS

As with undersea cables and gas pipelines, a reasonable distance should also be kept for shipwrecks. The data about shipwrecks was obtained from the SIPAM database. The objective is to maintain at least a 1 km distance from each wreck [52], these locations should be excluded, and the distance maximised.

5.3.8. DISTANCE FROM COASTLINE

The distance to the coast should be minimised in order to allow communication with the onshore station or the harbour. The near-shore areas are not considered due to view protection, only the EEZ areas. The distance from the coastline should not exceed 100 km. The objective of this constraint is to minimise the value.

5.3.9. EEZ AREA

The offshore wind infrastructure can be located inside the borders of the Polish EEZ. Therefore, the Polish territorial sea is excluded as well as the rest of the Baltic Sea. The objective is to locate the infrastructure inside the EEZ area.

5.4. ANALYTICAL HIERARCHY PROCESS

In order to assess the offshore wind potential, it is crucial to recognise the location constraints. Later, one should group the criteria and assign the importance to each one. To address the matter, an Analytic Hierarchy Process could be implemented. The AHP is a tool developed by Saaty to investigate complex problems. AHP is an example of a multi-criteria decision-making method (MCDM) and aims to assign priority using relative weights of criteria that influence a complex decision [64], [65]. Additionally, the AHP method is one of the most commonly used to analyse the current state of the technology. Other examples of tools include technology readiness level, S-curve analysis, and key technologies. The main purpose of the AHP tool is to reduce the uncertainty of the data accuracy and to facilitate the selection process. Typically, the methodology involves two steps: (1) a hierarchical structure development of the decision-making process; and (2) the criteria and options evaluation within the hierarchical structure. To compare the elements on each level of the hierarchical model, the pairs are considered using the relative scale from 1 to 9 (according to Table 5.2). As a result, the importance rating among all elements is determined [66].

Table 5.2 Scale of relative importance

Importance	Definition	Explanation
1	Equal importance	Two sub-objectives contribute equally to the objective
3	Weak importance of one over the other	Experience and judgement slightly favour one over another
5	Essential or strong importance	Experience and judgement strongly favour one over another
7	Demonstrated importance	A sub-objective is strongly favoured and its dominance demonstrated in practice
9	Absolute importance	The evidence favouring one sub-objective or another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values	A compromise is needed

source: compiled from [52]

The mathematical model is presented below (equations 5.1 - 5.10) [67]. All compared elements create a matrix form A with dimension *n* x *m* that reflects the number of elements.

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ a_{n1} & a_{n2} & \cdots & a_{nm} \end{bmatrix}$$

(5.1)

Inside the matrix, there are elements a_{ij} that express the ratio between the importance values of compared criteria *v*. The row number is *i*, and *j* refers to the column number.

$$a_{ij} = \frac{v_i}{v_j}$$

(5.2)

As a continuation, the normalised matrix B is created.

$$B = [b_{ij}]$$

(5.3)

The elements inside the matrix B are calculated according to the formula below.

$$b_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}}$$

(5.4)

Then, criteria weights are calculated as the arithmetic mean value for each row of the normalised matrix, creating matrix *w*.

$$w = [w_i]$$

(5.5)

$$w_i = \frac{\sum_{j=1}^{n} b_{ij}}{n}$$

(5.6)

Moreover, the consistency of the comparison matrix should be verified. Matrix *A* is consistent when the equation (5.7) is true, the product of criteria weight and initial value should be equal to the normalised value. However, a reasonable degree of inconsistency is allowed and common.

$$A \cdot w = B \tag{5.7}$$

The characteristic value, λ_{max} is calculated as the arithmetic mean value of the weighted sum and criteria weights ratio divided by the number of elements *n* according to the equation (5.8).

$$\lambda_{max} = \frac{\sum_{j=1}^{n} \left(\frac{\sum_{i=1}^{n} a_{ij} \cdot w_j}{w_i} \right)}{n} \tag{5.8}$$

Consistency index CI is calculated as follows.

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{5.9}$$

The consistency coefficient takes into account previously calculated CI value and a random index RI. Values of RI depend on the number of considered elements according to Table 5.3.

$$CR = \frac{CI}{RI} \tag{5.10}$$

Table 5.3 The random index *RI*

No. criteria	1	2	3	4	5	6	7	8	9	10
RI	0	0	0,58	0,9	1,12	1,24	1,32	1,41	1,45	1,49

source: compiled from [64]

Among the advantages of the AHP method are the following:

- provides a straightforward solution;
- can be applied in computer software;
- can address a wide range of complex decision problems;
- ability to assess consistency while utilising the method [52], [67].

In this study, the first step while performing the analysis using the AHP method was to develop the hierarchical structure taking into account the main goal of the process, then criteria (constraints) and alternatives. Optimal locations for offshore wind farm development recognition were formulated as the main goal. Nine criteria were selected and analysed, eight of which were used in the AHP method. The criteria or constraints are described in the previous chapter (*5.3. Criteria selection*).

The latter step was to determine the relative importance of the different criteria considering the main goal. The individual decision elements were compared on a scale from 1 to 9 (according to Table 5.2). For example, the *water depth* as well as the *wind velocity* were considered essential to the decision-making process of optimising the offshore wind farm location. Then, the model has been built as a pairwise comparison matrix (rating matrix). The length of the pairwise matrix is equivalent to the number of criteria. In this study, 8x8 (Table 5.4). The ninth criterion, *EEZ area* is not considered in the AHP calculations. The whole Exclusive Economic Zone of Poland is under analysis, and all sites are equally important.

The following step was to create the normalised pairwise matrix (Table 5.5). As a result, criteria weights that represent the relative importance of the chosen criteria were calculated. The next step was to investigate the consistency to check whether the values were accurate. Two indexes were obtained from the calculation, Consistency Index (CI) and Consistency Coefficient (CR). The latter was counterchecked with global standards:

- $CR \leq 5\%$, for 3x3 matrix
- $CR \leq 8\%$, for 4x4 matrix
- $CR \leq 10\%$, for the others matrix

Table 5.4 Pairwise comparison

Criteria		1	2	3	4	5	6	7	8
		wind velocity	water depth	distance from nature conservation areas (Natura 2000)	distance from submarine cables and gas pipelines	distance from shipping routes	fishing areas	distance from shipwrecks	distance from coastline
1	wind velocity	1	3	5	7	7	5	7	4
2	water depth	0,33	1	4	5	5	4	5	0,33
3	distance from nature conservation areas (Natura 2000)	0,20	0,25	1	3	3	4	3	0,25
4	distance from submarine cables and gas pipelines	0,14	0,20	0,33	1	2	3	2	0,20
5	distance from shipping routes	0,14	0,20	0,33	0,50	1	2	0,33	0,17
6	fishing areas	0,20	0,25	0,25	0,33	0,50	1	0,33	0,17
7	distance from shipwrecks	0,14	0,20	0,33	0,50	3	3	1	0,20
8	distance from coastline	0,25	3	4	5	6	6	5	1

source: own elaboration

Table 5.5 Normalised pairwise comparison

Criteria		1	2	3	4	5	6	7	8
		wind velocity	water depth	distance from nature conservation areas (Natura 2000)	distance from submarine cables and gas pipelines	distance from shipping routes	fishing areas	distance from shipwrecks	distance from coastline
1	wind velocity	0,415	0,370	0,328	0,313	0,255	0,179	0,296	0,633
2	water depth	0,138	0,123	0,262	0,224	0,182	0,143	0,211	0,053
3	distance from nature conservation areas (Natura 2000)	0,083	0,031	0,066	0,134	0,109	0,143	0,127	0,040
4	distance from submarine cables and gas pipelines	0,059	0,025	0,022	0,045	0,073	0,107	0,085	0,032
5	distance from shipping routes	0,059	0,025	0,022	0,022	0,036	0,071	0,014	0,026
6	fishing areas	0,083	0,031	0,016	0,015	0,018	0,036	0,014	0,026
7	distance from shipwrecks	0,059	0,025	0,022	0,022	0,109	0,107	0,042	0,032
8	distance from coastline	0,104	0,370	0,262	0,224	0,218	0,214	0,211	0,158

source: own elaboration

The tables below summarise the received results. The criteria weights are in range 0,030 – 0,349, and ranked from 1 to 8 (Table 5.6). *Wind velocity* was revealed the most significant criterion in the study, while *fishing areas* emerged to be the least important one. λ_{max} value was calculated at 8,866 and CI was at 0,124. As a result, the CR was equal to 8,8%, which corresponds with the theory (CR ≤ 10%) (Table 5.7).

Table 5.6 AHP calculation results – criteria weights

Criteria	**Criteria weights**	**Rank**
wind velocity	0,349	1
water depth	0,167	3
distance from nature conservation areas (Natura 2000)	0,091	4
distance from submarine cables and gas pipelines	0,056	5
distance from shipping routes	0,035	7
fishing areas	0,030	8
distance from shipwrecks	0,052	6
distance from coastline	0,220	2

source: own elaboration

Table 5.7 AHP calculation results - consistency

λ_{max}	**CI**	**CR**
8,866	0,124	8,8%

source: own elaboration

5.5. CRITERIA CLASSIFICATION

5.5.1. WIND VELOCITY

For wind energy potential, the input layer was in a raster format, and it presented the data for the whole Baltic Sea region. First, it was clipped to fit the EEZ borders, and then the map was created. As it was mentioned, usually areas with the mean value of 6,5 m/s or more are considered suitable for offshore wind development. The whole area of the EEZ has a wind velocity of 8,85 m/s or more, as it is shown in Figure 5.2. The most promising areas, with the highest values of wind speed, are in the north of the Polish EEZ. Table 5.8 presents the approach for assessing the suitability of sites. The lowest value was 8,85 m/s, and as a result, no area was excluded from the study according to the *wind velocity* constraint. Nevertheless, the three ranges which correspond to the suitability were proposed. For *marginally suitable* areas the assigned value was 1, and for *highly suitable* 3.

Table 5.8 Wind velocity distribution classification

Criteria	Suitability	Range	Assigned value
wind energy potential (wind velocity)	marginally suitable	8,85 – 9,1 m/s	1
	moderately suitable	9,1 – 9,36 m/s	2
	highly suitable	9,36 – 9,6 m/s	3

source: own elaboration

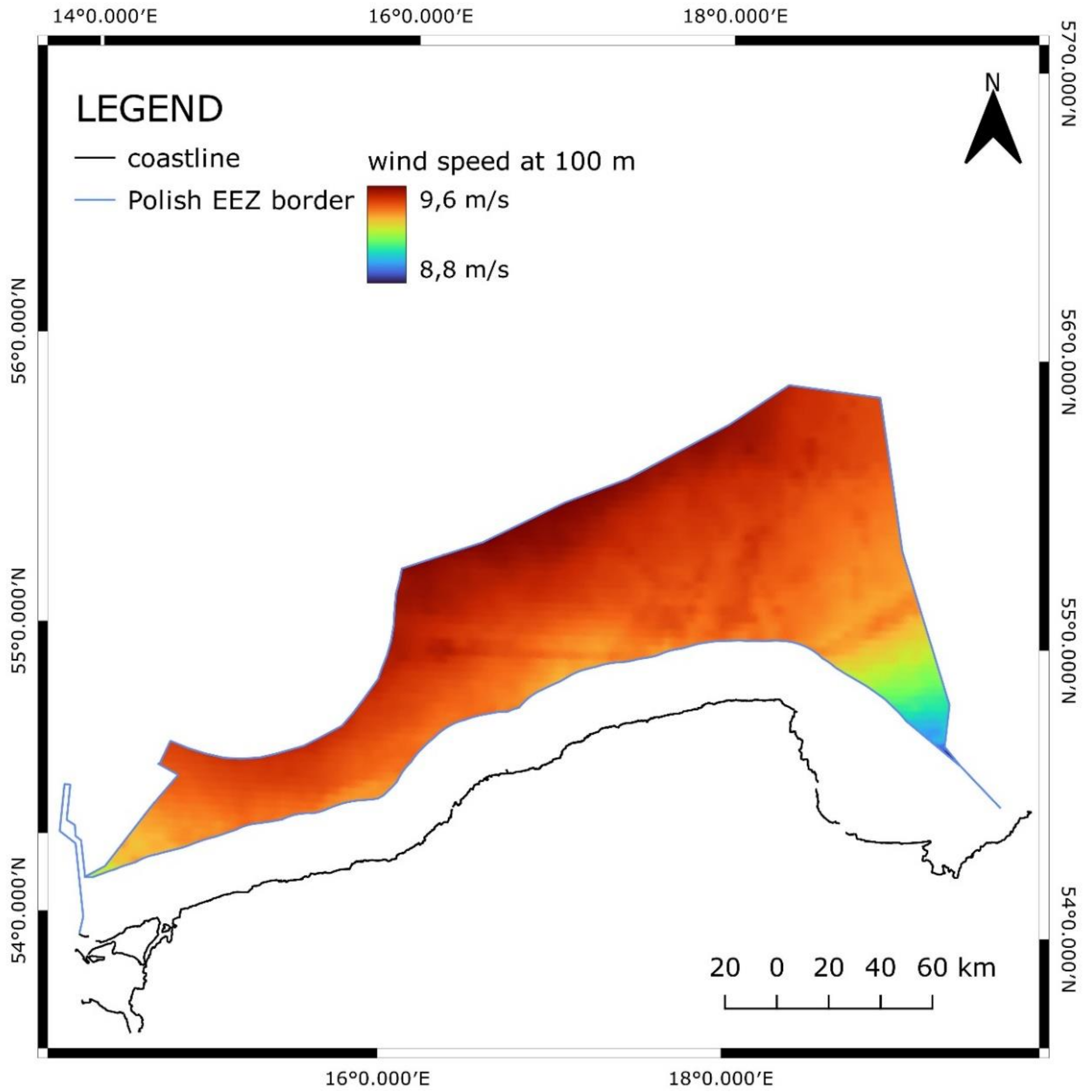

Figure 5.2 Wind velocity distribution map

source: own elaboration

5.5.2. WATER DEPTH

Similarly, for water depth the obtained data was in raster format, and first, it was necessary to convert it into vector format. As a continuance, the layer was clipped to fit EEZ borders. The water depth in the EEZ is within the range of 0 – 121 m. For offshore wind development, the appropriate value would be 100 m or less. Moreover, for fixed foundations, the maximal depth should be around 60 m, and for depths 60 – 100 m floating foundations would be preferred. Areas where the water depth is more than 100 m were excluded. Figure 5.3 shows the seabed characteristics. Table 5.9 presents the suitability classification.

Table 5.9 Water depth distribution classification

Criteria	Suitability	Range	Assigned value
water depth	excluded	< - 100 m	0
	marginally suitable	-100 – -66 m	1
	moderately suitable	-66 – -33 m	2
	highly suitable	-33 – -7 m	3

source: own elaboration

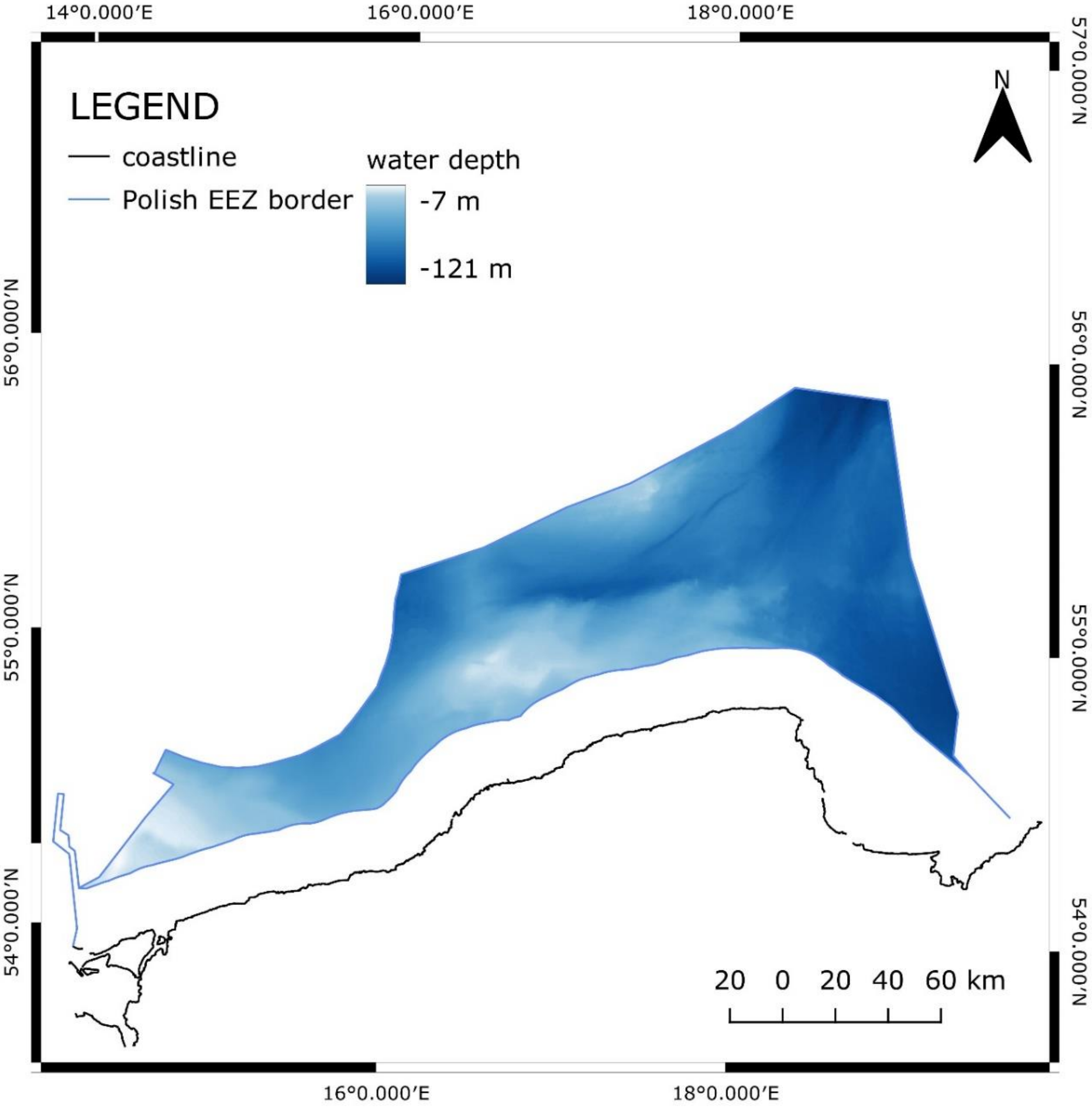

Figure 5.3 Water depth distribution map

source: own elaboration

5.5.3. DISTANCE FROM NATURE CONSERVATION AREAS (NATURA2000)

In the EEZ there are two types of nature conservation areas protected under Natura2000: conservation under the Bird Directive and conservation under the Habitats Directive. Three areas were identified however, two of them cover the same area. The names of the protected sites are: *Obszar specjalnej ochrony siedlisk "Ostoja na Zatoce Pomorskiej", Obszar specjalnej ochrony ptaków "Zatoka Pomorska", Obszar specjalnej ochrony ptaków "Ławica Słupska"*. For the mentioned areas, the data was stored in a vector format (polygon). It was necessary to clip the areas to fit the EEZ area. As a continuance, a buffer of 5 km was applied. The protected area as well as the 5 km buffer are excluded for offshore wind farm development. Taking into account the constrain regarding conservation areas, the area was divided into four ranges, and for each one, the value was assigned. Figure 5.4 presents selected areas with the buffer, and Table 5.10 the suitability distribution.

Table 5.10 Distance from nature conservation areas (Natura2000) classification

Criteria	Suitability	Range (buffer)	Assigned value
nature conservation areas (Natura2000)	excluded	< 5 km	0
	marginally suitable	5 – 25 km	1
	moderately suitable	25 – 50 km	2
	highly suitable	> 50 km	3

source: own elaboration

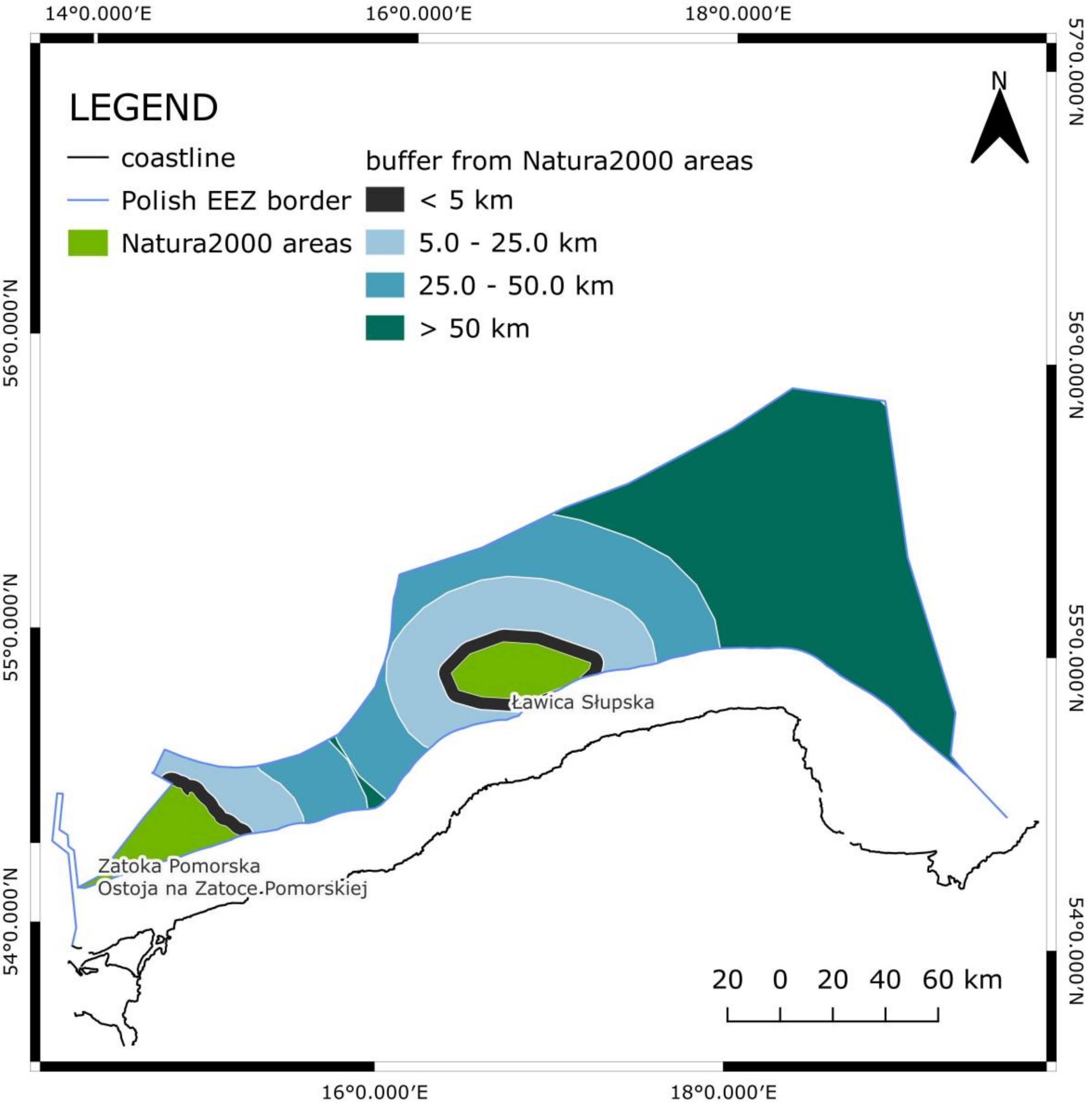

Figure 5.4 Distance from nature conservation areas (Natura2000) map

source: own elaboration

5.5.4. DISTANCE FROM SUBMARINE CABLES AND GAS PIPELINES

For submarine cables and gas pipelines, a buffer of 1 km was applied. Only existing cables and gas pipelines were taken into account. Figure 5.5 presents (from the left) the Baltic Pipe (gas pipeline), the high voltage cable 450 kV connecting Sweden and Poland, gas pipelines DN200 and DN250, and gas pipeline DN100. Table 5.11 presents the suitability classification according to this constraint.

Table 5.11 Distance from submarine cables and gas pipelines classification

Criteria	Suitability	Range (buffer)	Assigned value
Submarine cables and gas pipelines	excluded	< 1 km	0
	marginally suitable	1 – 25 km	1
	moderately suitable	25 – 50 km	2
	highly suitable	> 50 km	3

source: own elaboration

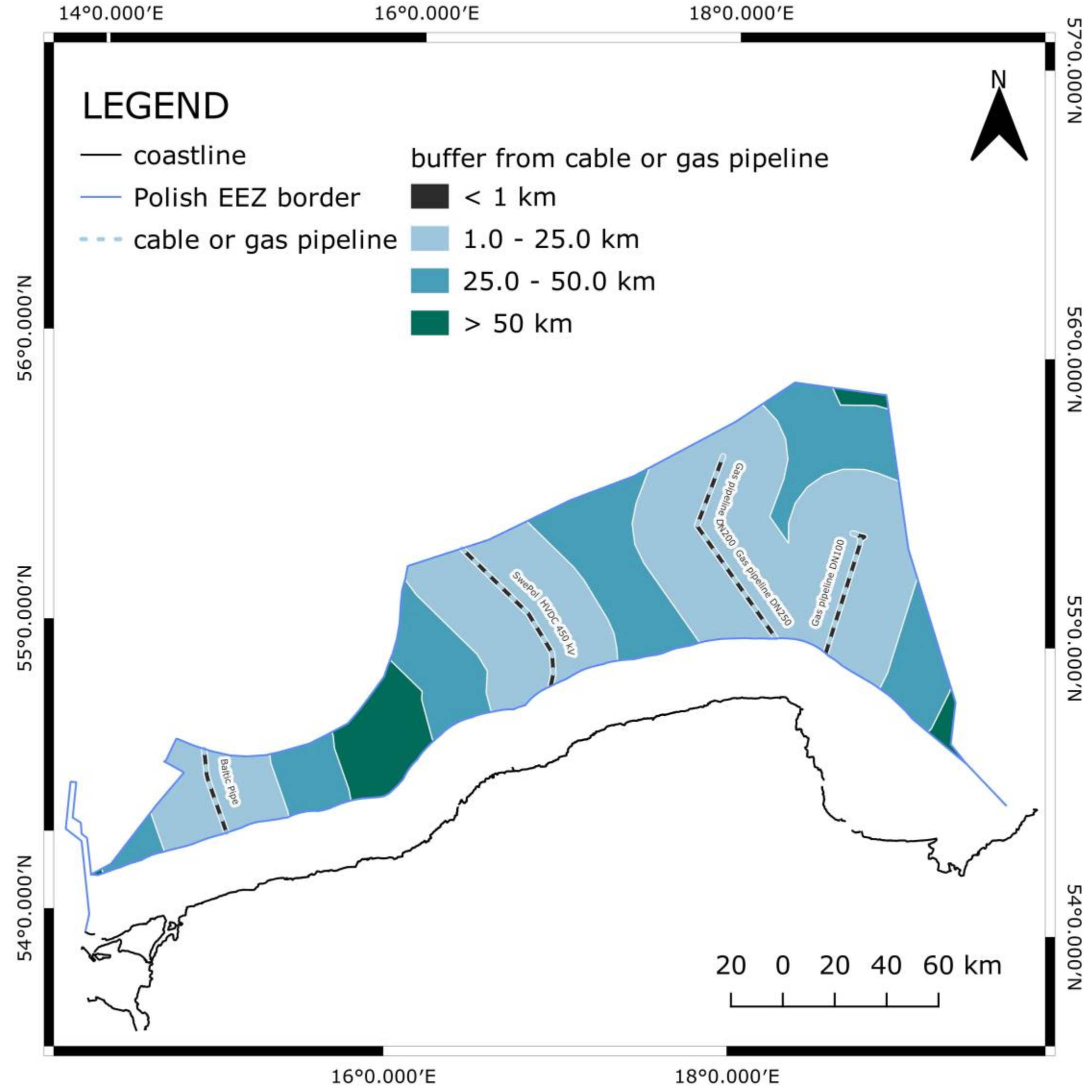

Figure 5.5 Distance from submarine cables and pipelines map

source: own elaboration

5.5.5. DISTANCE FROM SHIPPING ROUTES

The data about the most commonly used shipping routes was downloaded in a low-quality raster format. For that reason, the data was transformed into a vector layer. However, the precision of the presented shipping routes is not high, and therefore, should not be considered a crucial constraint. No area was excluded due to the lack of reliable data. For typical shipping routes, a line was drawn in the middle and then a buffer of 5 km was applied. However, these sites received *marginally suitable* rank, not *excluded*. Table 5.12 shows the suitability classification, and Figure 5.6 presents the shipping routes as well as the applied buffers.

Table 5.12 Distance from shipping routes classification

Criteria	Suitability	Range (buffer)	Assigned value
shipping routes	marginally suitable	< 5 km	1
	moderately suitable	5 – 25 km	2
	highly suitable	> 25 km	3

source: own elaboration

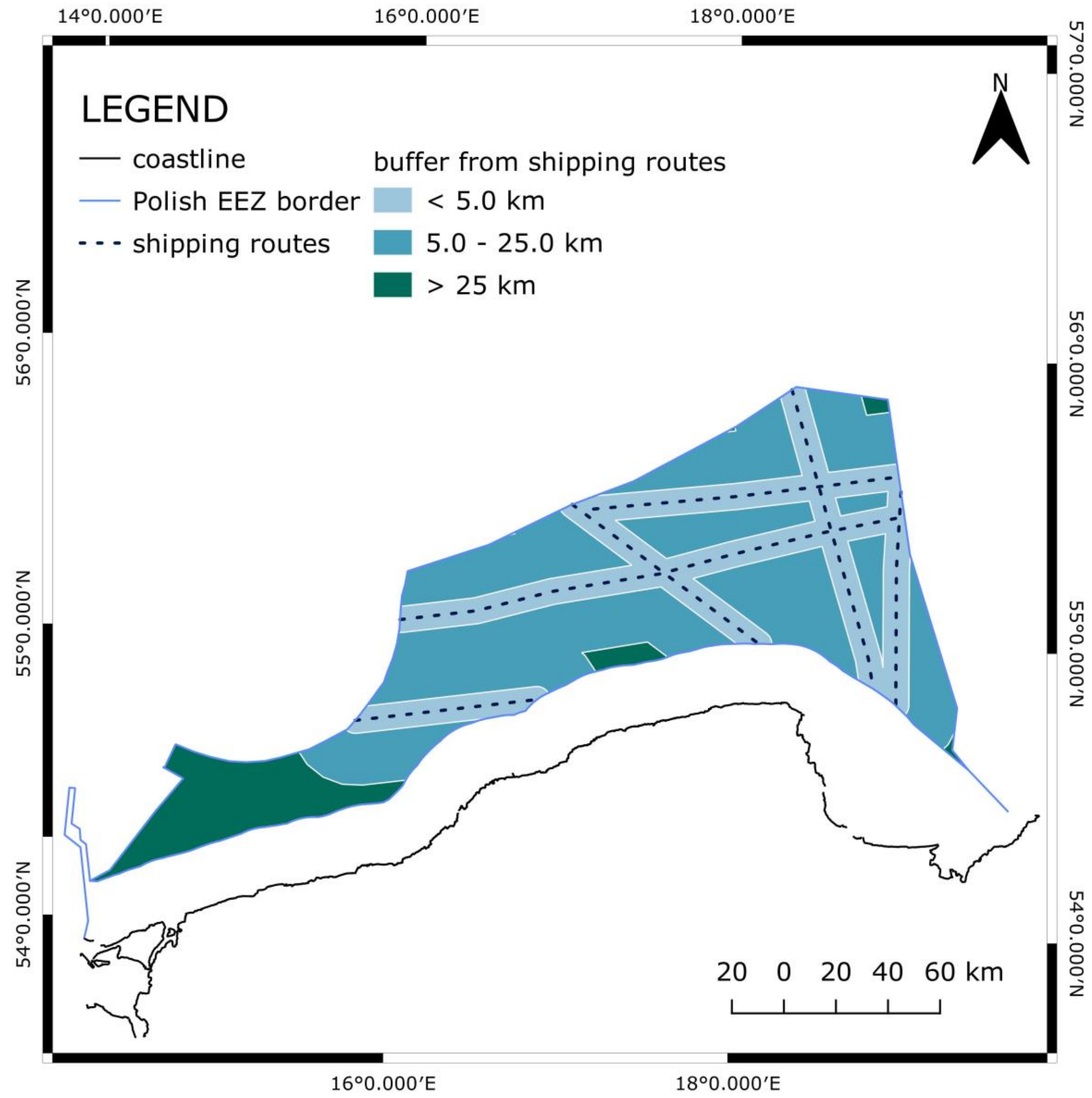

Figure 5.6 Distance from shipping routes map

source: own elaboration

5.5.6. FISHING AREAS

For fishing areas, the data considering the most frequently used sites was downloaded in raster format. The conversion to vector format was possible with the use of a tool in QGIS software. The areas were divided into three ranges that describe the fishing intensity: high, moderate, and low. Due to the uncertainty, no site is excluded. Table 5.13 presents the classification, and Figure 5.7 is the map of fishing intensity.

Table 5.13 Fishing intensity classification

Criteria	Suitability	Range	Assigned value
Fishing intensity	marginally suitable	high	1
	moderately suitable	moderate	2
	highly suitable	low	3

source: own elaboration

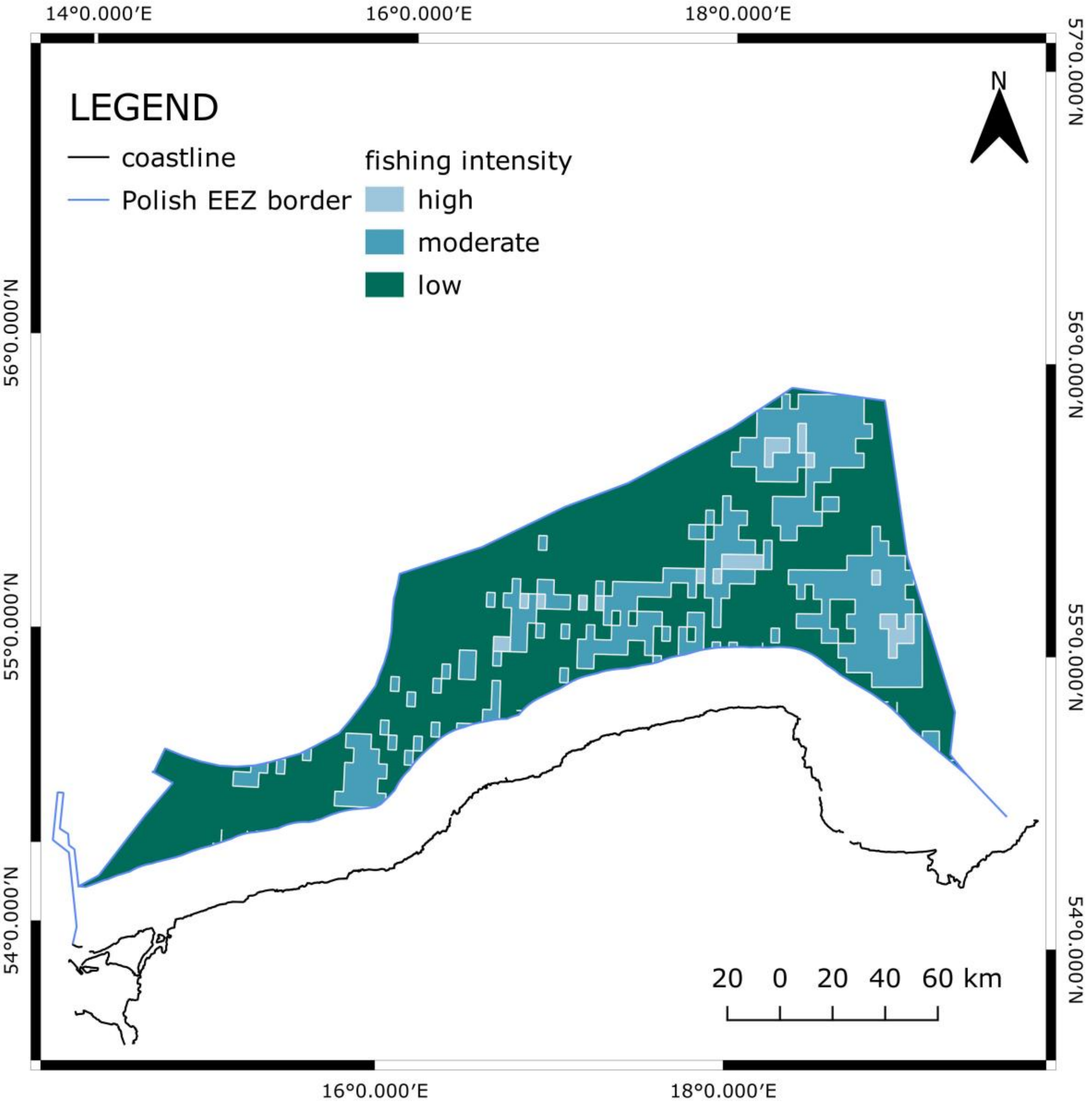

Figure 5.7 Fishing intensity map

source: own elaboration

5.5.7. DISTANCE FROM SHIPWRECKS

The data about shipwrecks was obtained in a vector format, more specifically, in points. First, these of the pointes that lied inside the EEZ area were selected. Then, the buffer of 1 km was applied, in order to find the excluded sites. Figure 5.8 presents the EEZ area with shipwreck locations. Additionally, a detailed frame that shows the applied buffer is provided. Table 5.14 presents the applied classification.

Table 5.14 Distance from shipwrecks classification

Criteria	Suitability	Range (buffer)	Assigned value
shipwrecks	excluded	< 1 km	0
	marginally suitable	1 – 5 km	1
	moderately suitable	5 – 25 km	2
	highly suitable	> 25 km	3

source: own elaboration

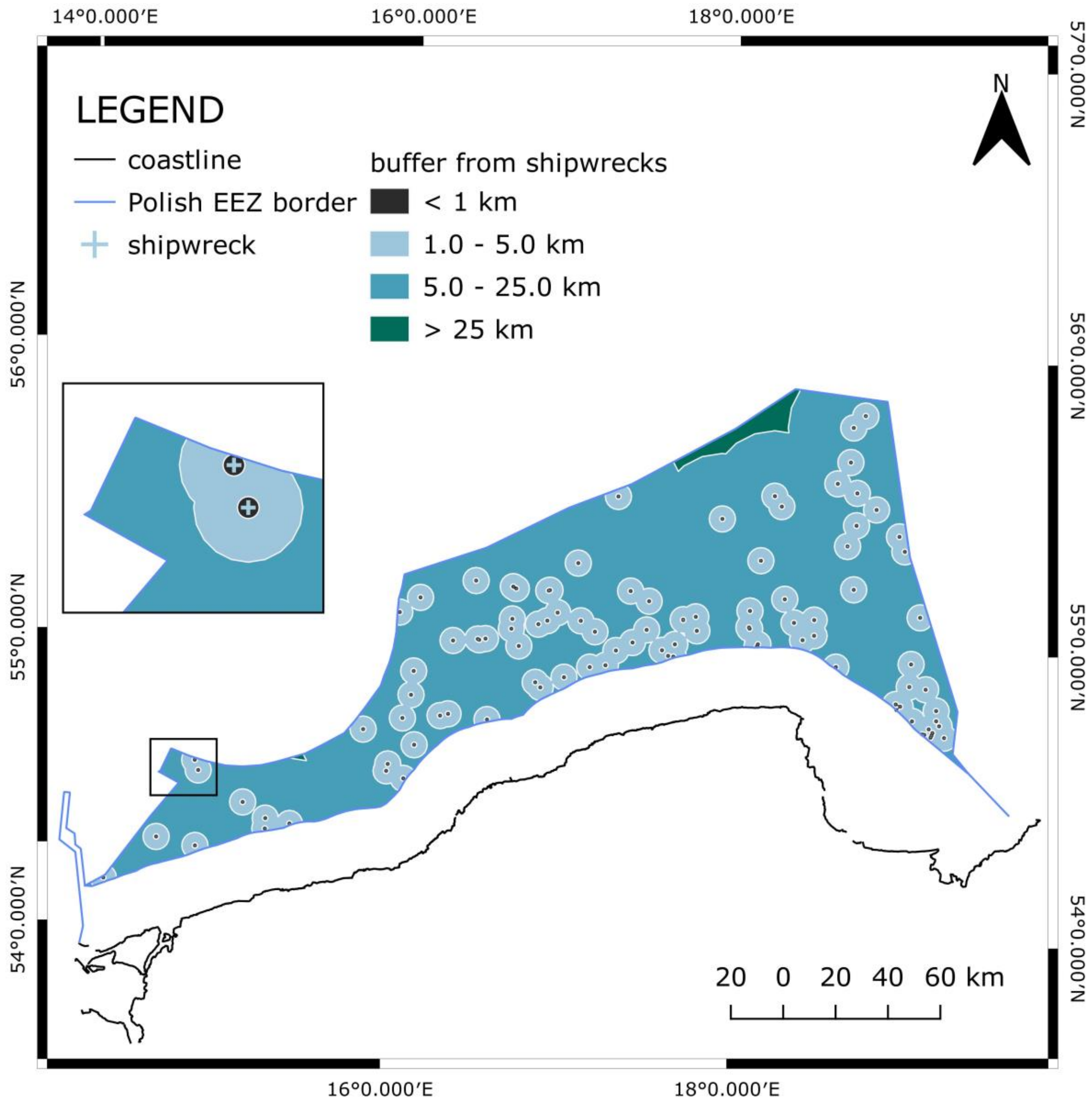

Figure 5.8 Distance from shipwrecks map

source: own elaboration

5.5.8. DISTANCE FROM COASTLINE

Distances from the coast were determined using the buffer tool. Areas close to the land were considered to be the most optimal. The classification is shown in Table 5.15. Figure 5.9 shows the distribution of distances.

Table 5.15 Distance from coastline classification

Criteria	Suitability	Range (buffer)	Assigned value
Coastline	excluded	> 100 km	0
	marginally suitable	75 – 100 km	1
	moderately suitable	50 – 75 km	2
	highly suitable	< 50 km	3

source: own elaboration

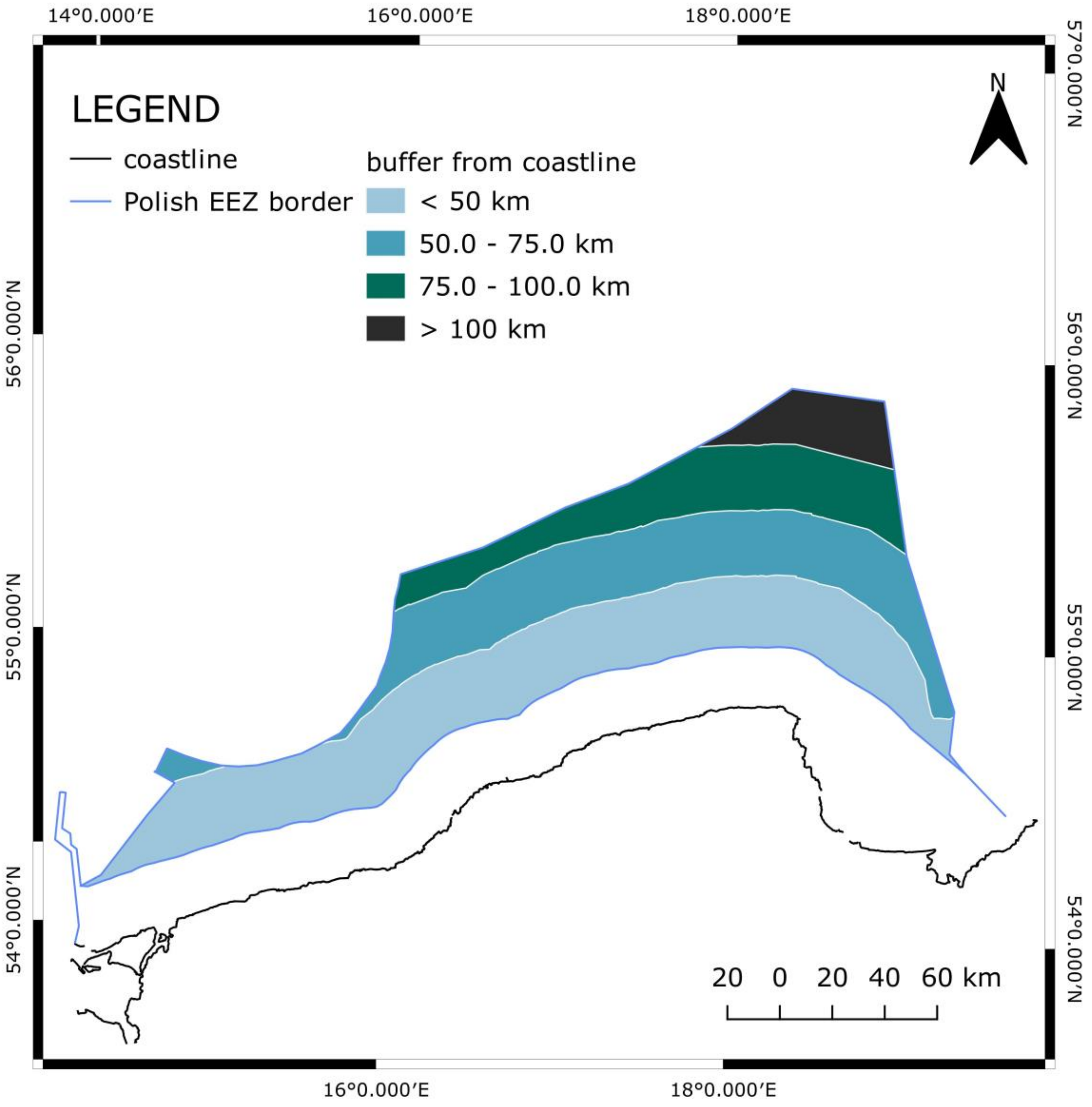

Figure 5.9 Distance from coastline map

source: own elaboration

5.6. ASSUMPTIONS

To estimate the offshore wind energy potential for the Polish EEZ, certain assumptions have to be made. As a result of the mapping and calculations performed in QGIS, an area was obtained where the location of offshore wind farms would be possible. Two important issues were assumed for the assessment of the power that could be installed: the type and power of a single turbine and the distribution of the turbines with each other. The use of turbines with a nominal capacity of 15 MW, manufactured by Vestas, was assumed. Similar components are planned to be used for the Baltic Power offshore wind farm planned in the Polish part of the Baltic Sea. The details of the proposed turbine are presented in Table 5.16.

Table 5.16 Technical parameters of the selected turbine
Source: compiled from [5]

Name	V236-15.0 MW
Rated power [MW]	15
Cut-in wind speed [m/s]	3
Cut-out wind speed [m/s]	31
Rotor diameter [m]	236
Swept area [m^2]	43,742
Blade length [m]	115,5
Energy produced per year [GWh]	80

In addition, it has been proposed to lay the turbines 2 km apart to minimise the risk of wake effect. The literature recommends a distance between 10 and 15 D, where D is the rotor diameter, as described further in *3.1.2. Offshore wind technologies*.

5.7. CALCULATIONS

Taking into consideration all of the abovementioned constraints as well as the assumptions regarding turbines, the calculations could be performed. At first, a site suitability map for offshore wind farms was created. To receive it, a grid layer was necessary. In this study, one with a spatial resolution of 1 km x 1 km was created. Then, all of the criteria maps were aggregated into one grid layer using the *join attributes by locations* tool. As a continuance, using equation 5.11, the final value $OWF_{suitability}$ was calculated for each square of the grid. In that equation, w_i is the criteria weight, and S_i refers to the suitability factor.

$$OWF_{suitability} = \sum_{i=1}^{n} w_i \cdot S_i$$

(5.11)

To calculate the final technical potential of the EEZ of Poland the total capacity of the offshore wind turbines should be computed. For the received area, points were inserted, leaving 2 km among them. Additionally, as described in *5.6 Assumptions*, 15 MW turbines would be considered. Equation 5.12 shows the mathematical formula that allows to receive the final result in GW, P_{OWF}. Parameter k is the number of dots that represent the turbines in the QGIS simulation

$$P_{OWF} = \frac{15 \cdot k}{1000}$$

(5.12)

6. RESULTS

The study concerned the investigation of the optimal offshore wind farm locations in the EEZ of Poland as well as the assessment of the energy potential. In the theoretical part, the literature was reviewed to observe the previous approaches. As a result, the factors that influence the OWF location were identified. The methodology applied in this study included an Analytical Hierarchy Process (AHP), a multi-criteria decision-making method (MCDM) and calculations in QGIS and Excel software. For each constraint, a layer was created and excluded areas were determined. The areas were classified into four ranges of suitability: marginally, moderately, highly, and excluded. The weights were assigned for all of the constraints using the AHP method. All of the layers were then combined into one grid layer, and the most promising areas were selected. At this point, the overall value of each square of the grid was calculated. Mathematically, it took into account the weight of the criteria and the suitability value specified for each square of the grid. The sum of the mentioned product expresses the final suitability factor. The values were then grouped into 3 ranges. With the necessary assumptions, the technical potential of the EEZ of Poland was calculated.

6.1. EXCLUDED AREAS

In the study, the EEZ of Poland is considered. However, not the whole area (approx. 22 500 km^2) is suitable for offshore wind development. Numerous constraints restrict the area. The literature mentions technical, regulatory and economic limitations [53]. This study focused on technical constraints, however, some regulatory and economic aspects were also considered. Nine criteria were identified:

1. wind velocity;
2. water depth;
3. distance from nature conservation areas (Natura2000);
4. distance from submarine cables and gas pipelines;
5. distance from shipping routes;
6. fishing areas;
7. distance from shipwrecks;

8. distance from coastline;
9. EEZ area.

During the preliminary analysis, it was determined which criteria are related to the exclusion of sites. These areas were then mapped in QGIS software according to the proposed methodology. For *water depth* areas with the depth of 100 m or more were excluded due to lack of appropriate foundation technology. The development of *Nature conservation areas* protected under the Natura 2000 programme is prohibited. Additionally, a 5 km buffer from these areas was not considered. *Submarine cables, gas pipelines* and *shipwrecks'* locations were excluded as well as a 1 km buffer from them. Since data about *shipping routes* and *fishing areas* was not highly reliable no sites were removed from further study in relation to these constraints. Nevertheless, *distance from the coast* should not exceed 100 km, and further areas were excluded from the study. Areas in proximity to the shore have not been disregarded as only the EEZ is taken into account. The categories in Table 6.1 are related to the exclusion of certain sites. Moreover, there are areas not considered in the study due to more than one constraint. The total value of the excluded area equals to 5018,852 km^2 which is 22,3% of the EEZ of Poland. Figure 6.1 presents the map of the excluded areas. All of the abovementioned areas were aggregated into one.

Table 6.1 Excluded areas

Name of the constraint	**Excluded area [km^2]**
Water depth	1530.021
Nature conservation areas and a 5 km buffer	2374.788
Submarine cables and gas pipelines and 1 km buffer	470.352
Shipwrecks and 1 km buffer	304.160
Distance to the coast	1212.724
TOTAL	5018.852

source: own elaboration

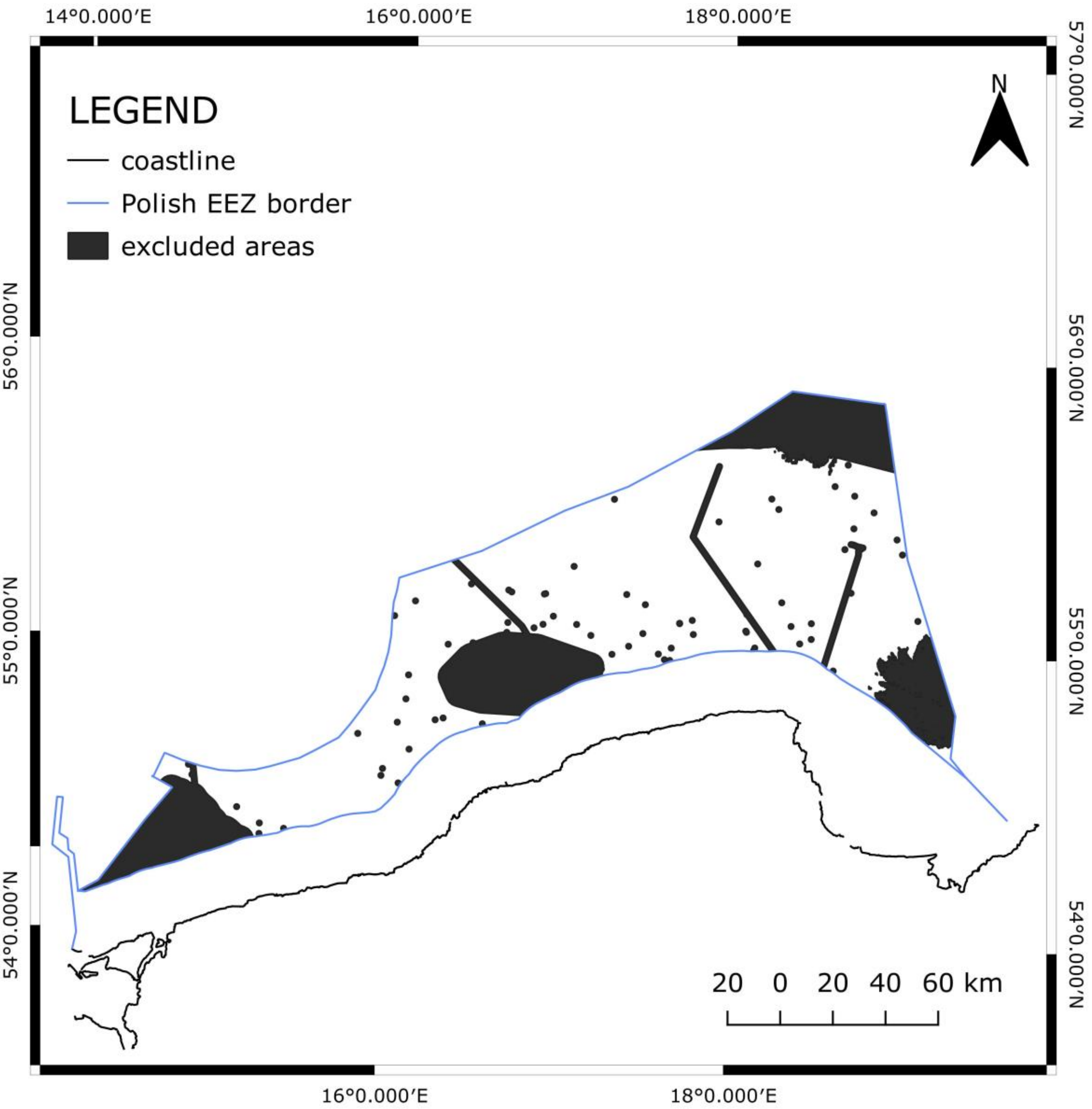

Figure 6.1. Results – excluded areas

source: own elaboration

6.2. SUITABLE AREAS

To assess the energy potential of the EEZ of Poland, the model in QGIS software was developed. Eight layers were considered, and each influenced the suitability of the area. For that reason, the maps of suitability were created individually for every layer. The details of the proposed ranges of suitability were described in the methodology chapter. However, for each layer, three levels of suitability: *marginally*, *moderately*, and *highly* were proposed.

All of the layers combined into one grid layer allowed the calculation of the final value for each square of the grid. A spatial resolution of 1 km x 1 km was applied to receive the detailed results. After the summation of all layers' values and weights obtained from the AHP process, final values were obtained. The results were in a range from 1,494 to 2,801. It was decided to divide the results into three groups, as described in Table 6.2. The sites *marginally suitable* for OWF development covered an area of 2178,97 km^2 which is equal to 10,26% of the total EEZ area. *Moderately suitable* was an area of 10312,8 km^2, and a share of 48,56%. Moreover, *highly suitable* was an area of 3726,9 km^2, a share of 17,55%. The remaining area (5018,9 km^2, and a share of 23,63%) was excluded, as described in *6.1. Excluded areas*. The total area predisposed for OWF development was 16218,67 km^2. The share of each area is presented on the chart (Figure 6.2). As mentioned, the minimal value observed was 1,494, and the maximal 2,801. The mean value was 2,272, and the median was 2,217. The standard deviation was 0,227.

Table 6.2 Suitable areas

Suitability	**Values**	**Area [km^2]**	**Share**
marginally	1,494 - 2,0	2178,97	10,26%
moderately	2,0 – 2,5	10312,8	48,56%
highly	2,5 – 2,801	3726,9	17,55%

source: own elaboration

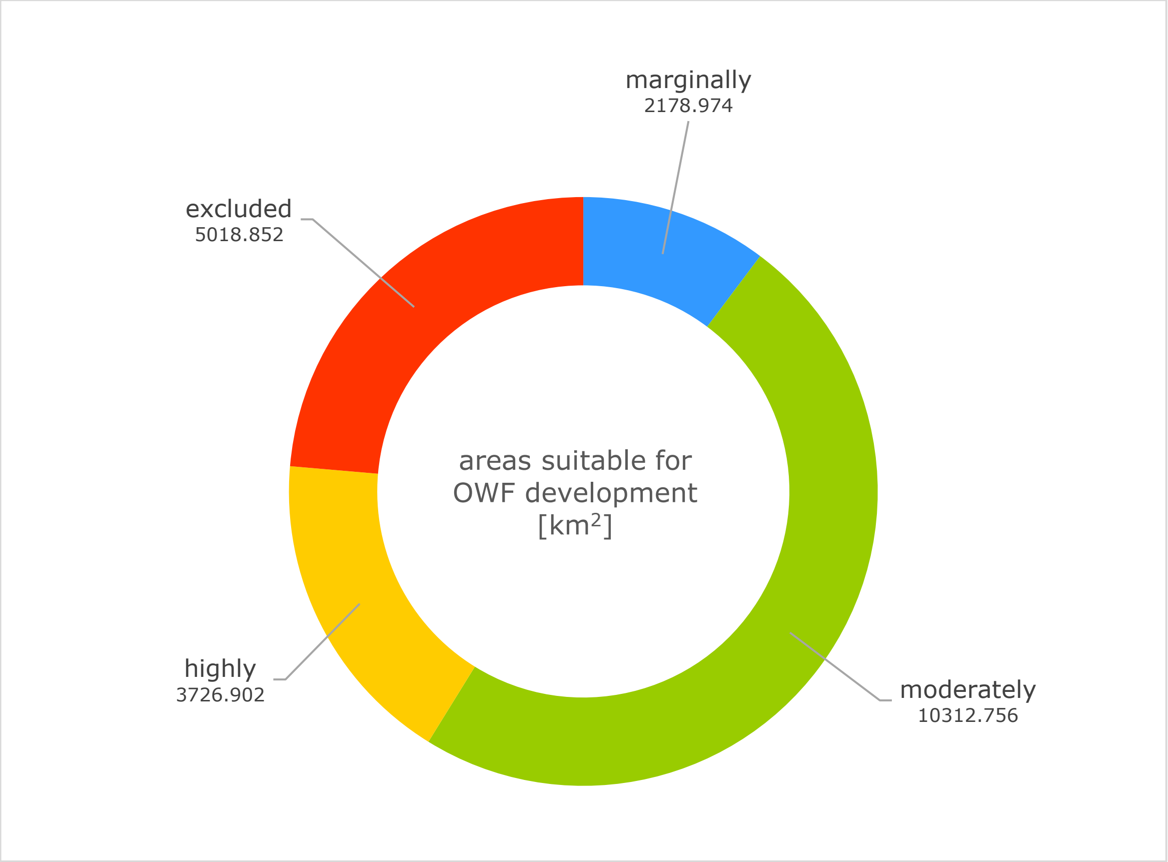

Figure 6.2 Results – areas suitable for OWF development

source: own elaboration

The areas suitable for OWF development are distributed as shown in the map (Figure 6.3). Areas highly suitable are in the south of the EEZ. Areas marginally suitable are located mostly in the northern part of the EEZ. The remaining sites represent moderate suitability for OWF development.

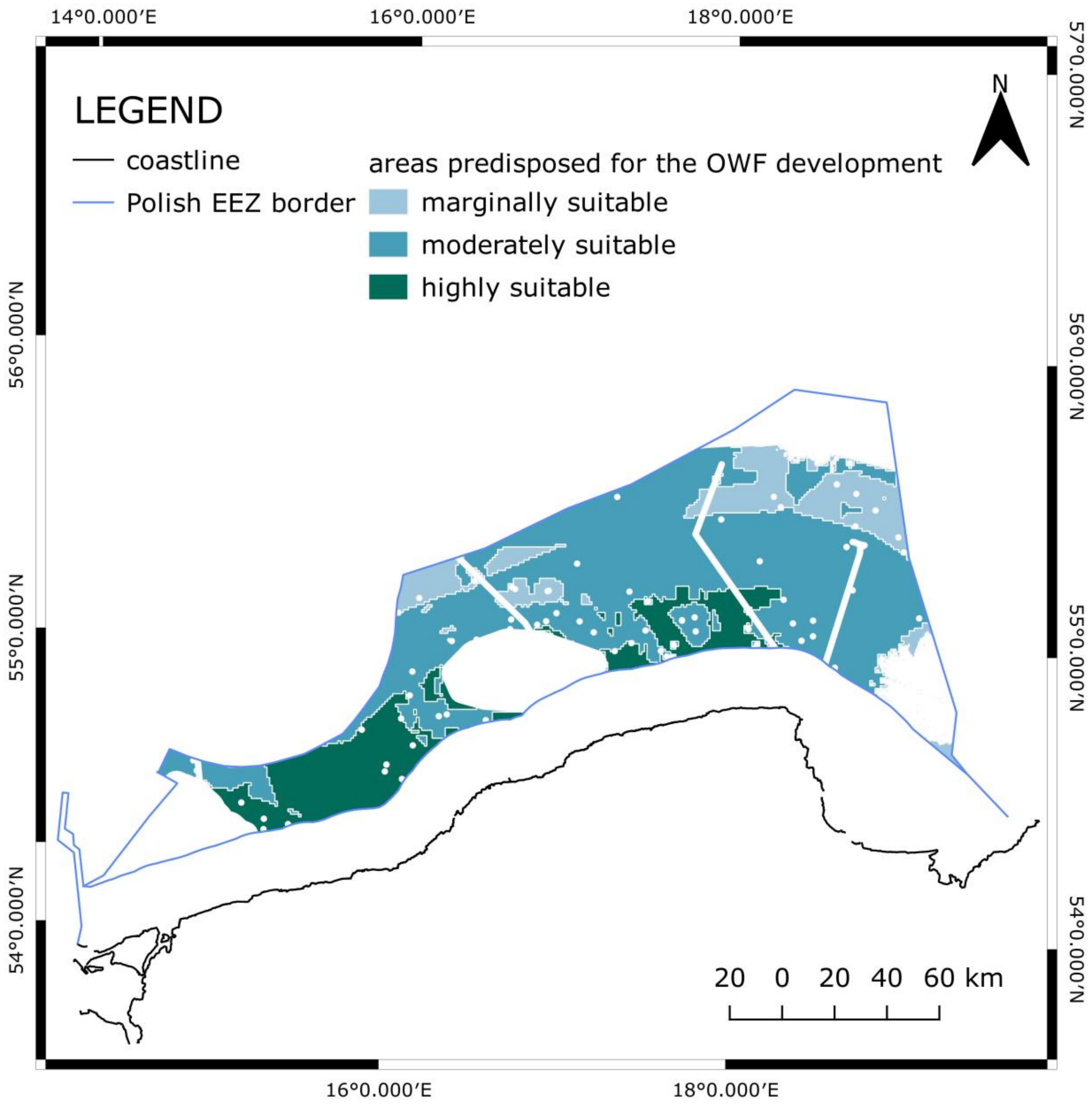

Figure 6.3 Results – areas suitable for OWF development

source: own elaboration

6.3. OFFSHORE WIND POTENTIAL OF THE EEZ OF POLAND

To assess the offshore wind potential of the Polish part of the Baltic Sea, nine constraints were considered as well as necessary assumptions. The latter was further discussed in *5.6 Assumptions*. The dots that represented the locations of the turbines were distributed in the area suitable for OWF development, as shown in Figure 6.4. In total, 3664 turbines with a rated power of 15 MW were situated. Considering all of the suitable locations previously identified, the technical potential of the EEZ of Poland would be 54,96 GW of power. The technical potential only in *highly suitable* areas would be equal to 15,24 GW.

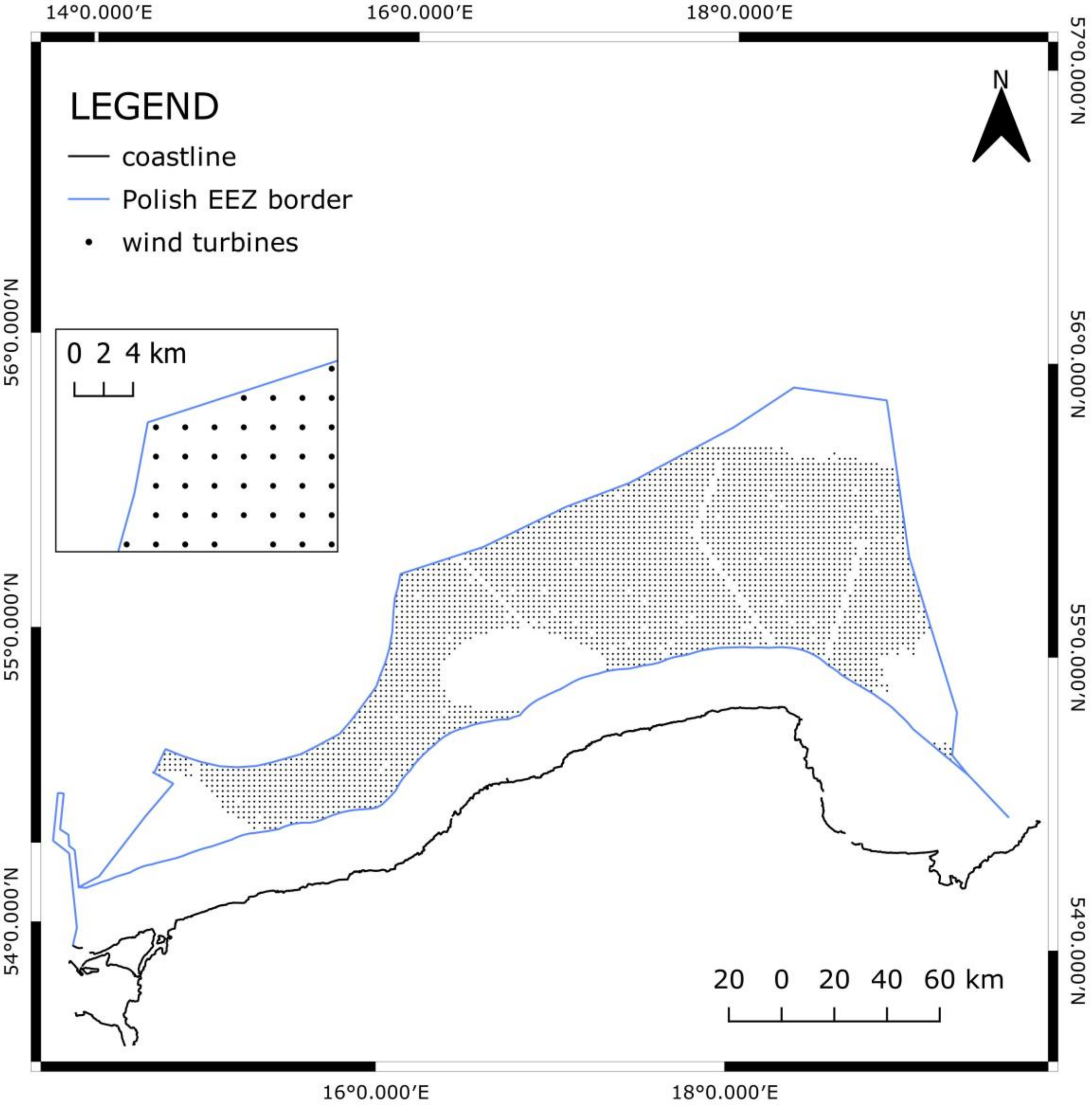

Figure 6.4 Results – wind turbine locations

source: own elaboration

7. DISCUSSION

During the study, two main objectives were identified. The former was to assess the potential for offshore wind farms in the EEZ of Poland. To address this matter, the multi-criteria analysis was performed using the QGIS software. As a result, the potential was estimated from 15 GW (*highly suitable* areas) to almost 55 GW (all suitable areas). These values were obtained by taking into account the assumption regarding the distribution of the turbines (2 km among the turbines). With other distances, the values obtained would be correspondingly different. If the distance of 2.3 km is maintained, the technical potential would be 41,8 GW. Whereas at 2.5 km, the potential would be 35,2 GW.

The latter objective concerned the identification of the optimal sites for offshore wind farms. Figure 6.3 shows the areas predisposed for OWF development, divided into three ranges: *marginally suitable*, *moderately suitable*, and *highly suitable*. The most optimal conditions for OWF are in the south of the EEZ of Poland due to the proximity to the coast, relatively shallow waters, and appropriate wind conditions. On the other hand, the *marginally suitable* areas for OWF are located in the north of the EEZ of Poland, further from the coast, where the sea is deeper.

QGIS software might be used as a tool to support the assessment of the areas for OWF. Using the raw data downloaded from different sources, the criteria could be processed. Some of the data was in raster format, and first, it was necessary to convert it into vector format. Impact maps with distances were created for each constraint. In QGIS software it was possible to determine the suitability of the areas predisposed for OWF locations. However, the assessment of the importance of the selected criteria was performed with AHP. As a result, the three most significant criteria in the study were: *wind velocity*, *distance from coastline*, and *water depth*. On the other hand, the least important criteria resulted *fishing areas*, mostly due to the lack of precise data.

The study showed key aspects that should be considered while deciding on the OWF location. *Wind velocity* remains the most significant criterion, the wind conditions must be favourable. However, water depth and distance from shore are also considered important criteria. In addition, constraints such as *distance from* *nature conservation areas (Natura 2000)*, *distance from submarine cables and gas pipelines*, and *distance from shipping routes*, *fishing areas*, and *distance from shipwrecks* were taken into account in this study. Literature mentions numerous different constraints, nevertheless, it is important to note that there is no universal set of such constraints and it would be different for each location. To make the study more precise, other data might be considered. For example, only existing submarine cables and gas pipelines were implemented. *HarmonyLink* will be the HVDC connection between Poland and Lithuania, and its location should be considered. Additionally, no oil and gas fields were taken into account. More detailed data regarding shipping routes and fishing areas should be applied.

Another aspect that would need to be considered is the development of offshore projects in the sites identified in Act [7]. However, it was decided not to exclude these areas from the analysis, but only to verify their suitability according to the proposed methodology. Thus, the areas where the OWF are to be built were found to be *highly* or *moderately suitable*. The exceptions are small areas excluded from the analysis due to the presence of shipwrecks. However, it is likely that areas designated for OWF wrecks do not represent a significant obstacle to construction and subsequent operation.

8. SUMMARY AND CONCLUSIONS

Renewable energy sources are currently becoming more and more important worldwide. This is due to climate change and the need to stop burning fossil fuels. One of the fastest-growing technologies is offshore wind energy. New farms are being planned and built in Asia, North America and Europe. Moreover, there are plans to build OWFs in the Polish part of the Baltic Sea as well. Projects with a total capacity of 5.9 GW have received support in the contract for difference (CfD) formula. Nevertheless, site selection for the development of an OWF project is complex and involves numerous constraints. Optimisation of the process has been the subject of this study. To address the matter, research questions were raised. They are concerned with the determination of limitations to the location of OWF and their implementation in the QGIS environment. In addition, it was assumed that the analysis would identify areas in the Polish EEZ suitable for the development of OWF projects, as well as determine the technical potential of the EEZ.

The study was divided into two parts. At first, a theoretical introduction to offshore wind energy was presented. Chapter *3.1. Wind energy technologies* described the history of wind energy use, characterising both onshore and offshore wind. In addition, the most important elements of OWF are presented: turbines, foundations, cabling, offshore substation, and onshore substation. On the other hand, chapter *3.2. Wind energy development* described different experiences from around the world, Europe and Poland. The next chapter presented the limitations of OWF construction, the optimisation methods mentioned in the literature, as well as the use of GIS tools. The latter part of the study concerned the practice. To find optimal locations for OWF development, the area under analysis and constraints were initially identified. Then, the available data was verified and nine categories were selected for further analysis: *wind velocity*, *water depth, distance from nature conservation areas (Natura 2000)*, *distance from submarine cables and gas pipelines*, *distance from shipping routes*, *distance from fishing areas*, *distance from shipwrecks, distance from coastline*. Eight of them were subjected to the AHP method, which is an example of the MCDM method. The ninth category assumed that the infrastructure would be located inside the EEZ of Poland. After conducting the AHP method, the category weights were determined. At the same time, the data for each constraint was implemented in QGIS and processed. Distances and suitability ranges were indicated for each layer. Then, all constraints were combined on a grid layer with a resolution of 1 km^2. In this way, final values were determined, taking into account suitability factors and criteria weight.

The main objectives of the study were to identify optimal areas for OWF development and to assess the technical potential of the EEZ of Poland. Calculations showed that approximately 16218,67 km^2 would be suitable for OWF, of which 3726,9 km^2 was identified as *highly suitable*. In addition, the potential of the selected area was estimated at almost 55 GW (including 15 GW in the *highly suitable* area). The energy produced by offshore wind farms would provide electricity for millions of Polish households. Wind energy is a cheap and clean source, and its use will improve the quality of life.

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