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Alexandre Pereira, Aikaterini Mitsakou, Stefan S. Blagojevic, Brian O. Hansen, Anastasia Ioannou, Jake Badger

Final Report

March, 2024



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Contractor: Danish Energy Agency

Report E-0254

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DTU Wind

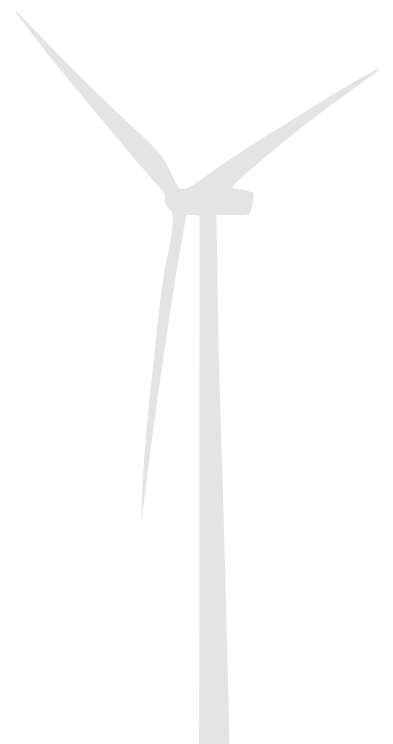
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Executive Summary

This study presents DTU Wind's assessment of three potential sites for development of offshore wind energy in Ukraine. The assessment is made according to DTU Wind's methodology for preliminary analysis of offshore wind farm projects and applying global databases and industry-standard tools to provide consistent insights and comparisons of potential offshore sites.

The Danish Energy Agency (DEA) has requested DTU Wind to undertake a pre-feasibility study within the maritime zone of the Republic of Ukraine, from the Black Sea to the Crimea peninsula and to the Sea of Azov areas. The study includes a preliminary analysis of wind resources, the identification of most suitable locations for offshore wind farms, the energy production simulation for three hypothetical offshore wind farms, and the estimation of the levelized cost of energy (LCOE).

DTU Wind worked collaboratively with representatives of the World Bank to identify potential constraints and important issues for consideration regarding the development of offshore wind energy in Ukraine. Additional input opportunities occurred during an online meeting organised by DEA with several local stakeholders.

The wind resources as well as digital maps of orography and roughness were obtained from the Global Wind Atlas (GWA). The most relevant offshore wind climate parameters used in the study can be found in chapter 2.

DTU Wind performed a geospatial assessment of offshore areas within the EEZ of Ukraine (owing to the lack of a maritime spatial plan for Ukraine), and the areas identified in this study will eventually need to be confirmed as available for the development of offshore wind energy projects.

Several site-specific constraints were considered as exclusion or restriction zones. The databases used for the geospatial analysis, described in chapter 3, are available and may be used in the future for enhancing the current study, in case that new data or different constraints become available. Two large areas off the coast of Ukraine have been indicated for development of offshore wind projects, one area of approximately 30.000 km² with shallow water depths suitable for bottom-fixed foundation technology and another area of approximately 20.000 km² with water depth equal or greater than 60 m suitable for development of offshore wind projects with floating wind turbines.

Three hypothetical offshore wind farms were modelled using WAsP, the industry-standard software for wind resource assessment and wind farm planning. Two sites are in shallow waters, suitable for bottom-fixed foundations. Another site is in relatively deeper waters, where floating foundations might be needed. Wind data from Global Wind Atlas were used due to the lack of local measurements. The layouts were defined using best practices to minimise wake losses. Taking all losses into account, the preliminary estimations indicate capacity factors of 39%, 36.9%, and 33.2% for Site 2, Site 1, and Site 3, respectively.

The range of LCOE for the hypothetical offshore wind projects in Ukraine have been estimated based on several simplifying assumptions and are subject to Ukraine-specific data limitations. The actual cost for offshore wind in Ukraine will depend on the ability to secure an affordable supply chain and workforce and grid connection. As such, for the LCOE calculation, certain external factors, particularly those stemming from the ongoing geopolitical situation, have not been explicitly incorporated into our analysis.

The initial capital and financing costs for pioneering projects in emerging markets, such as Ukraine, are anticipated to be higher, primarily due to the inherent risks of being the first of their kind. Lowering the financing costs can be accomplished through concessional financing sourced from international financial institutions. While the pre-feasibility study hasn't delved into such scenarios, they can be explored in subsequent stages to assess potential options for project implementation

There are promising perspectives for the use of offshore wind in Ukraine, as pointed out here although this report should be interpreted as guidance only due to variability in wind energy deployment methods, along with the evolution of technology and changes in costs. This work may be used for planning the next steps of the development of an offshore wind project in Ukraine which might include measurement campaigns, environmental assessments, and a more detailed conceptual design of an offshore wind farm.

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List of Abbreviations

AEP	Annual Energy Production	IEC	International Electrotechnical Commission
AIS	Automatic Identification System	IMF	International Monetary Fund
ASL	Above Sea Level	IUCN	International Union for Conservation of Nature
BF	Bottom-fixed	LCOE	Levelized Cost of Energy
BNEF	Bloomberg New Energy Finance	OPEX	Operational Expenditures
BZ	Bessel Zooming	QGIS	Quantum Geographic Information System
C_t	Thrust Coefficient	RIX	Ruggedness Index
CAPEX	Capital Expenditures	UDEPP	Ukraine-Denmark Energy Partnership Program
DEA	Danish Energy Agency	UTM	Universal Transverse Mercator
DEVEX	Development Expenditures	WACC	Weighted Average Cost of Capital
DTU	Technical University of Denmark	WAsP	Wind Atlas Analysis and Application Program
DTU Wind	DTU Department of Wind and Energy Systems	WCMC	World Conservation Monitoring Centre
EEZ	Exclusive Economic Zone	WGS	World Geodetic System
EIA	Environmental Impact Assessment	WTG	Wind Turbine Generator
FID	Financial Investment Decision		
GIS	Geographic Information System		
GPS	Global Positioning System		
GWA	Global Wind Atlas		
GWC	Generalised Wind Climate		

1 Introduction

The Ukraine-Denmark Energy Partnership Program (UDEPP) is a collaborative effort between Ukraine and Denmark, funded by the Neighborhood Program under Denmark's Ministry of Foreign Affairs. Its primary goals are to enhance the conditions for sustainable energy investments in Ukraine and help the country reach its renewable energy, energy efficiency, and energy independence objectives. The Danish Energy Agency (DEA) plays a crucial role by offering technical assistance to Ukrainian partner institutions. This assistance covers areas such as energy policy development, economic diplomacy, and bolstering Ukraine's energy security. Essentially, UDEPP aims to facilitate Ukraine's transition towards a more sustainable and secure energy future through cooperation with Denmark. As a part of this agreement, the DEA asked DTU Wind and Energy Systems (DTU Wind) to conduct an initial evaluation of Ukraine's offshore wind energy potential.

This study contributes to a comprehensive pre-feasibility analysis of offshore wind energy within the maritime zone of Ukraine. It includes the selection of suitable areas based on geospatial analysis, calculation of wind resources starting at individual wind turbine level, layout design for 600 MW hypothetical offshore wind farms at three different sites, estimation of the levelized cost of energy (LCOE) and a discussion on scaling-up offshore wind farm deployment for each site.

The report provides a comprehensive overview of the inputs, methods, and assumptions collaboratively discussed with representatives of the World Bank and several local stakeholders. It subsidises the preparation for the next steps in planning the development of offshore wind energy projects in Ukraine: start specific measurement campaigns, execute environmental assessments, and feasibility studies for a conceptual design of an offshore wind farm.

2 Wind Meteorology

The DTU Wind methodology, described in the Global Wind Atlas [1], has been used to analyse the wind meteorology of the offshore areas around Ukraine. DTU owns and continues developing the Global Wind Atlas (GWA), which attracts over 50,000 worldwide user each month. This web-based application is designed to assist policymakers, planners, and investors identify high-wind areas suitable for wind power generation anywhere in the world. It offers preliminary calculations and allows users to conduct online queries, providing access to up-to-date datasets and modelling methodologies.

In this study, the GWA is utilised to acquire digital maps and wind climate data, allowing a preliminary estimate of the energy yield for potential wind farms using DTU's industry-standard WAsP software [2].

The main wind parameters and statistics presented in this report may be used for the pre-feasibility study of wind power projects as well as for defining adequate locations for the installation of measurement stations. The objective of installing measurement stations is to acquire energy-specific data required by developers and investors to finance wind farm projects.

2.1 Offshore Wind Climate in Ukraine

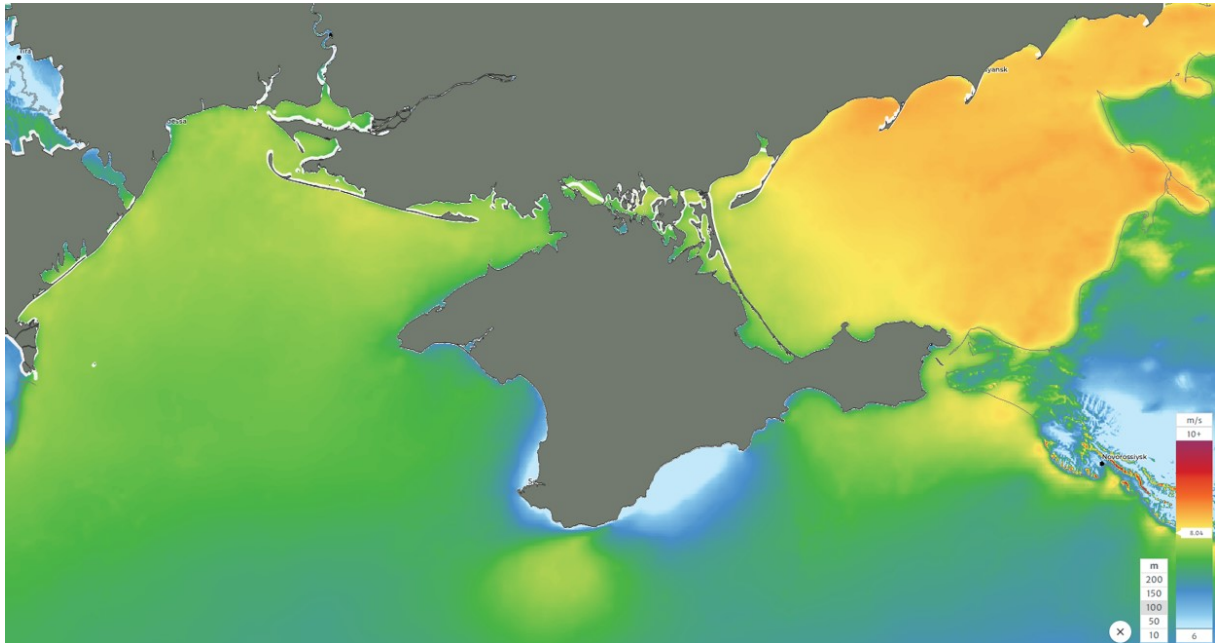
The wind potential normally increases with height, and the increase in mean wind speed at increasing heights has been modelled by the GWA using a roughness length and a modified log law. Figure 1, obtained from the GWA, depicts the offshore mean wind speed at 100 and 150 meters ASL around Ukraine, showing an expected increase in wind potential.

Another study about the offshore wind resources in the Black Sea, made by Everoze using data generated by Vortex [3], shows similar results for the vertical wind profile although the horizontal variation of wind resources seems to indicate a different pattern. The Everoze study does not include the entire Black Sea but it is possible to infer an increasing wind potential towards the sea from the Ukrainian coastline while the GWA shows opposite gradient at 150 m height. A detailed investigation of the wind resources in the region was not the scope of this work but DTU Wind would suggest additional research, using specific measurements or available information (e.g. satellite images), to confirm the wind resources close to the coastline of Ukraine in the Black Sea.

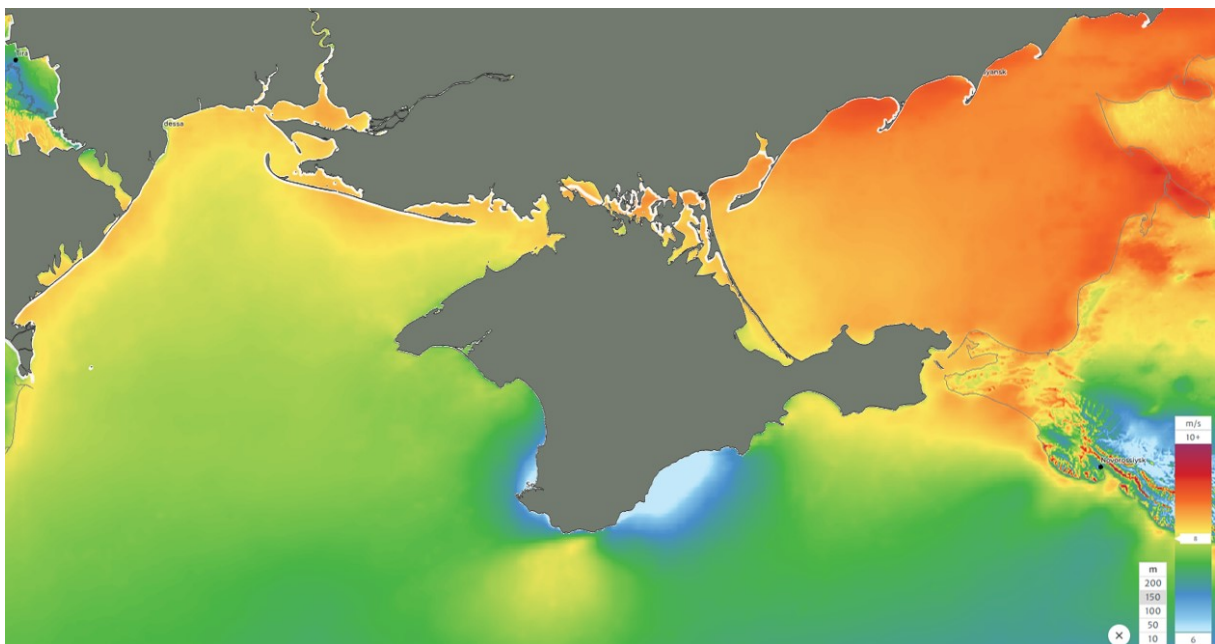
Current market data suggests that upcoming offshore wind turbine projects will likely feature hub heights of around 150 meters above the surface. In light of this, various wind-related metrics and statistics in this report, such as mean wind power density, air density, seasonal variations, extreme winds, and the frequency distributions associated with both wind speed and direction, have been tailored to this specific height.

2.1.1 Mean Wind Power Density

Figure 2 shows the offshore mean wind power density at 100 meters ASL with wind frequency roses for three different areas around Ukraine. The mean wind power density, represented in



(a) Mean wind speed at 100 m ASL.



(b) Mean wind speed at 150 m ASL.

Figure 1: Offshore data from the Global Wind Atlas. Mean annual wind speed in m/s.

the figure in 9 classes from Class 1 (350-400 W/m²) to Class 9 (750-800 W/m²), indicates the potential energy content of the wind flow at a specific height. In addition, the wind roses show the dominant directions of occurrence of the wind. In the Sea of Azov, the prevailing wind directions are from the Northeast, while in the northern Black Sea, all northerly sectors are relevant.

The mean wind power density is a primary indicator for evaluating wind energy potential and is crucial in wind project site selection. Notably, a large area in the Sea of Azov presents good wind resources, Class 6 and Class 7. There is also an area in the South of Crimea with higher wind resources, Class 8. However, smaller and very localised, it implies a mesoscale effect due to the orographic features of the southern part of the peninsula.

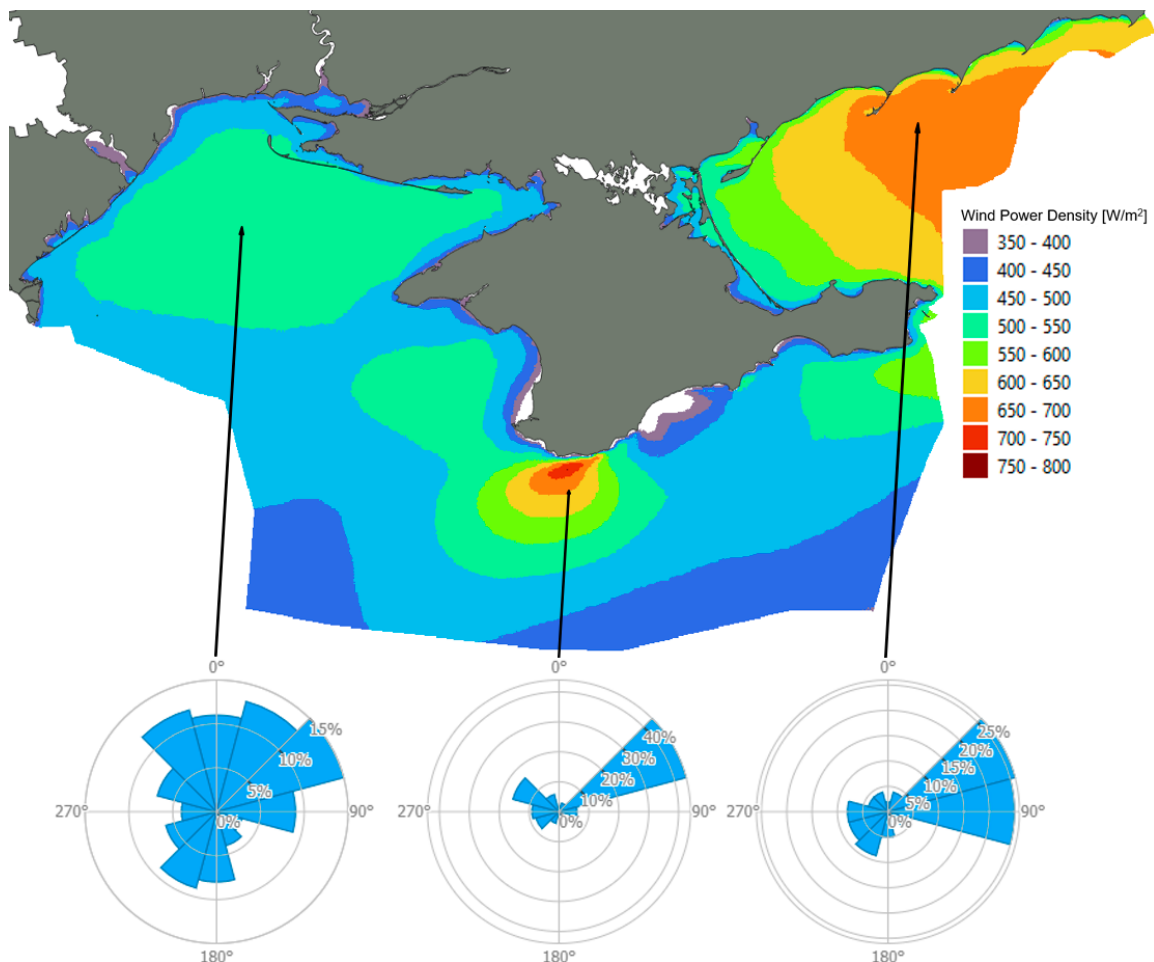


Figure 2: Offshore mean wind power density in W/m² at 100 m ASL and wind frequency roses at three different locations. Data from the Global Wind Atlas.

2.1.2 Frequency Distribution of Wind Speed

The frequency distribution of the mean wind speed for the northern Black Sea area, as seen in Figure 3a, was calculated from the GWA data with the WAsP model. The estimated Weibull parameters at 150 m ASL are 2.06 for the shape factor (k) and 9.2 m/s for the scale factor (A). The air density is estimated at 1.214 kg/m³, and the resulting mean wind power density is 614 W/m². The Figure 3b shows the results for the Sea of Azov area where the Weibull parameters are estimated $k = 1.94$ and $A = 9.7$ m/s, resulting in a higher mean wind power density of 771 W/m².

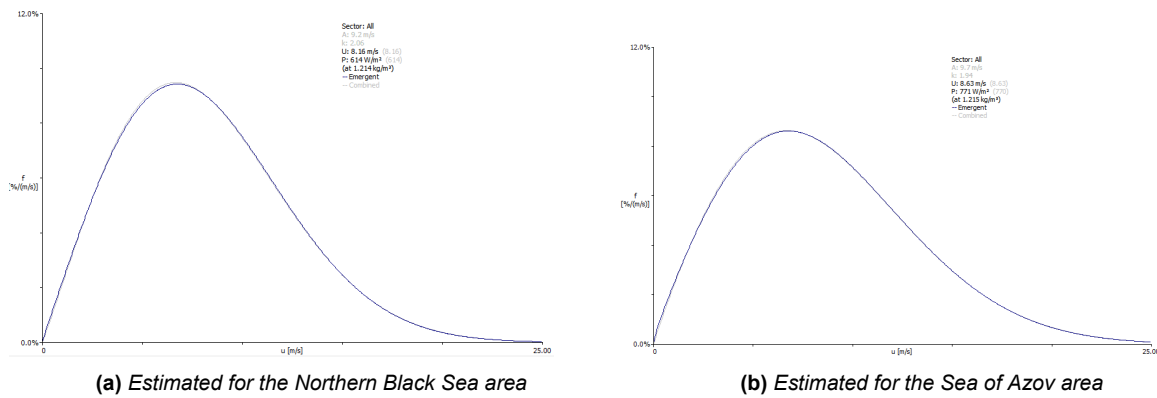


Figure 3: Frequency distribution of the mean wind speed at 150 m height.

2.1.3 Intra-annual Variability of Wind Speed

All three areas mentioned previously present similar monthly variations of mean wind speed. There is a significant intra-annual variability of wind potential with a low wind season from May to September and a peak windy period from December to March, as shown in Figure 4.

2.1.4 Extreme Wind Speed

The extreme mean wind speed shown in Figure 5, represented by the maximum 10-minute average wind speed with a recurrence period of 50 years, V_{50} , was obtained from the Global Atlas of Siting Parameters [4]. Two zones can be seen in the figure, one zone that includes most coastal areas, a yellow class with extreme wind speeds ranging from 28 to 35 m/s, and another large zone including a great part of the sea area, an orange class where the extreme wind speed is estimated to be in the range from 35 m/s to 42 m/s.

2.2 Summary and Discussion

The wind characteristics over the sea around Ukraine have been obtained from the GWA at heights of 100 m and 150 m due to the lack of qualified surface wind measurements. The wind resource information from the GWA can be used for preliminary estimation of offshore wind generation in Ukraine, although the uncertainties of the wind characteristics might be as high as around 20%.

A specific site-oriented measurement campaign following the IEC61.400 standard and MEAS-NET guidelines is recommended for the wind characterization in order to reduce the uncertainties of the wind potential and the extreme wind conditions. It is important to consider that local data is required for the wind turbine design and for assessing durability, performance, energy yield, installation, operation and maintenance assumptions.

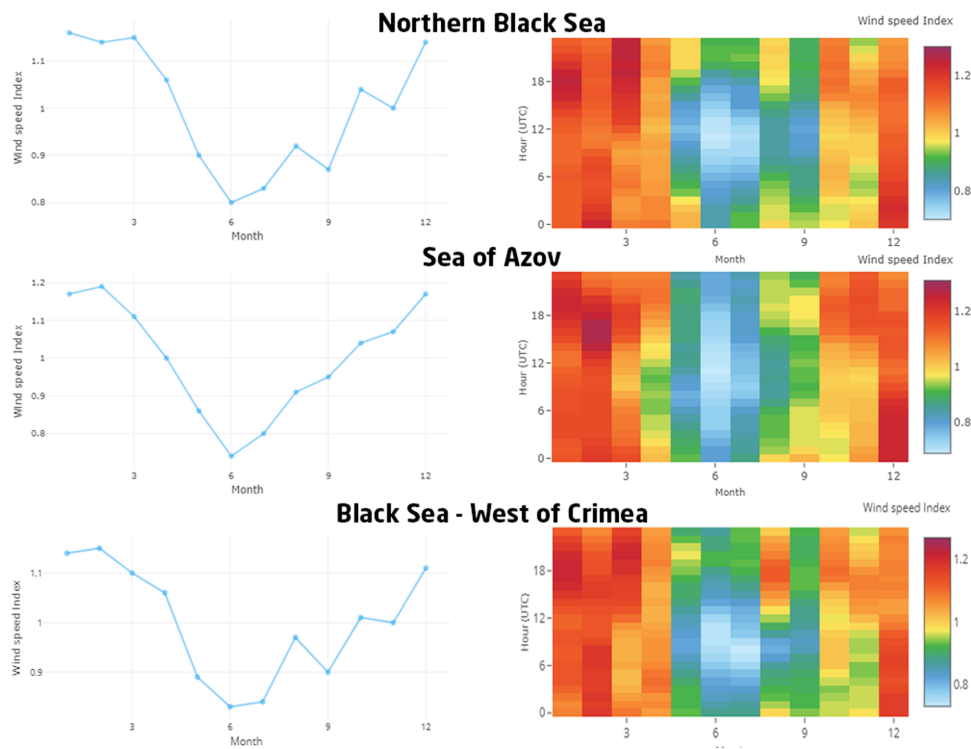


Figure 4: Monthly variation of mean wind speed (left) and variation of the normalised mean wind speed over the month of year and hour of day (right) for three offshore locations. Data and graphs from the GWA.



Figure 5: Extreme wind speed (V_{50}) in m/s at 150 m ASL. Data from the Global Atlas of Siting Parameters [4].

3 Geospatial Analysis

This chapter outlines the spatial GIS analysis to incorporate a range of spatial constraints, including environmental impact mitigation, into our early-stage pre-feasibility assessments. However, it is important to note that a full Environmental Impact Assessment (EIA) is beyond the scope of this study.

QGIS, a free and open-source geographic information system application, was used to create a GIS workspace that incorporates relevant data from publicly available sources and site-specific information from Ukraine. A set of criteria has been used to determine the most suitable areas for developing offshore wind projects.

While the list of constraints in this report is not exhaustive, it includes the most important layers of information related to potential environmental and social impacts. The method of analysis described in this report can be extended in future updates or studies to include additional relevant spatial constraints.

3.1 Site Selection Criteria

Several criteria may be taken into account for site selection, ranging from the exclusive economic zone (EEZ) to environmental restrictions and wind resource potential, the relevance of them depends on site-specific and project-specific conditions.

3.1.1 Exclusive Economic Zone

The first step of the geospatial analysis is to enter the area of interest, in this case the Exclusive Economic Zone (EEZ) of Ukraine. For this study, the Danish Energy Agency (DAE) requested that DTU Wind include all coastline areas from the Black Sea to the Crimea peninsula and to the Sea of Azov areas. The EEZ of Ukraine is presented together with the land part in Figure 6. The EEZ was derived from MarineRegions.org [5], while the land area has been retrieved from the 'Official Boundaries Data Catalog' of the World Bank [6].

3.1.2 Marine Protected Areas

The marine protected areas in the EEZ of Ukraine are presented in Figure 7. The marine protected areas data was derived from the dataset 'Marine Protected Areas' from UNEP-WCMC and IUCN (2023) of Protected Planet [7].

3.1.3 Shipping Routes

The global shipping traffic density includes all ship categories combined based on the 'Global Ship Density' dataset from the World Bank's Data Catalog, as a result of a partnership with the International Monetary Fund (IMF) and support from the World Bank's ESMAP and PROBLUE programs [8].

The global shipping raster layers have been created using IMF's analysis of hourly Automatic Identification Systems (AIS) positions received between January 2015 and February 2021 and represent the total number of AIS positions that have been reported by ships in each grid cell with

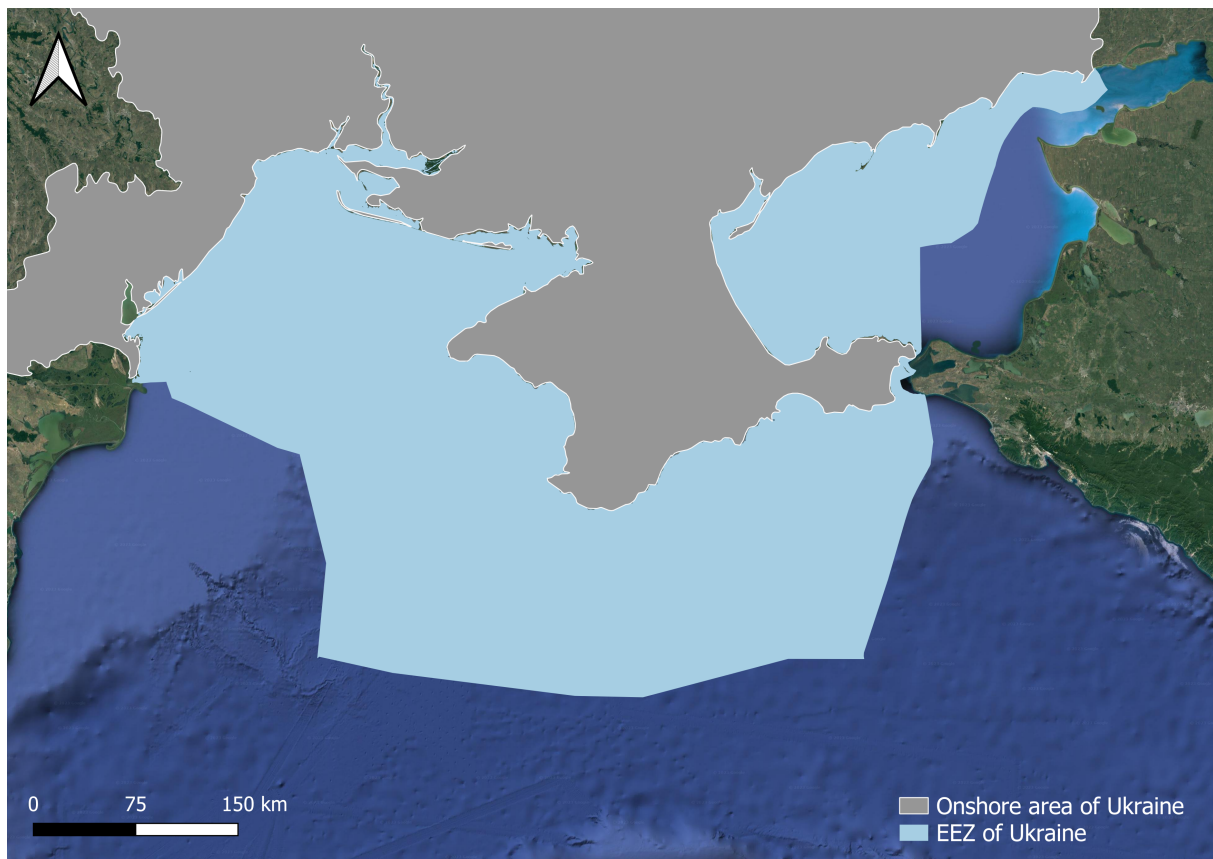


Figure 6: Exclusive Economic Zone (EEZ) and onshore area of Ukraine. [5], [6]

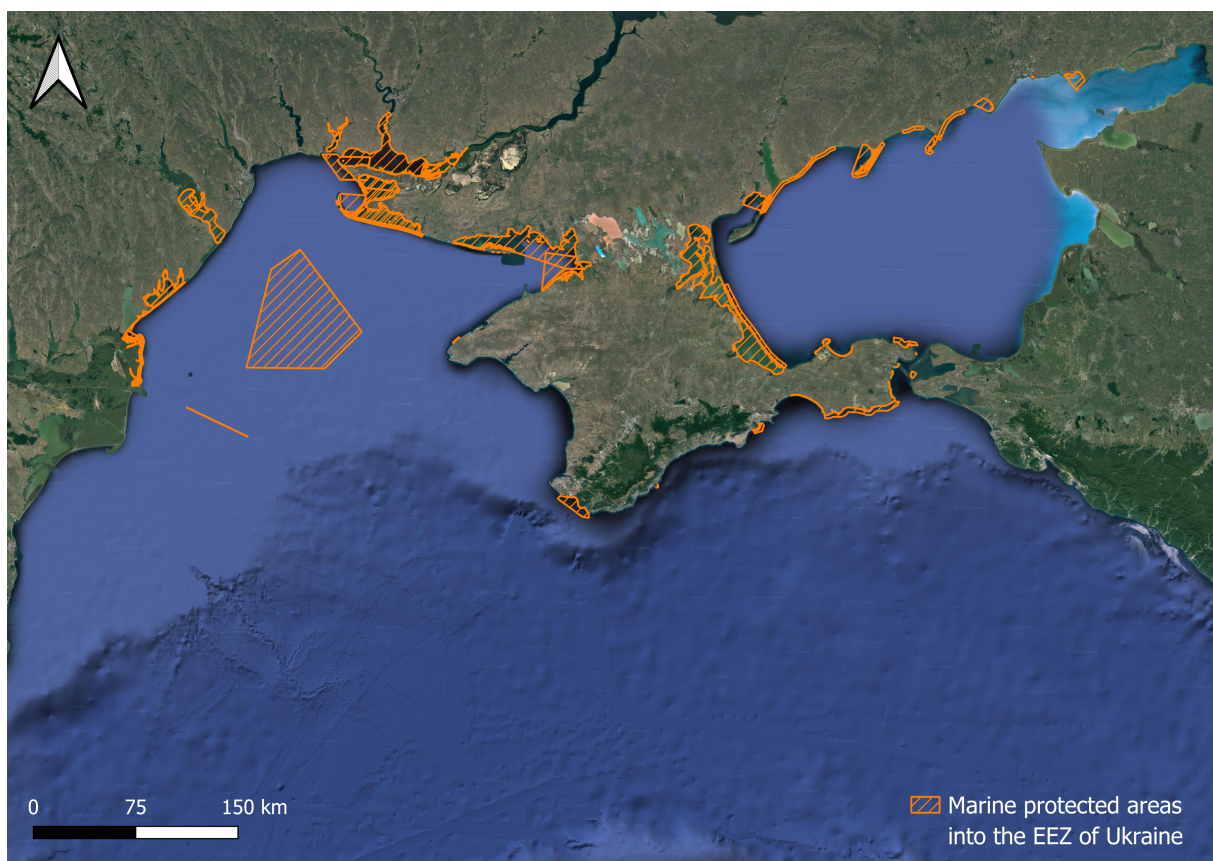


Figure 7: Map showing marine protected areas inside the EEZ of Ukraine. [7]

dimensions of 0.005° by 0.005° (approximately a 500 meters x 500 meters grid at the Equator). The AIS positions may have been transmitted by both moving and stationary ships within each grid cell; therefore, the density is analogous to the general intensity of shipping activity. The shipping density in the EEZ of Ukraine ranges from 0 to 44,304,051 entries.

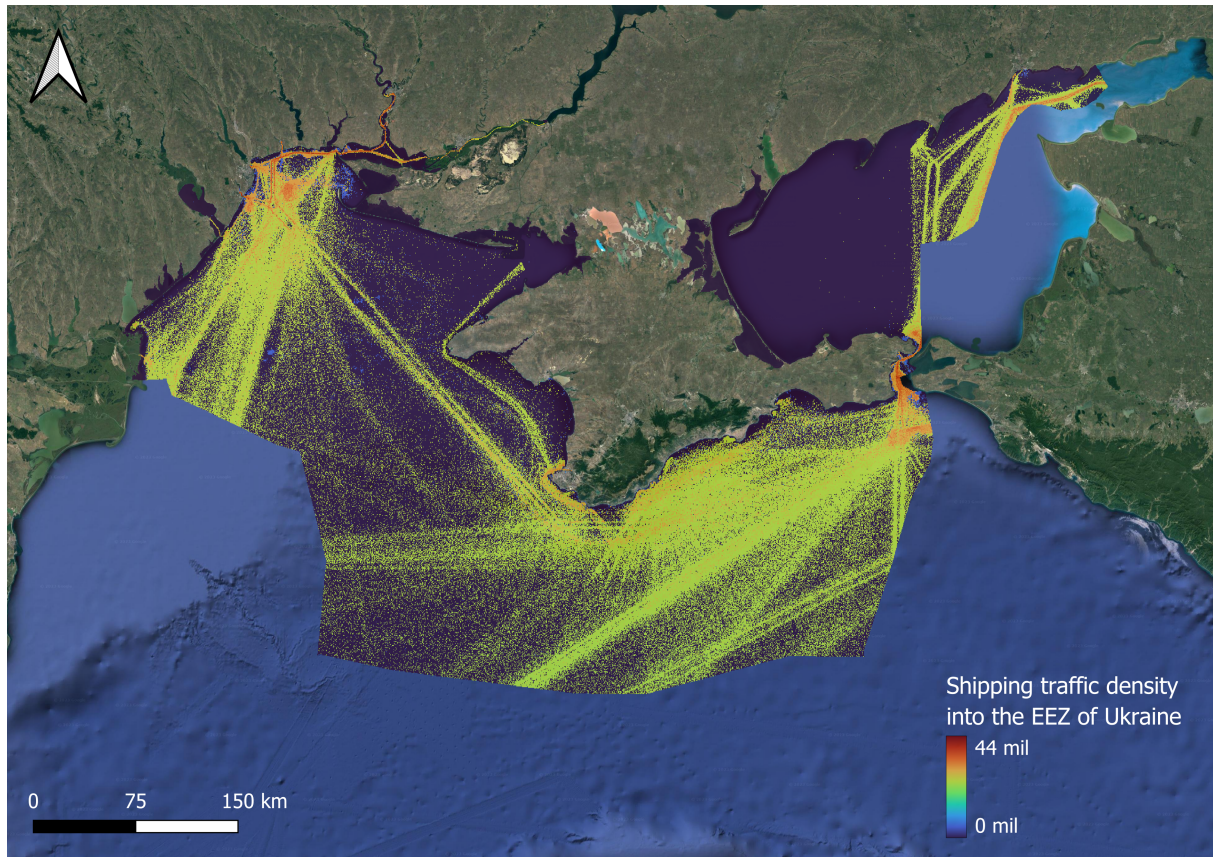


Figure 8: Map showing the shipping traffic density. [8]

3.1.4 Mean Wind Power Density

The mean wind power density retrieved from Global Wind Atlas [9] is also included as a site selection criterion to identify the areas of interest. This study has decided to focus on areas with a mean wind power density greater than 500 W/m^2 as it represents a typical threshold for good wind potential. The highlighted area in Figure 9 shows good wind resources for offshore wind projects.

3.1.5 Bathymetry

Another site selection criterion is bathymetry, specifically water depth, which significantly influences decision-making related to wind turbine foundations. We have decided to include all areas with water depths ranging from 0 meters to 1000 meters but divided this range into two categories: a) shallow waters (0-50 meters); and b) deep waters (50-1000 meters), which includes conditions for two main types of foundations, bottom-fixed and floating technologies, respectively. However, it is most common to prioritise areas with water depths of up to 50 m, a threshold considered feasible for bottom-fixed foundations. Figure 10, obtained from the GWA [9], displays the bathymetry information. The large green area in the figure, represents water depths of 0-50m, suitable for bottom-fixed type of foundations.

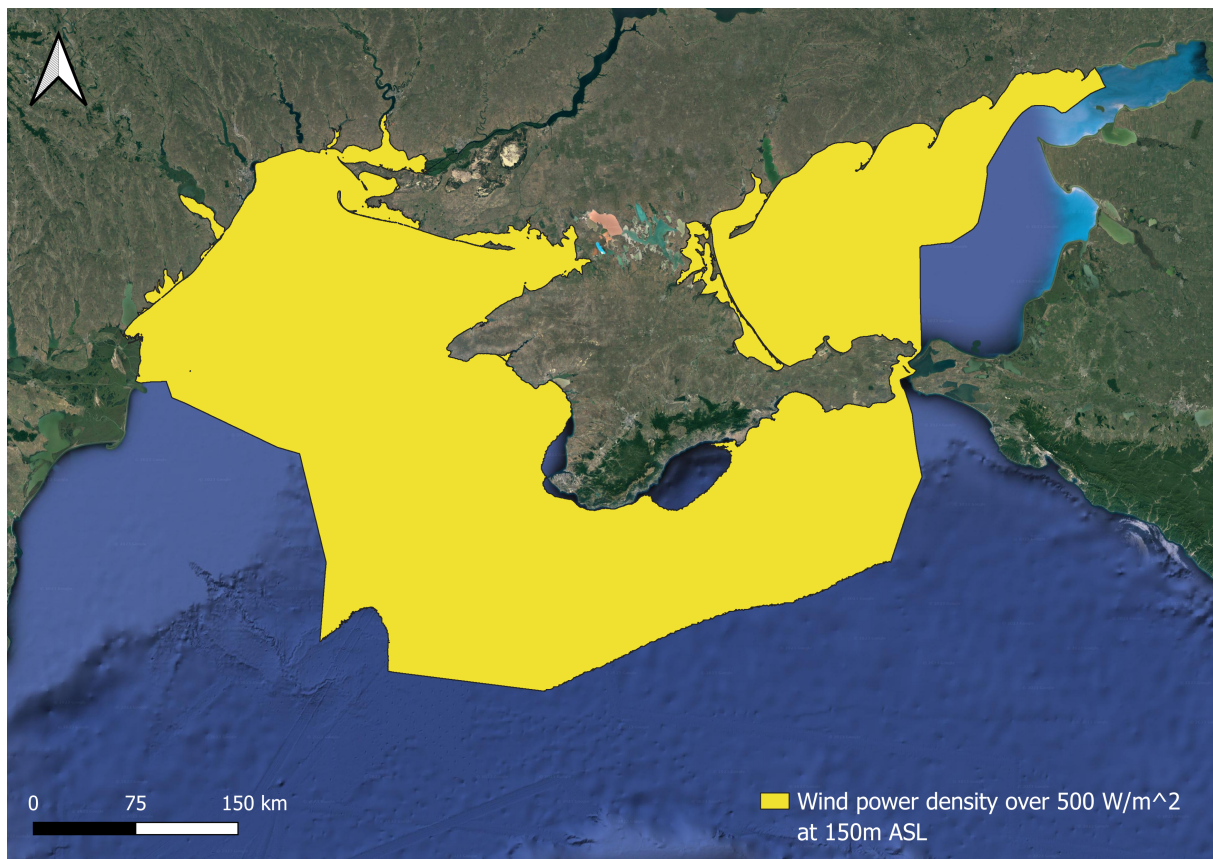


Figure 9: Map showing areas of mean wind power density over 500 W/m^2 at 150 m ASL. [9]

3.1.6 Additional Potential Constraints

The following information has been collected as images only and might be included in similar studies if the information is made available in GIS format data files.

Critical Habitats

The global critical habitat screening layer serves as an assessment tool used during the initial phases of projects, and it is presented in Figure 11. It helps identify and evaluate the potential impact of a project on areas designated as 'Critical Habitat' according to International Finance Corporation's (IFC's) Performance Standard 6 (PS6). This layer essentially maps out regions or operations that might intersect or affect these vital habitats, allowing project planners to take necessary precautions or adjustments to minimise negative impacts on these critical areas ([10]).

Key Biodiversity Areas

Key Biodiversity Areas (KBAs) are locations that play a crucial role in maintaining biodiversity across terrestrial, freshwater, and marine ecosystems. These sites are pinpointed by local stakeholders through national procedures, employing a universally accepted set of scientific benchmarks to identify them ([11]). In Figure 12, the key biodiversity areas are showcased alongside both terrestrial and marine protected areas on a unified map.

Wetlands

Ramsar wetlands, termed as "internationally important" by the Convention on Wetlands, are specifically designated by each participating nation. Upon joining the Convention, each nation

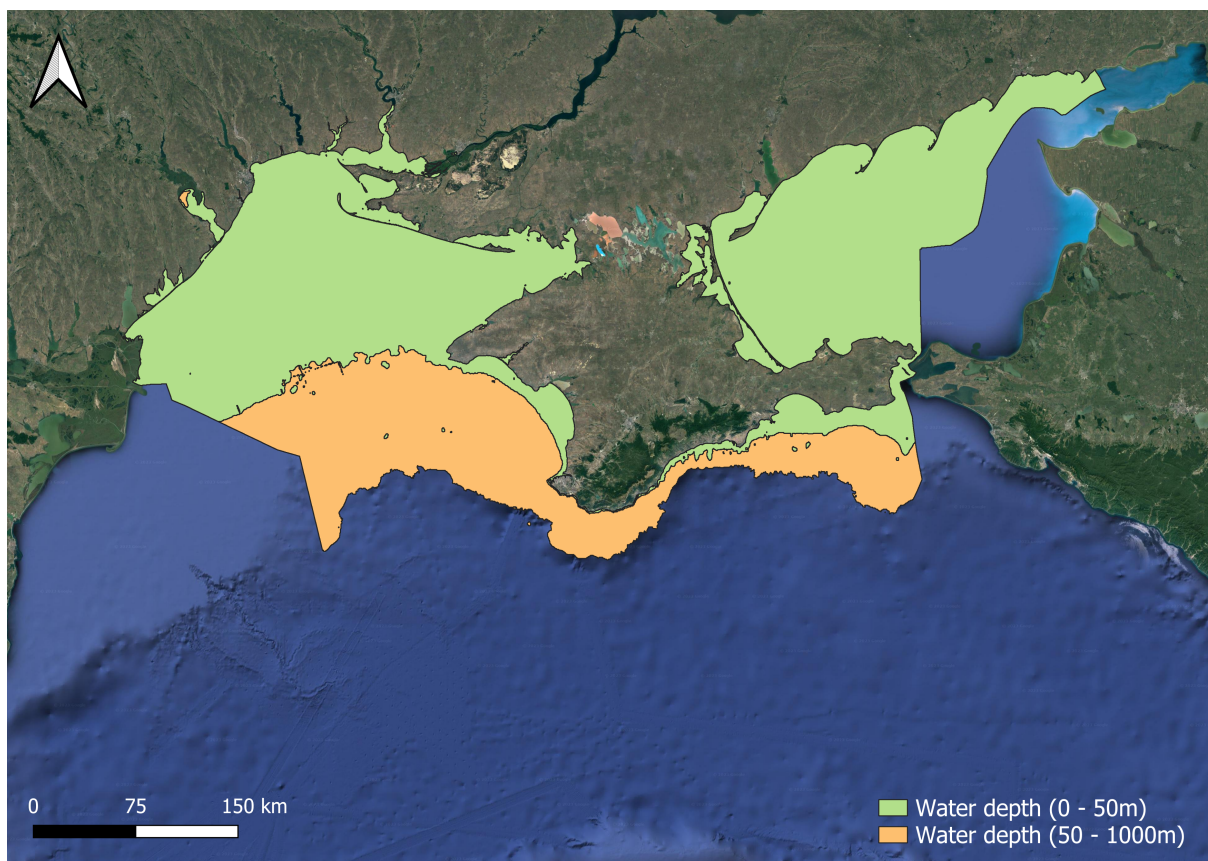


Figure 10: Water depths divided into two categories: shallow (0m-50m) and deep (50m-1000m). [9]

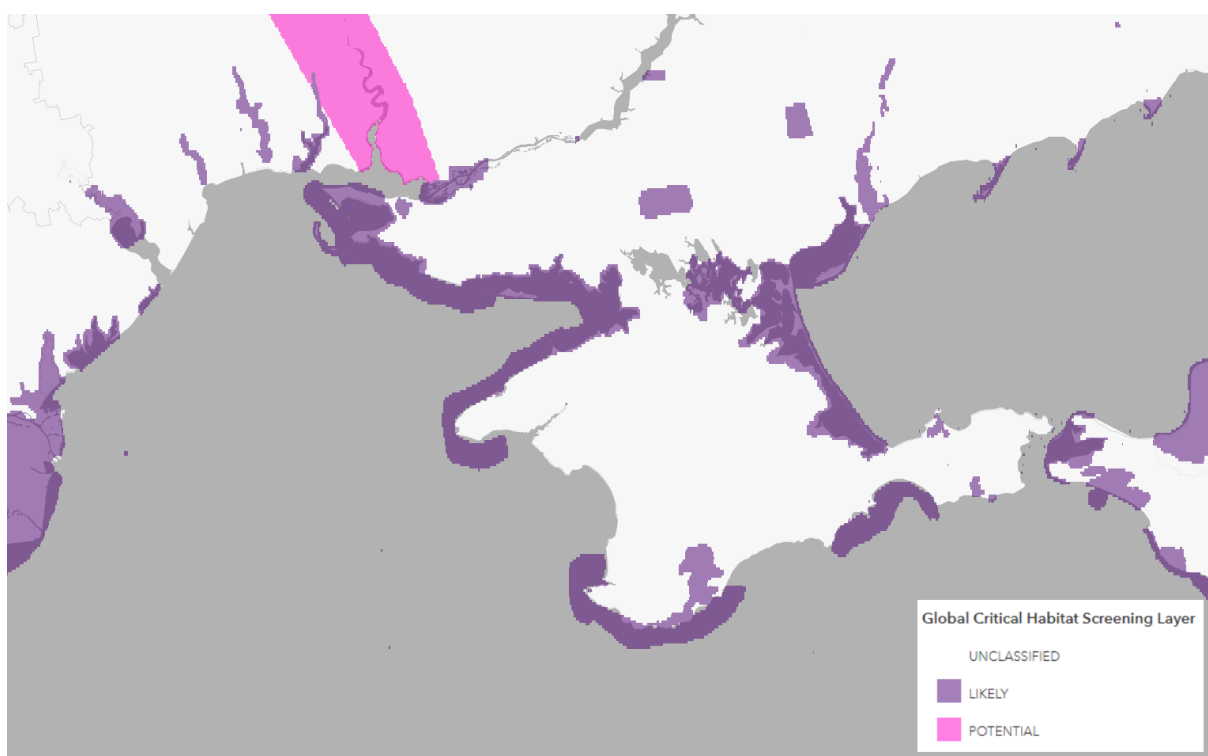


Figure 11: Global critical habitat screening layer focused on the EEZ of Ukraine [10].

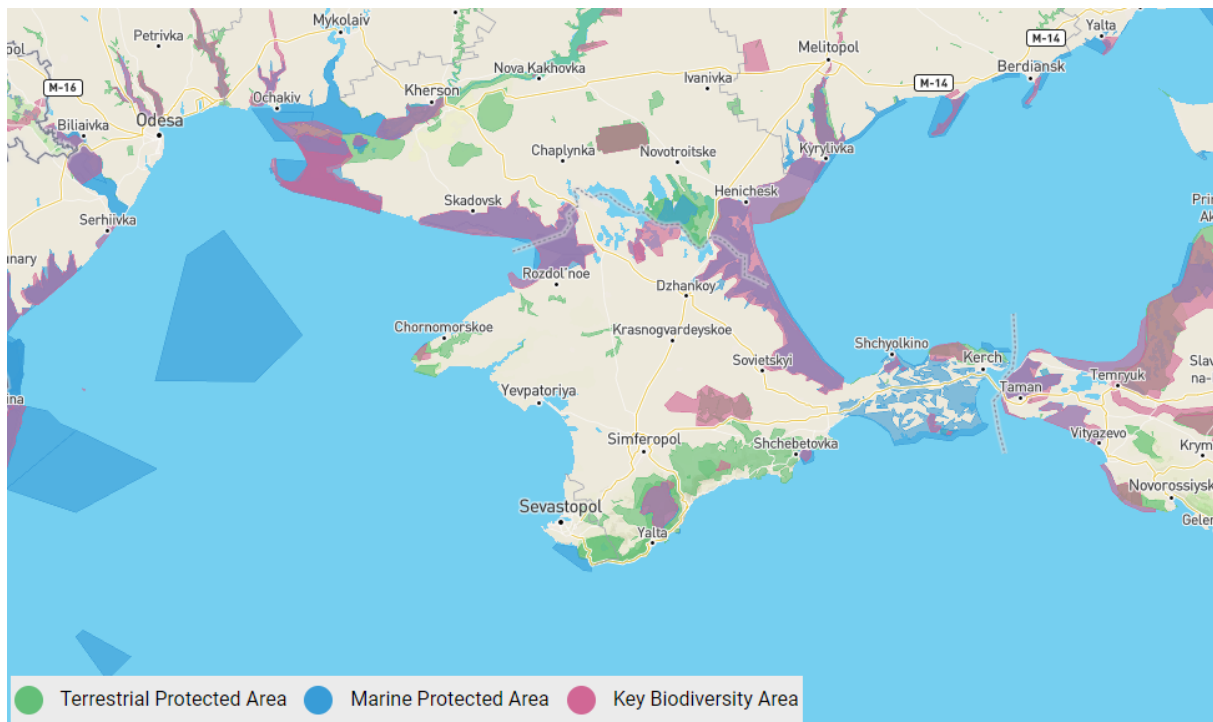


Figure 12: Map showing the overlap between Key Biodiversity Areas and Protected Areas [11].

commits to assigning at least one wetland within its borders to be included in the List of Wetlands of International Importance, known as the Ramsar List [12]. These designated Ramsar sites carry both national and global significance, recognized not only for their value to the respective countries but also for their critical importance to humanity as a whole. The general types of wetlands of international importance, as defined by the Ramsar Convention on Wetlands, are presented in Figure 13.

Seagrass Areas

The global distribution of Seagrasses dataset, compiled by the United Nations Environment World Conservation Monitoring Centre (UNEP-WCMC), encompasses worldwide occurrences of seagrasses [13]. It includes both point locations and polygons documenting seagrass presence from 1934 to 2015. This dataset provides details on seagrass family, genus, and species, along with the respective country of occurrence and information on whether the seagrass habitat falls within a protected area. The global distribution of Seagrasses focused on Ukraine's offshore area is presented in Figure 14.

Marine Mammals

According to the website OBIS-SEAMAP [14], marine mammals are a diverse group of animals that live in the ocean and depend on it for their survival. Some examples of marine mammals are whales, dolphins, porpoises, seals, sea lions, walruses, sea otters, polar bears, manatees, and dugongs. They belong to different orders and families within the class Mammalia. Figure 15 and Figure 16 present the marine mammals within the EEZ of Ukraine, where the grids are color-coded by the number of records or animals respectively.

Bird Flyways

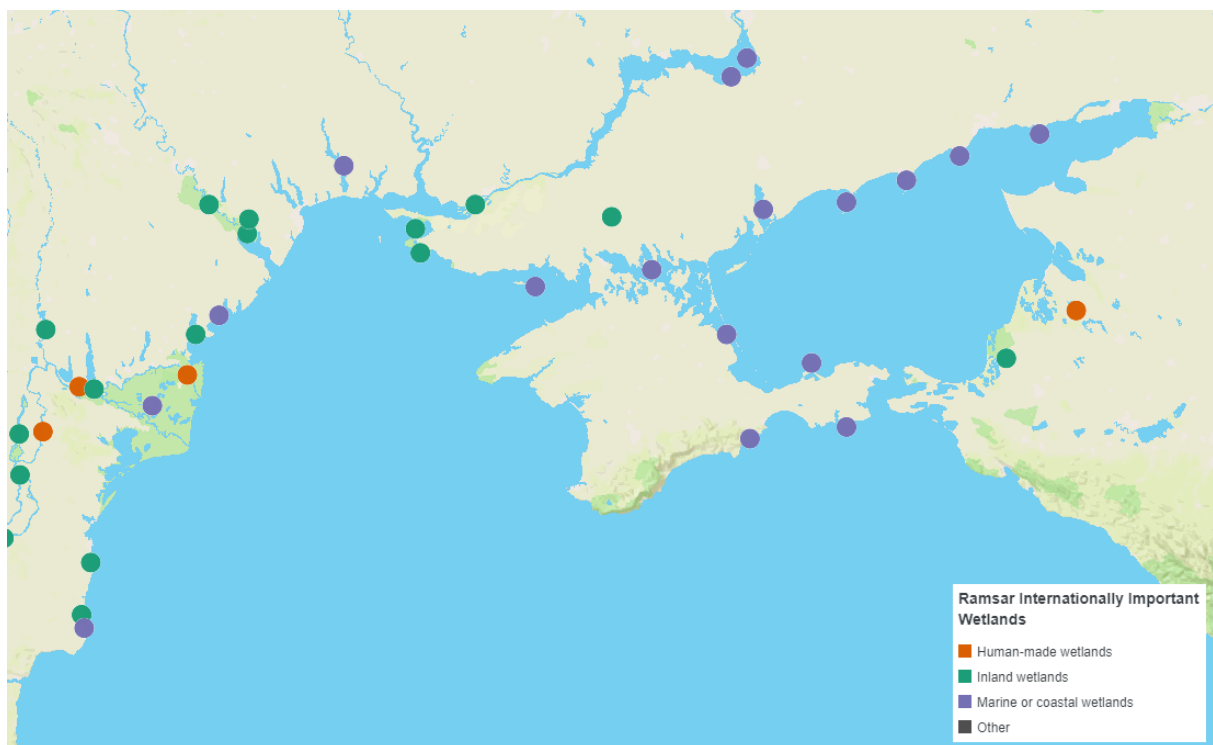


Figure 13: *Wetlands from Ramsar Convention on Wetlands [12].*

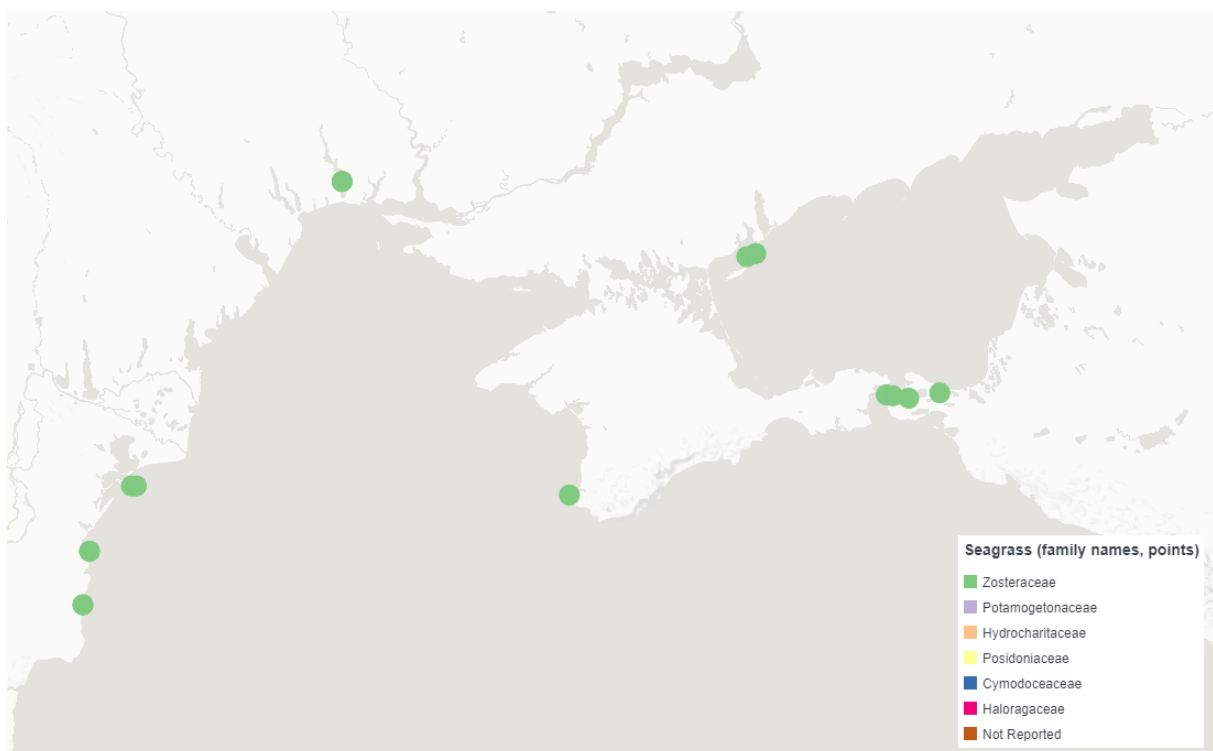


Figure 14: *Seagrass locations displayed by family name [13].*

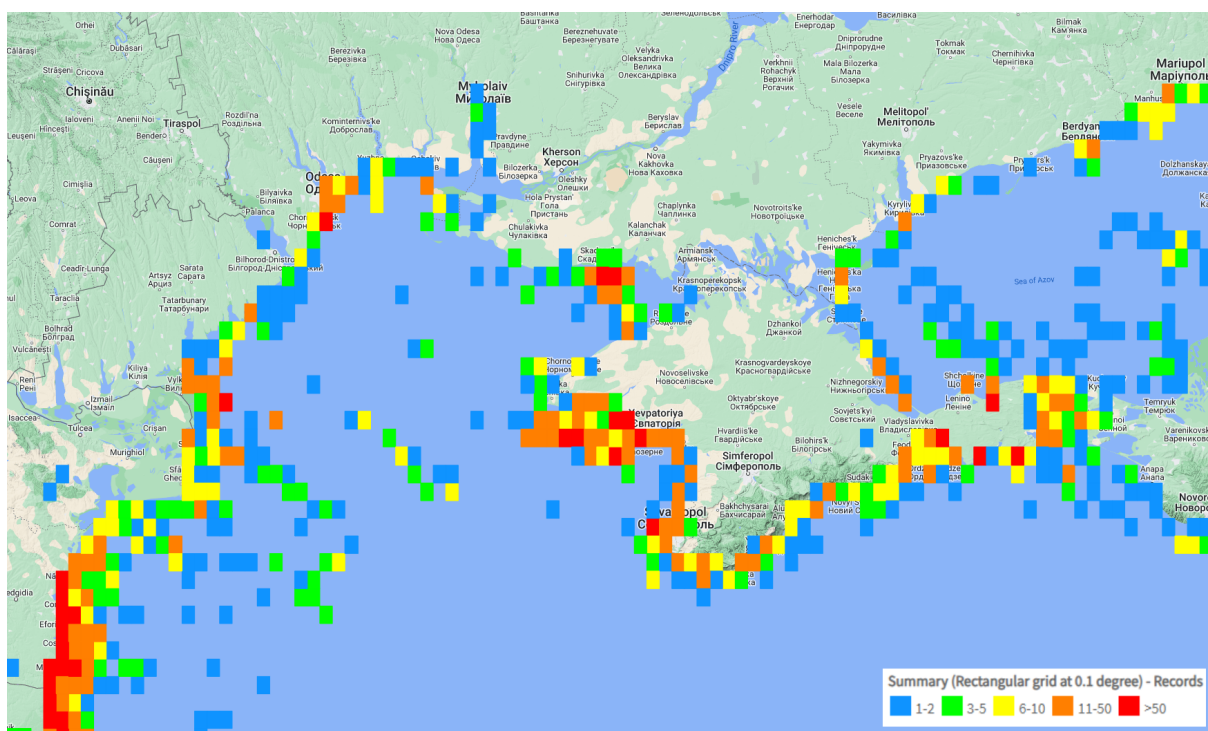


Figure 15: Grid representation of marine mammal records [14]

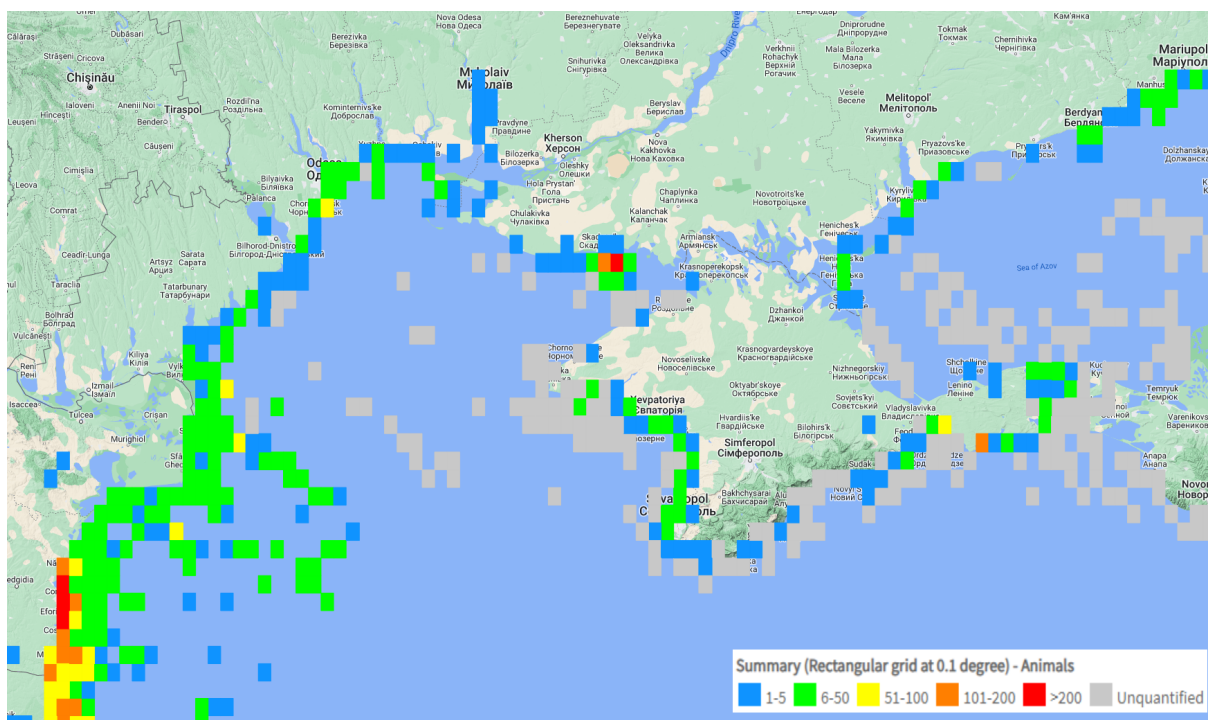


Figure 16: Grid representation of marine mammal animals [14]

The map depicted in Figure 17, derived from BirdLife [15], illustrates the primary migratory bird flyways across the Mediterranean and the Black Sea. Notably, the map reveals that none of these flyways extend across the Black Sea region.

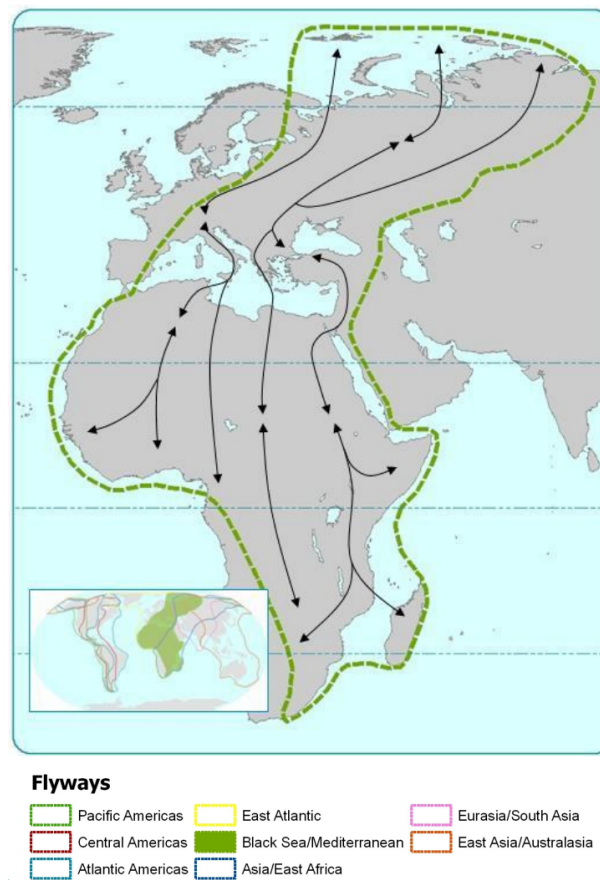


Figure 17: Bird flyways over Mediterranean and Black Sea [15]

Ports and Airports

The surrounding area's ports and airports are presented in Figure 18. While the presence of airports might impose a restriction for siting a wind farm, the ports are an advantage as the important infrastructure required for installing and operating offshore wind farms.

Fishing Activity

The fishing activity registered in 2021 is presented in Figure 19. Fishing activity has to be considered in the early stages of wind farm planning to take into account potential impacts on fish and restrictions on shipping routes.

3.1.7 Other Constraints

Several types of constraints could have been considered restrictions for determining exclusion zones and selecting areas with minimum impacts, such as tourism activities, diving, wreckage, mining, military, aviation, migratory paths, ecosystems, etc. However, DTU Wind did not have access to additional data and/or information about other constraints around Ukraine to use in the analysis at this study stage.



Figure 18: *Locations of ports [16] and airports [17]*

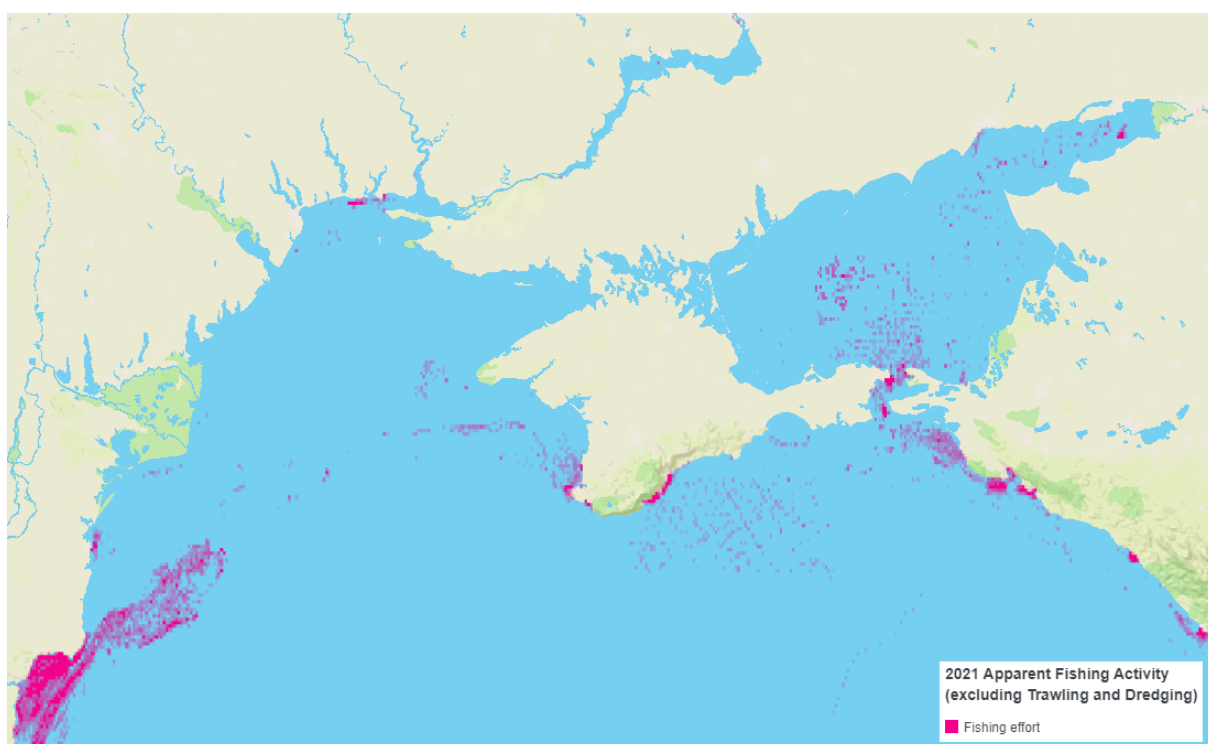


Figure 19: *Apparent fishing activity in 2021 [18]*

3.2 Available Area Selection

The criteria for selecting a suitable area includes the most feasible characteristics for an off-shore project, which normally involves a combination of good wind potential, closeness to the shore, and shallow water depths; still, some site-specific constraints might need to be taken into consideration to minimise any potential impact on the environment, culture, security, and on social and commercial activities. This study incorporates the following site selection criteria into the geospatial analysis using QGIS: high wind potential areas inside the EEZ with suitable bathymetry excluded coastal zones, protected areas, and high-density shipping traffic.

Figure 20 presents the workflow for selecting areas for either bottom-fixed or floating wind turbines. The process begins by subtracting a 10km buffer zone from the coastal line into Ukraine's Exclusive Economic Zone (EEZ), as depicted in Figure 6. Next, the marine protected areas, illustrated in Figure 7, are also excluded by adding a safety buffer zone of 2km.

Given the interest in focusing on the most resourceful areas, only the zone with a wind power density greater than 500 W/m^2 , as shown in Figure 9, is selected. The resulting area is separated into two parts, one with water depths of up to 50m, suitable for bottom-fixed wind turbines and another with water depths greater than 50m for floating wind turbines.

Finally, the shipping density layer, which is depicted in Figure 8, is excluded after a minimum threshold of 30 million is applied. This threshold represents approximately two-thirds of the maximum shipping range over the Exclusive Economic Zone (EEZ) of Ukraine, which recorded 44,304,051 entries between January 2015 and February 2021 [8]. Additionally, a safety buffer zone of 250m is included.

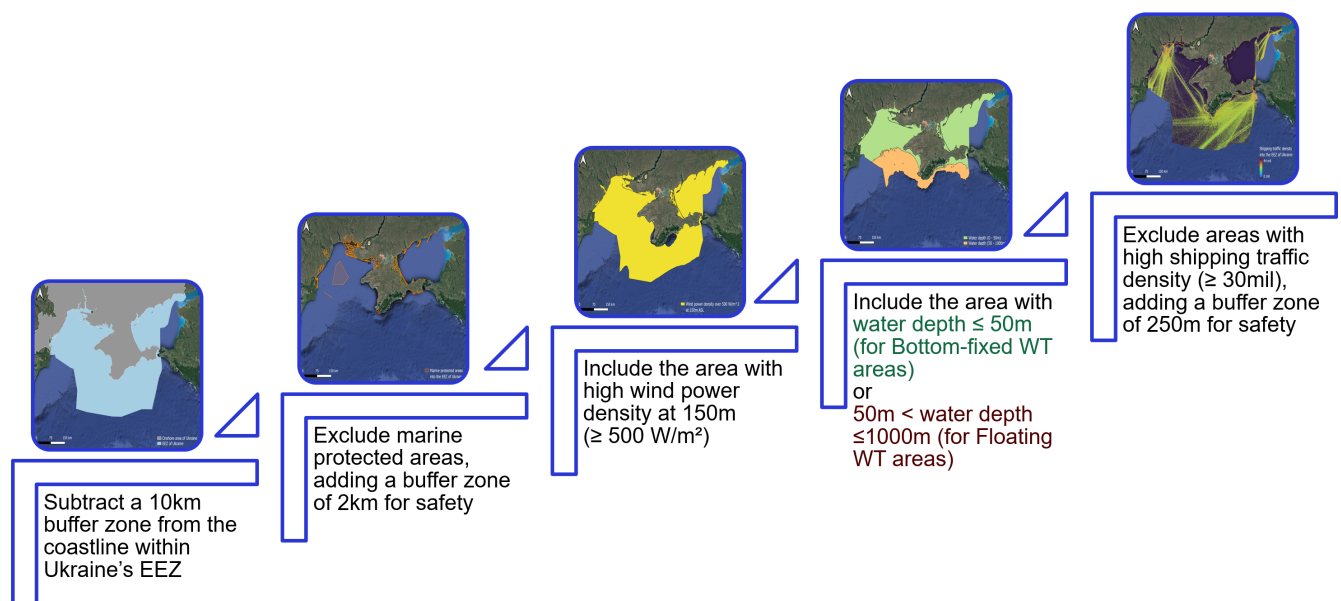


Figure 20: Criteria and restrictions for area selection applied in this study.

The result of the site selection process described above is presented in Figure 21 for bottom-fixed and floating wind turbines.

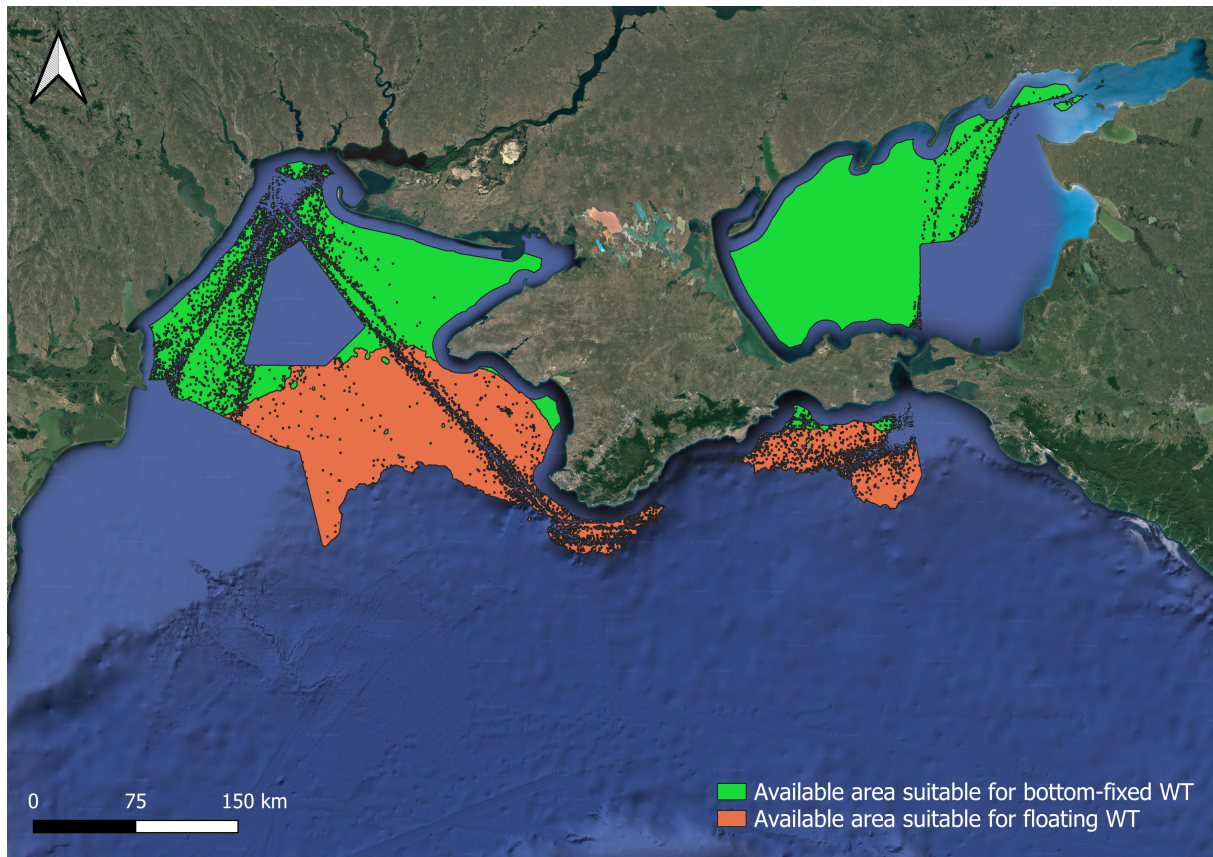


Figure 21: Selected areas for preliminary offshore wind farm assessment.

3.3 Summary and Discussion

The simplified geospatial assessment of the sea area in the EEZ of Ukraine was performed due to the lack of a maritime spatial plan for Ukraine. The objective was to select locations to be prioritised for the feasibility studies of offshore wind projects.

The site selection criteria include good wind potential, shallow water depths, and some site-specific constraints estimated by DTU Wind using best practices guidelines.

The databases used for the geospatial analysis are publicly available and may be used in the future to enhance the current study in case that new data or different constraints become available.

4 Energy Yield Assessment

This chapter introduces the framework for our case study centred on three hypothetical wind farms in Ukraine. Our primary objective is to analyse the potential energy yield, considering various project configurations and characteristics within the designated available area shown in chapter 3.

The wind power projects are simulated in detail using the industry-standard software WAsP 12.8 (Wind Atlas Analysis and Application Program) [2], which includes a microscale wind flow model coupled with a wake model to calculate the long-term mean annual energy production. All data, models, and parameters used in the calculations are described below.

4.1 Inputs

4.1.1 Wind Data

The Global Wind Atlas (GWA) provides Generalised Wind Climate (GWC) data for any location in the world within 200 km from coastlines. The concept of a generalised wind climate, a key element of the wind atlas methodology developed at DTU Wind and fully explained in the European Wind Atlas [19], has been used in numerical wind atlas methodologies, where mesoscale modelling output is generalised before being applied in microscale modelling with WAsP.

As explained in chapter 2, we rely on the GWA for wind data due to the absence of good quality energy-specific wind measurements in the area of interest. In wind power development, the GWA data is predominantly utilised during the exploration phase and the preliminary stages of wind resource assessment before on-site meteorological measurement stations are deployed. It is important to note that relying solely on GWA data for the specific siting of wind farms may not meet the rigorous financial and technical criteria required by investors and stakeholders.

The current GWA version uses large-scale wind climate data provided by atmospheric re-analysis data, available from ERA5 dataset for the period 2008-2017 [20]. The generalised wind climate file, used as input in the present study, contains the sector-wise frequency of occurrence of the wind (the wind rose) and the wind speed frequency distributions in the same sectors (as Weibull A- and k-parameters). This information is a generalised site-independent description of the wind climate in a certain area.

DTU has adopted the procedure of downloading one GWC data file for each of the turbine positions to ensure that the spatial variation of the wind characteristics in the offshore area due to mesoscale effects would be included in the analysis. The air density was also calculated for each wind turbine position using the meteorological information obtained from the GWC data. The average meteorological parameters for this location are the mean temperature of 13 °C, the mean air pressure of 101,578 Pa, and the mean relative humidity of 75% at approximately 30 meters above sea level.

4.1.2 Wind Turbine

The selection of the wind turbine model for this preliminary study was based on the highest nominal capacity and hub height amongst the most common wind turbines installed in recent offshore wind projects and with available tested power curves.

Some characteristics of the wind turbine selected are presented in Table 1. It has a rated power of 8.25 MW with a rotor diameter of 164 m and 140 m hub height above sea level. The wind turbine power curve and thrust coefficient (C_t) curve can be seen in Figure 22.

Table 1: Basic specifications for the 8.25 MW wind turbine used in the study.

Parameter	Value
Rated power	8.25 MW
Hub height	140.0 m
Rotor diameter	164.0 m
Cut-in wind speed	4.0 m/s
Rated wind speed	13.0 m/s
Cut-out wind speed	25.0 m/s

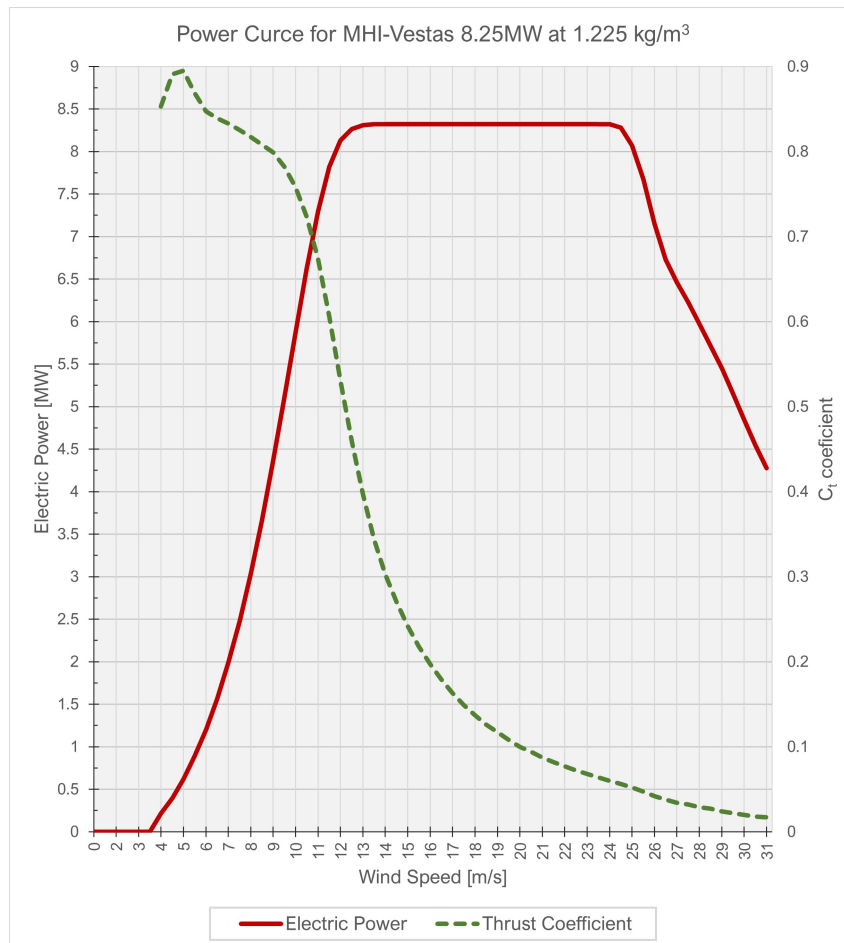


Figure 22: Power and thrust coefficient curves for modelling the wind turbine in WAsP.

4.1.3 Site Locations

Three sites have been selected within the available area to develop hypothetical wind farms with different water depths, distance to shore, distance to port and wind resources. A summary of the sites' characteristics is presented in Table 2 and their location in Figure 23. The mean wind speed and the mean wind power density shown in the table are derived from the GWA at the locations of the reference points at 140 m above sea level.

Site 1 and Site 2 are located in shallow waters of around 25- and 8-meter average water depths, respectively, where common bottom-fixed foundations could be applied. For Site 3, a more complex structure or even a floating foundation must be considered, as the average water depth is around 55 meters. Site 2 presents the most favourable conditions, e.g. the highest wind resources, with an indicative mean wind power density of 754 W/m^2 at 140 m above sea level, the shortest distances to shore and to port, and the lowest water depths. On the other hand, Site 3 has the most challenging characteristics: the deepest waters, the longest distances to shore and port, and the lowest mean wind power density.

The locations are indicative, and further investigations will be required to confirm the characteristics of the sites - for example, with measurements of bathymetry and wind resources - and assess the environmental and social impacts of offshore wind farms.

Table 2: Main characteristics of the wind farm sites.

Characteristic	Site 1	Site 2	Site 3
Reference Point			
X [m]	442441.2 m	304283.3 m	410996.4 m
Y [m]	5083352.0 m	5148659.0 m	5003947.0 m
Average water depth	25 m	8 m	55 m
Distance to shore	15.3 km	13.7 km	45.9 m
Distance to port	124 km (Odessa)	112 km (Mariupol)	161 km (Odessa)
Mean wind speed	8.12 m/s	8.58 m/s	7.76 m/s
Mean wind power density	600 W/m^2	754 W/m^2	549 W/m^2

4.1.4 Digital Maps

According to WAsP best practices, the elevation map should extend at least several (2-3) times the horizontal scale of significant terrain features from any mast or wind turbine position. The roughness map should extend at least $\max(150 \times h, 10 \text{ km})$, where h is the turbine hub height, which translates to 21 kilometres considering the hub height of 140 m.

The digital maps (including surface roughness and terrain elevation) are downloaded from the GWA Map Warehouse using WAsP Map Editor. For the elevation, a 10 m interval is chosen for the height contour lines. The digital maps adopt the UTM coordinate system based on the WGS-84 datum (zone 36 and 37 for Ukraine) and are shown in Appendix A.1.

4.1.5 Wind Farm Layouts

DTU Wind has prepared three different layouts of 72 wind turbine positions each, resulting in a total capacity of 594 MW (approximately 600 MW). The different layouts have been conceived due to the various wind direction frequencies (or wind roses) in each location. For example,



Figure 23: Map showing the site locations and layouts of three hypothetical wind farms.

considering the omnidirectional characteristics of the wind at Site 1, located in the Northern Black Sea, the wind farm layout was designed with 8 rows of 9 wind turbines with a separation of 10 times the rotor diameter (10D) between wind turbines and similar row spacing of 10D. On the other hand, the layout of Site 2, located in the Sea of Azov, has 3 rows of 24 turbines each, with a turbine spacing of 4D and a row spacing of 10D. The rows are oriented nearly perpendicular to the prevailing wind direction to account for the unidirectional wind characteristics in this area. For Site 3, located in the Black Sea west of Crimea, the layout uses 6 rows of 12 turbines oriented to fit the main wind directions in this area, with a turbine spacing of 7D and a row spacing of 10D.

In figures 24, 25, and 26, the final wind farm layouts with circles representing the location of the turbines are shown for Sites 1, 2, and 3, respectively.

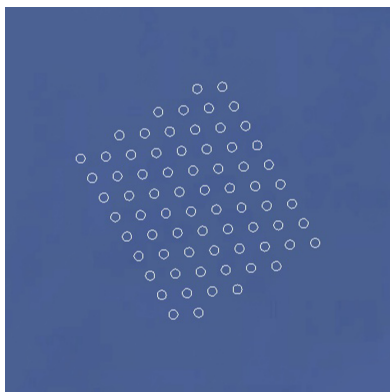


Figure 24: Site 1 wind farm layout

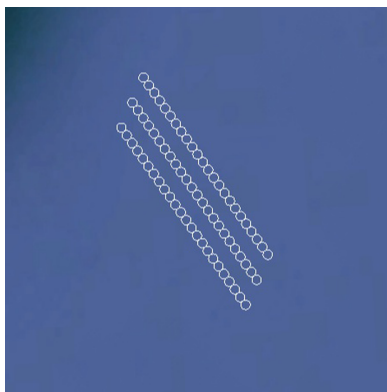


Figure 25: Site 2 wind farm layout

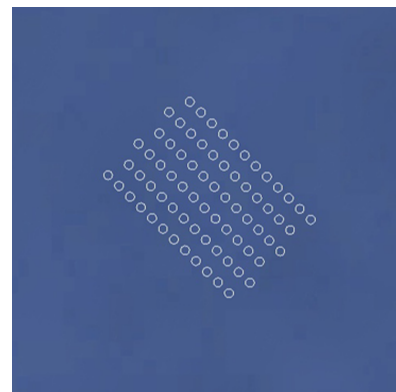


Figure 26: Site 3 wind farm layout

Table 3: Layout characteristics of the wind farm sites.

Characteristic	Site 1	Site 2	Site 3
Location	Northern Black Sea	Sea of Azov	Black Sea - West of Crimea
Number of rows	8	3	6
Turbines per row	9	24	12
Turbine spacing	10D	4D	7D
Row spacing	10D	10D	10D

4.2 Wind Farm Calculations

4.2.1 Wind Flow Modeling

The WAsP software utilises the IBZ flow model, derived from the BZ model of Troen [21], to calculate the wind velocity perturbations induced by orographic features such as single hills or more complex terrain. The IBZ model was developed with the specific purpose of detailed wind energy siting in mind and has the following general features:

- It employs a high-resolution, zooming, polar grid (with the centre point located at a selected point of interest). The polar grid has 72 rays separated by 5° and 100 radial stations on each ray with each radial interval 6% larger than the previous interval). This is coupled with a map analysis routine to calculate the potential flow perturbation profile at the central point of the model.
- It integrates the roughness conditions of the terrain surface into the spectral or scale decomposition. The inner-layer structure is calculated using a balance condition between surface stress, advection, and the pressure gradient.
- It uses an atmospheric boundary layer thickness of approximately 1 km to force the large-scale (say, more than a few kilometres) flow around high-elevation areas.

The recommended operational envelope of the WAsP model corresponds to terrain slopes up to about 0.3. Given the offshore location of the sites and the clear absence of challenging land features in the vicinity of the wind farms, the use of WAsP is considered suitable.

4.2.2 Wake Model

WAsP includes the PARK2 wake model to consider internal wake losses from one wind turbine to another within a wind farm. The PARK2 wake model has been calibrated and validated against production data from several offshore wind farms at different conditions. The calibration has resulted in a recommended value for the wake decay constant of the PARK2 wake model [22]. In this study, the PARK2 model was configured with the offshore wake decay constant of 0.06.

4.2.3 Wind Climates

In Figure 27, Figure 28 and Figure 29, the wind frequency rose and the Weibull distribution at wind turbine hub height, 140 meters ASL, is shown for Site 1, 2, and 3, respectively. The resulting wind climates were derived from WAsP based on GWC data at three representative locations, one for each wind farm. The wind farm calculation procedure has included wind climate predictions for each wind turbine position.

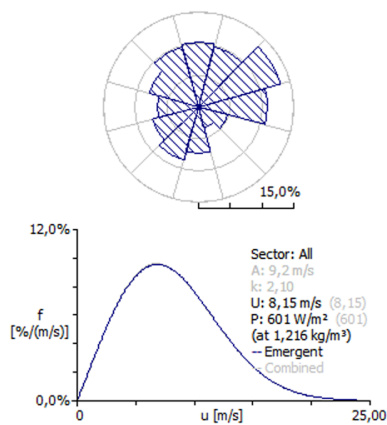


Figure 27: Wind frequency rose and Weibull distribution for Site 1.

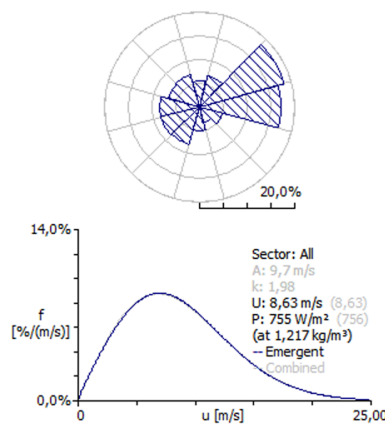


Figure 28: Wind frequency rose and Weibull distribution for Site 2.

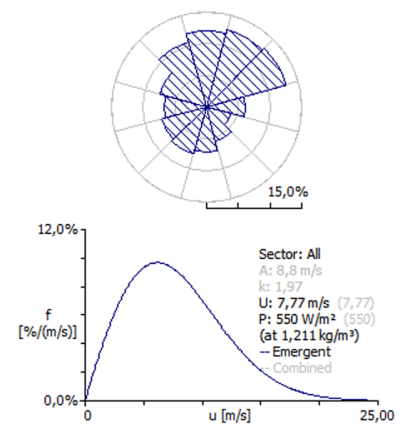


Figure 29: Wind frequency rose and Weibull distribution for Site 3.

4.2.4 Energy Yield Results with Wake Losses

The annual energy production results after a few iterations of the wind farm layout to reduce wake losses are presented in Table 4. The mean wind speed is the reference wind speed at hub height - an average value of all wind turbine positions - and the wake loss is the total losses due to the turbulent interaction among the wind turbines of the same wind farm. The Potential AEP shown in the table is the total annual energy production reduced by the wake losses only. The energy yield results are greatly impacted by the differences in wind energy resources of the sites.

Table 4: Initial results for wind farm sites.

Parameter	Site 1	Site 2	Site 3
Mean wind speed	8.1 m/s	8.6 m/s	7.8 m/s
Wake loss	6.88%	8.69%	9.41%
Potential AEP	2106.6 GWh	2223.8 GWh	1892.1 GWh

4.2.5 Net Energy Yield Results with Additional Losses

The calculation of the potential AEP, shown in the previous section, only includes the wake loss. In reality, wind farms might be impacted by several factors or losses such as blockage loss, turbine availability loss, balance of plant availability loss, grid availability loss, electrical efficiency loss, sub-optimal wind farm performance loss, high-wind hysteresis loss, high-temperature de-rating loss, blade degradation loss, non-technical curtailments, etc.

The losses used in this study are calculated or estimated according to methodologies described in *CREYAP 2021* by Badger et al. [23]. The net annual energy production, also described as P50, is derived from the potential AEP multiplied by a factor of 0.912, representing the estimated total additional losses of a usual offshore wind farm.

The final results of net AEP (P50) and the capacity factors, which account for all losses, are presented in Table 5. The capacity factor for a wind farm is defined as the ratio of its net AEP over a period of time to its potential output had it operated at its full nameplate capacity throughout the same time frame.

The annual mean capacity factor (CF) in %, can be expressed as:

$$CF = \frac{\text{Net AEP}}{\text{Wind farm capacity rating} \times 8766} \quad (1)$$

where the denominator represents the maximum possible AEP calculated based on the wind farm capacity and the total number of hours in a year (365.25 days multiplied by 24 hours per day).

Table 5: Final results for wind farm sites.

Parameter	Site 1	Site 2	Site 3
Total losses	17.8%	20.1%	21.0%
Net AEP	1921.2 GWh	2028.1 GWh	1725.6 GWh
CF	36.9%	39.0%	33.2%

4.3 WAsP Workflow

As a summary of this chapter, the workflow of a wind farm energy production calculation using WAsP is outlined below.

1. **Site Identification:** Based on restrictions described in chapter 3, an area suitable for offshore wind projects is determined. Potential sites with superior wind resources were investigated on the western side of the available area. Two potential site locations were pinpointed:
 - Site 1 with shallow waters, suitable for bottom-fixed turbines
 - Site 2 with shallow waters, suitable for bottom-fixed turbines
 - Site 3 with deep waters, favorable for floating wind turbines
2. **Digital Mapping:** Using tools such as QGIS and WAsP Map Editor, the area was modelled with a high-resolution digital map, capturing details of the terrain: Orography (elevation) and land cover (roughness)
3. **Wind Turbine:** The power and thrust coefficient curves for the generic 8.25 MW wind turbine were adopted for the simulations. A hub height of 140 m was considered, and the Svenningsen extrapolation method was applied to correct the power curve based on air density variations
4. **Wind Farm Layout:** Each of the three wind farms consist of 72 turbines at a total capacity of 594 MW. The farms were positioned in locations with favourable wind resources. The farm layouts were oriented to align nearly perpendicular to the prevailing wind direction to minimise wake effects.
5. **Wind Resource Data:** Generalised wind climates from the Global Wind Atlas were applied for each wind turbine position. It included meteorological parameters relative to the calculation of air density

6. **Wake Effects:** The selected wake model was PARK2 with decay coefficient 0.060, 5 sub-sectors and 1 m/s resolution for the wind speed. The terrain context for the simulation was forced to be offshore
7. **Simulations:** WAsP computes the wind resources, the wake effects, and the energy yield of each wind turbine. An iterative process allows the optimisation of the layout to maximise the Annual Energy Production (AEP) and Capacity Factor (CF)
8. **Technical Losses:** After calculating the potential AEP, the results are refined by including all technical losses and contingencies expected in a wind farm. The estimated losses used in this study are based on methodologies described in *CREYAP 2021* by Badger et al. [23]. The final result is the wind farm's net annual energy production, also described as P50.

4.4 Summary and Discussion

Three hypothetical wind farms were modelled using WAsP, the industry-standard software for wind resource assessment and wind farm planning, and estimated annual energy production was obtained based on the assumptions given.

Site 1 and Site 2 are in shallow waters, suitable for bottom-fixed foundations and Site 3 is in relatively deeper waters, where floating foundations might be needed.

Wind data from Global Wind Atlas were used due to the lack of local measurements. The layouts were defined using best practices to minimize the impacts of wake effects.

The preliminary estimations indicate capacity factors of 39%, 36.9%, and 33.2% for Site 2, Site 1, and Site 3, respectively.

The procedure described in this chapter may be used for updating the energy yield calculation whenever relevant site and project-specific data becomes available such as local metocean data, or if there is a change of wind turbine model and height, or a different layout is adopted.

5 Levelized Cost of Energy

This chapter outlines our estimates of the levelized cost of energy (LCOE), i.e., the average cost per unit of electricity over the lifetime of the project (alternatively, the minimum required price for the investment to break-even) that takes into account the time value of money and the generation pattern.

5.1 LCOE Methods and Data

The LCOE can be calculated by applying the following relationship:

$$LCOE = \frac{I_0 + \sum_{t=1}^n \frac{TC_t}{(1+r)^t}}{\sum_{t=1}^n \frac{q_t}{(1+r)^t}} \quad (2)$$

where, I_0 : initial investment cost (euros); TC_t : annual total cost (euros /year); q_t : amount of produced electricity in year t ; r : discount rate reflecting time value of time (%); n : Operational lifetime of the asset (years).

To estimate LCOE, we follow the approach of [24] and [25], which conducted pre-feasibility studies for offshore wind in Mauritius and Egypt, respectively. The approach used in these studies was built on that used by the International Energy Agency (IEA) Wind Task 26 [26] [27]. For ease of access and transparency, we fully reproduce the approach in this section.

We estimate an LCOE range for each hypothetical offshore wind project in Ukraine and a baseline project. The baseline project represents a typical offshore wind project in the mature Western and Northern European markets: Denmark, the Netherlands, the UK, Belgium, and Germany. The reason for using a mature market as the baseline is because it provides a large pool of data from different wind farm sizes and site characteristics (wind farm capacity, water depth, distance from port, etc.), sourced from a reliable and official channel (Bloomberg New Energy Finance), ensuring a robust foundation for analysis and comparison.

5.1.1 Net AEP and project characteristics

We will use the net AEP values and wind farm characteristics for the hypothetical offshore wind projects presented in Chapter 4. For the baseline case, we calculate net AEP from an assumed net capacity factor of 48% [24] [27]. This is also consistent with a recent report from WindEurope [28], which states that net capacity factors of new offshore wind farms in Europe are around 50

We assume the baseline case uses the same wind turbine and number of turbines as the hypothetical offshore wind projects. We use parameters related to the average water depth, distance to shore, and distance to port, based on data from Bloomberg New Energy Finance (BNEF), following a similar approach as in [24].

5.1.2 Costs

To estimate costs, we start from per MW offshore wind capital expenditures (CAPEX) and operational expenditures (OPEX) data from Bloomberg New Energy Finance (BNEF) [5]. BNEF does not have development expenditures (DEVEX) data, so we assume DEVEX is equal to 3% of total CAPEX, following [26] [27].

[29] provides historical data and future projections per MW CAPEX and OPEX for several offshore wind markets (low, mid, and high values) for bottom-fixed projects. For the baseline case, we establish CAPEX and OPEX ranges using the mid values for the five mature markets in Northern and Western Europe represented by the baseline case. BNEF does not have data for Ukraine or any comparable country. Therefore, for the bottom-fixed Ukraine projects, we use the same data as the baseline case and then make adjustments based on market immaturity and project characteristics (water depth, distance to shore, and distance to port).

A market immaturity premium is applied to account for the lack of an established supply chain (also reflecting competition with established markets from an OEM perspective) in the emerging Ukrainian market. Therefore, it is assumed that, all else equal, CAPEX is higher in immature markets than in mature markets. In the absence of data from previous studies to approximate the level of the immature market premium, we estimate two scenarios. Scenario 1 is a low CAPEX scenario where the immature market premium is 5%. Scenario 2 is a high CAPEX scenario with an immature market premium is 20%. We adjusted the CAPEX range for the bottom-fixed hypothetical projects using the ORE Catapult model ([25]) based on wind farm characteristics, including water depth, distance to shore, and distance to port. We then measured the percentage difference in CAPEX (as estimated by the ORE Catapult model) between the baseline project and the hypothetical projects and updated the CAPEX range accordingly. This led to a downward adjustment of 1% for the near-coast hypothetical projects.

For the floating project (West of Crimea), we use the same OPEX range as the bottom-fixed projects. CAPEX, however, is substantially higher for floating projects. Therefore, we start from LCOE estimates for four hypothetical floating offshore wind projects in Egypt analysed in [25]. Three of the projects use wind turbines with similar capacity ratings (8 MW). We take the average of these projects as our midpoint value. We then create a range that is equal to that of the baseline project for consistency. We do not apply a market immaturity premium because floating foundations technology is new everywhere.

We assume a seven-year development phase and 25-year operating phase:

- Development phase (five years): 2024 – 2028
- Financial investment decision (FID): 2029
- Construction (two years): 2029-2030
- Operation (25 years): 2031-2055

The BNEF values, therefore, are for projects financed in 2029. Values reported in American dollars were converted to Euros using average exchange rates from 2 January 2023 to 7 November

2023 (1 USD = 0.9252 EUR) [30]. Unless otherwise noted, monetary values are expressed in 2022 EUR.

5.1.3 Discounted cashflow analysis

We use an internally developed discounted cash flow model to derive the LCOE based on the energy production and cost estimates, considering the time value of money. The cash flow model incorporates a suite of additional finance-related inputs.

Most important is the weighted average cost of capital (WACC), which represents the financing costs of the investment. The WACC is the weighted average of the cost of debt (i.e., the interest rate on money borrowed) and the cost of equity (i.e., the expected rate of return on equity invested) for the project, accounting for the tax rate.

[31] and [32] estimate that Ukraine has a nominal WACC (not adjusted for inflation) of 14% - 16% for renewable energy. Note that DTU Wind assumes that the values are nominal although neither study specifies whether the WACC is real or nominal. In converting to a real WACC (adjusted for inflation), we assume a 5% inflation rate, equal to the National Bank of Ukraine's targeted inflation rate. This leads to a real WACC of 8.6% to 10.5%. For the floating wind project, we add an additional 200 basis points to account for the added risk that comes with a nascent technology [33], leading to a WACC of 10.6% - 12.5%. For the baseline project, we assume a real WACC of 2.5% - 3.2% (with an inflation rate of 2%) based on BNEF projections for the five mature markets.

Other important inputs include the corporate tax rate and the annual allowable rate of depreciation (used for tax deductions). Ukraine has a corporate tax rate of 18% [34] and a depreciation term of (minimum) five years [35]. For the baseline case, we assume a 25% corporate tax rate and 15-year depreciation term (7% of project cost per year), based on [27].

5.1.4 Component shares

We also break out the LCOE estimates into component shares: financing costs, CAPEX (including DEVEX), OPEX, and taxes. To do this, we compare each LCOE estimate to the LCOE under a scenario where the WACC, which represents financing costs, is 0%. The financing cost share is calculated as the percentage change from the estimated LCOE to the LCOE where WACC = 0%. The CAPEX/DEVEX, OPEX, and tax shares are then calculated for the WACC = 0% scenario and then multiplied by one minus the financing cost share.

5.1.5 Interpretation

The actual cost of offshore wind development for any particular project cannot be known until the development process begins. This is where developers expend significant resources conducting site studies and determining actual costs of materials, transportation, installation, etc., for that particular site, based on proprietary data and models and discussions with potential contractors. In addition, as noted above, our main data source—BNEF—lacks CAPEX and OPEX data for immature offshore wind markets, including Ukraine and the surrounding region. We make adjustments based on [31] and [32] and [33], but these adjustments are at best-educated guesses.

Therefore, our results cannot be seen as precise estimates of the LCOE. They can be used to

compare the three Ukrainian projects and the baseline project to gain a broad understanding of where Ukraine's offshore wind resources are in relation to the mature European markets. It is also important to note that the estimates are future-oriented (they account for expected cost decreases from now until the assumed FID date in 2029). As a result, we anticipate a potential decrease in the Levelized Cost of Electricity (LCOE) value if the financial investment decision (FID) date is moved beyond 2029. This reflects the expected reduction in CAPEX and OPEX due to learning curve effects.

5.2 LCOE Results

Table 6 presents the main results of the LCOE analysis, including LCOE estimates for the baseline wind farm and the three hypothetical wind farm projects and a breakdown of how the LCOE is spread between financing costs, CAPEX, OPEX, and taxes. LCOE estimates are in real terms and exclude subsidies.

As expected, the baseline project has the lowest LCOE: €48 - €64 per MWh. The next lowest is the bottom-fixed projects under the low CAPEX scenario (i.e., we assume that market immaturity only increases CAPEX by 5%). Site 2, in the Sea of Azov, comes in at €91 - €131 per MWh, and Site 1 in the Northern Black Sea at €98 - €142 per MWh. The LCOEs for these projects are approximately 10% - 15% higher under the high CAPEX scenario (i.e., where market immaturity increases CAPEX by 20%).

Table 6: LCOE estimates and component shares.

Project	Real LCOE 2022 [€/MWh]	Financing costs share	CAPEX share	OPEX share	Taxes share
Baseline	48 - 64	22% - 28% (€11 - €18)	50% - 52% (€25 - €32)	18% - 22% (€11 - €12)	4% (€2 - €3)
Low CAPEX					
Site 1	98 - 142	51% - 58% (€50 - €82)	29% - 34% (€34 - €41)	11% - 12% (€12 - €15)	3% (€3 - €4)
Site 2	91 - 131	50% - 58% (€46 - €75)	28% - 34% (€30 - €37)	11% - 13% (€12 - €15)	3% (€3 - €4)
High CAPEX					
Site 1	111 - 161	51% - 52% (€57 - €72)	33% - 34% (€37 - €47)	11% - 13% (€14 - €15)	3% (€4 - €5)
Site 2	102 - 148	55% - 58% (€52 - €86)	29% - 34% (€35 - €43)	10% - 11% (€12 - €15)	3% (€3 - €4)
Site 3	223 - 294	60% - 65% (€124 - €192)	26% - 30% (€67 - €77)	6% - 7% (€16 - €17)	3% (€7 - €8)

Floating offshore wind projects are immature and risky, leading to substantially higher CAPEX and financing costs. In addition, Site 3, located West of Crimea, has a significantly lower capacity factor than the other projects. As a result, the LCOE for Site 3 is the highest by a wide margin: €223 – €294 per MWh. Figure 30 presents mean values of LCOE and the share of different costs for illustrative purposes across various scenarios. The main cause for the discrepancy

between this study's baseline project and the Ukrainian hypothetical projects is financing costs.

A comparison of relevant project characteristics, such as NET capacity factor, average water depth, average distance to shore and the real WACC highlights that the WACC for Ukraine is 3.5 - 4 times that of the baseline case, Table 7. The higher WACC is not specific to offshore wind in Ukraine but is generally characteristic of emerging economies. If we assume the WACC for all projects is equal to that of the baseline project, the resulting LCOEs of the Ukrainian hypothetical projects in shallow waters would be much closer to that of the baseline project, Table 8. This suggests that a strategy for project financing is key for the feasibility of offshore wind projects in Ukraine and other emerging markets.

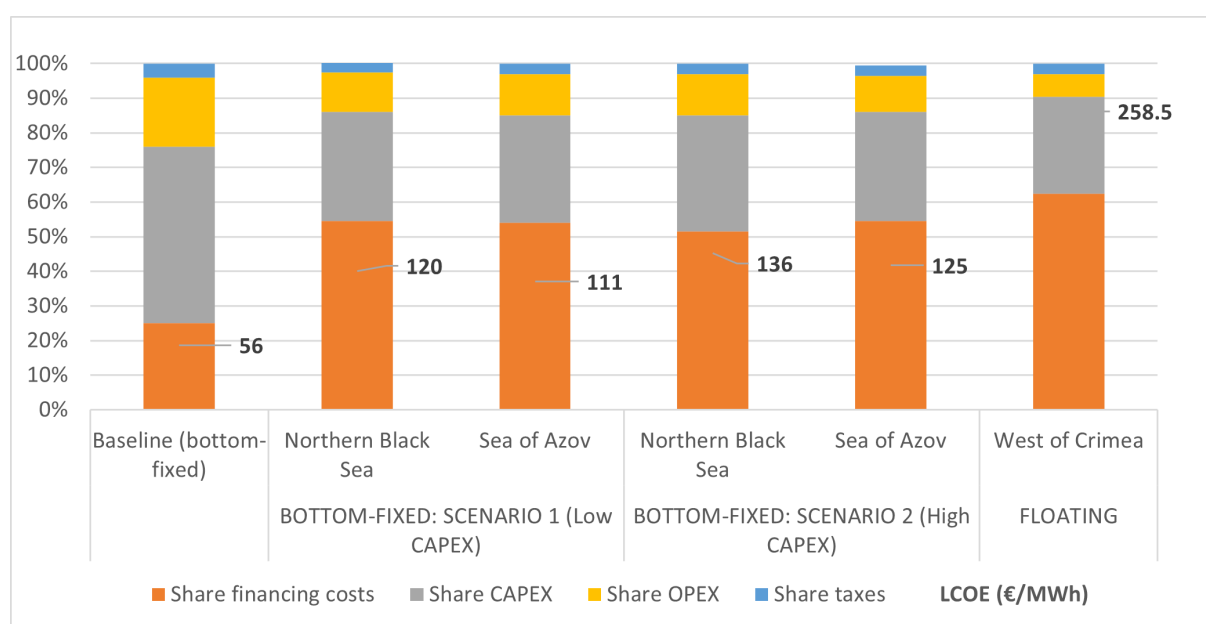


Figure 30: Mean real LCOE values and mean shares of costs for offshore wind projects across different scenarios.

Table 7: Selected project characteristics and finance metrics.

Project	Foundation Type	Capacity Factor	Water Depth	Distance	Real WACC
Baseline	bottom-fixed	48%	33m	61km	2.5% - 3.2%
Site 1	bottom-fixed	36.9%	25m	24km	8.6% - 10.5%
Site 2	bottom-fixed	39%	8m	22km	8.6% - 10.5%
Site 3	floating	33.2%	55m	53km	10.5% - 12.5%

Table 8: LCOE in €/MWh assuming baseline project WACC (2.5% - 3.2%).

Site	Low CAPEX	High CAPEX
Site 1 (Northern Black Sea)	61 - 81	68 - 91
Site 2 (Sea of Azov)	57 - 75	63 - 84
Site 3 (West of Crimea)		115 - 141

It is also helpful to put the LCOE values into the broader offshore wind market perspective. The Figure 31 provides LCOE ranges (excluding subsidies) for different countries for projects

financed in 2022. While these ranges are for current projects and are expected to continue to fall for future projects, it is worth noting that the preliminary LCOE estimates for the Ukrainian bottom-fixed projects fall well within these ranges.

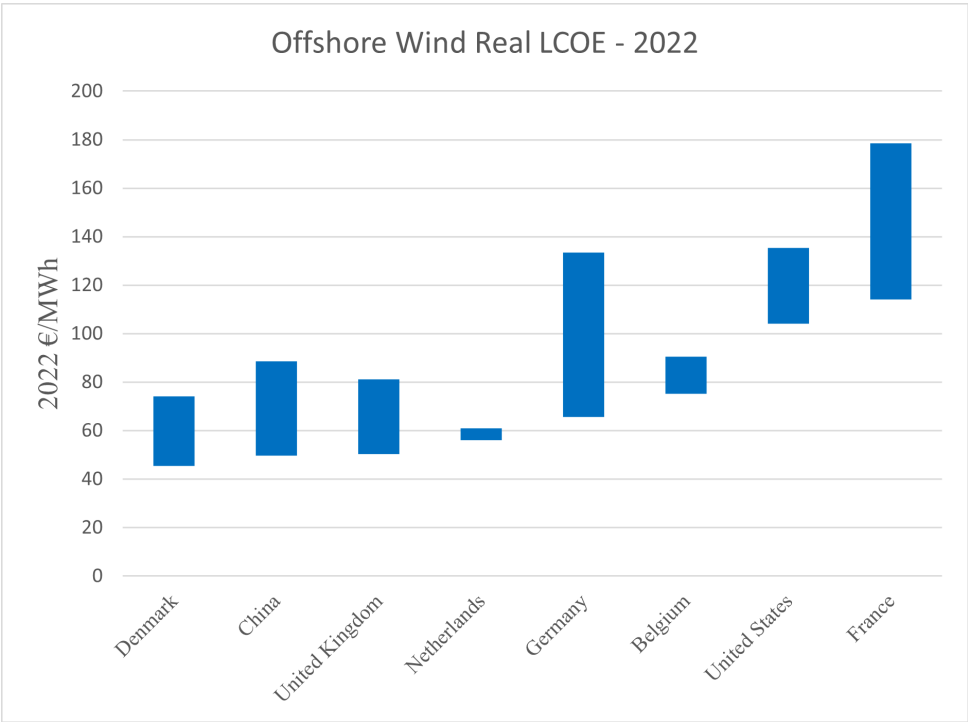


Figure 31: Real LCOE ranges for offshore wind projects financed in 2022 (Source: BNEF [29]).

5.3 Summary and Discussion

It is important to re-emphasise that the results presented in this section are based on several simplifying assumptions. The actual cost for offshore wind in Ukraine will depend on, e.g., the ability to secure an affordable supply chain and workforce and grid connection. As such, for the LCOE calculation, certain external factors, particularly those stemming from the ongoing geopolitical situation, have not been explicitly incorporated into our analysis. These impacts could encompass but are not limited to, inflationary pressures, uncertainties in the grid infrastructure, and potential disruptions in the broader supply chain. The exclusion of these factors is a deliberate choice made to maintain the focus of the feasibility study on the core aspects of the offshore wind project. However, as the geopolitical situation evolves, it is strongly recommended that subsequent phases of the project development process carefully reassess and incorporate any emerging considerations related to the broader economic, political, and infrastructural landscape in Ukraine.

As previously highlighted, the initial capital and financing costs for pioneering projects in emerging markets are anticipated to be higher, primarily due to the inherent risks of being the first of their kind. To address these challenges and alleviate the risk exposure for private investors, it is worth exploring the use of risk mitigation strategies. These can be in the form of capital grants (which could be used to fund DevEx costs for example), public sector equity stake in the project or/and public sector financing and ownership of the export and transmission systems. These

would effectively transfer part of the burden of total project CapEx from the private developer to the public sector [36]. Lowering the financing costs can be accomplished through concessional financing sourced from international financial institutions (such as the European Bank for Reconstruction and Development (EBRD), International Finance Corporation (IFC), Nordic Finance Corporation (NEFCO), European Investment Bank (EIB), etc.), which have offered assistance in funding Ukraine's renewable energy sector in the past [31]. While the pre-feasibility study hasn't delved into such scenarios, they can be explored in subsequent stages to assess potential options for project implementation.

6 Scaling up

The total area available for offshore wind development in Ukraine is approximately 50.000 km², according to the analysis method explained in chapter 3, of which 29.699 km² is suitable for bottom-fixed wind turbines, and 19.439 km² for turbines with floating foundations. We can make an order of magnitude estimate of the installed capacity of offshore wind farms using an average installed capacity density of 1 MW/km² which gives around 30 GW for bottom-fixed wind farms plus 20 GW for floating wind farms. These estimations should be interpreted as guidance only due to large variation in how wind energy deployment can be conducted and how technology and costs develop in time.

DTU Wind is interested in applying the latest research results on the performance of very large wind farm clusters subject to mesoscale wind farm wake effects. A good review of the advancements in this area can be found in [37]. In particular, it is interesting to investigate the performance of huge wind farm clusters because these might alter the atmospheric flow on scales not captured by conventional wind turbine wake modelling approaches. However, given the applied constraints, the energy yield estimates of the maximum installed capacity cannot be validated simply because farms on this scale do not yet exist.

In this study, we apply the findings of [38], which investigated the further energy yield losses due to mesoscale wind farm wake effects, calculating wake losses for huge clusters for several capacity densities and sizes of wind farms (areas), considering a fixed staggered wind farm layout. The research indicates that the wake losses are not only dependent on the capacity density; other parameters, such as the layout geometry of the wind farm and the wind speed distribution by direction at the site, are also of great importance.

The aim is to estimate the impacts of increased wind capacity on power generation efficiency due to increased wake losses. We start with the 600 MW hypothetical projects developed in chapter 4, where their main characteristics, layout's total area, installed capacity density (CD), wake losses and NET capacity factor, are presented in Table 9. As all projects have the same installed capacity (600 MW) and Site 1 has the lowest capacity density, 2.6 MW/km², it occupies the largest area, 230 km².

Table 9: Estimated wake effects on 600 MW wind farms with different installed capacity densities.

Parameter	Site 1	Site 2	Site 3
Area	230 km ²	82 km ²	160 km ²
CD	2.6 MW/km ²	7.2 MW/km ²	3.7 MW/km ²
Wake losses	6.9%	8.7%	9.4%
NET CF	36.9%	39.0%	33.2%

We considered an expansion of the hypothetical projects developed in chapter 4 with a factor 5 increase in the capacity of each farm. The results for scaling up the hypothetical offshore wind

farm projects to 3 GW capacity each are presented in Table 10, including the expected NET capacity factor. The wake losses for the 3 GW hypothetical projects were obtained from [38] choosing carefully an efficiency reduction expression that includes the data obtained for the 600 MW hypothetical projects. For example, the 600 MW wind farm in Site 2 with an area of 82 km² and wake loss of 8.7% was increased to 3 GW using an area of 410 km² (keeping the capacity density constant) resulting in a wake effect of 23%. On the other hand, the expanded 3 GW project at Site 1 has an area of 1.150 km² compared to 230 km² of the original 600 MW project and an increased wake loss of 16% compared to 6.9%.

Table 10: Wake effects on 3 GW wind farms with different capacity densities.

Parameter	Site 1	Site 2	Site 3
Area	1150 km ²	410 km ²	800 km ²
CD	2.6 MW/km ²	7.2 MW/km ²	3.7 MW/km ²
Wake losses	16%	23%	18%
NET CF	33.5%	33.4%	30.3%

6.1 Summary and Discussion

This chapter shows an investigation of the impact of scaling up the three hypothetical offshore wind farms developed in a previous chapter. The performance of large wind farm clusters depends on the capacity density of the layout because of the wake effects; therefore, the focus is to estimate the increase of wake losses when extending the initial 600 MW projects to 3 GW capacity.

The study shows that 3 GW wind farms might operate with NET capacity factors of around 33.5%, compared to 37%-39% of smaller (600 MW) projects. However, energy yield and loss calculations shall be confirmed during a detailed feasibility analysis using local wind measurements and other site-specific information.

7 Conclusion

This report presents a preliminary feasibility study for offshore wind in Ukraine. The work involved the identification of wind power potential and main wind characteristics of the region, the creation of a GIS workspace to aggregate all relevant information, the application of procedures for selecting the most suitable areas, simulation of wind farms with a microscale flow model, estimation of a minimum price at which energy produced must be sold for three hypothetical offshore wind projects.

DTU Wind has been helping the wind industry to develop tools and methods for wind farm development based on state-of-the-art technology. This work involves the application of DTU Wind software WAsP and DTU Wind free access tool Global Wind Atlas (GWA), which is combined with an analysis method for the pre-feasibility of offshore wind projects.

The wind characteristics over the seas in the EEZ of Ukraine have been obtained from the GWA, including mean wind speed, mean wind power density, and mean wind power rose. The areas with good wind resources have been identified as candidates for wind energy projects.

The geospatial assessment of the sea space was used to select suitable areas with the most feasible characteristics for an offshore project – having a combination of good wind potential, closeness to the shore and shallow water depths – yet respecting some site-specific constraints to minimise the potential negative impact of future wind farms onto the environment, culture, security, and on social and commercial activities.

Three hypothetical offshore wind farms were modelled using the industry-standard wind resource assessment software WAsP with inputs (wind data, meteorological parameters, orography, and surface roughness) obtained directly from the GWA. The wind farms of 600 MW nominal capacity each were investigated regarding their estimated performance – annual energy production and capacity factor – and the levelized cost of energy. Two sites are located in an area of shallow waters suitable for using bottom-fixed foundations, while Site 3 is located in water depths greater than 50 m, requiring floating wind turbines. The capacity factor of around 37% was determined for Site 1, 39% for Site 2 and 33% for Site 3. Site 2 shows better performance due to its location in a zone of higher wind resources.

The databases and the procedure used for the geospatial analysis and wind farm simulations are made available by DTU Wind. They may be used in the future to enhance the current study, consider new or different constraints, include other areas, select a different wind turbine model, have access to site and project-specific data, etc.

The DTU Wind analysis indicates that the LCOE for the floating offshore wind project (Site 3) is the highest by a wide margin. On the other hand, the other two sites present LCOE in the same range of €90 - €140 per MWh, although much higher than the baseline project, an estimate which falls well within the range for current projects financed in 2022 in countries such as Germany, USA and France. The WACC for Ukraine is around 3.75 times that of the baseline project. If we

assume the WACC for the Ukrainian hypothetical projects in shallow waters is equal to that of the baseline project, the resulting LCOEs would be much closer to that of the baseline project, suggesting that financing costs are causing the biggest impact on the feasibility of the projects.

The assessment of scaling-up options discussed in this report provides estimates for increasing the offshore wind capacity. Expanding the hypothetical wind farm sites from 600 MW to 3 GW rated capacity will reduce the capacity factors to 33.5% for Site 1, 33.4% for Site 2 and 30.3% for Site 3 due to the increase of wake losses.

The results of this early-stage study should be interpreted as guidance only due to variability in wind energy deployment methods, along with the evolution of technology and changes in costs. The values discussed here can be considered as rough yet qualified estimates of different installed capacity scenarios, given the applied constraints.

It should highlight the need for onsite measurements, thorough data validation, and the integration of a multitude of parameters to describe the complexity of the offshore environment, setting a robust metocean baseline for developers and consultants to make informed decisions on turbine model selection, foundation design, and provide adequate information to execute feasibility studies.

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Appendix

A.1 Elevation and land cover maps of Ukraine

This report utilizes the UTM coordinate system based on the WGS-84 datum (zone 36 and 37).

The elevation and roughness maps can be seen in Figure A.1, Figure A.2, Figure A.3, Figure A.4, Figure A.5, and Figure A.6.

Note that for Site 3, elevation is not a requirement, given the site's considerable distance from the coast. The roughness map consists of water surface only.

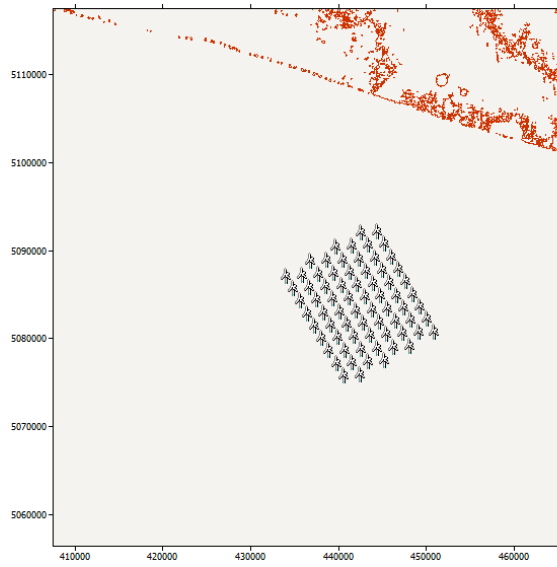


Figure A.1: Elevation map used for Site 1

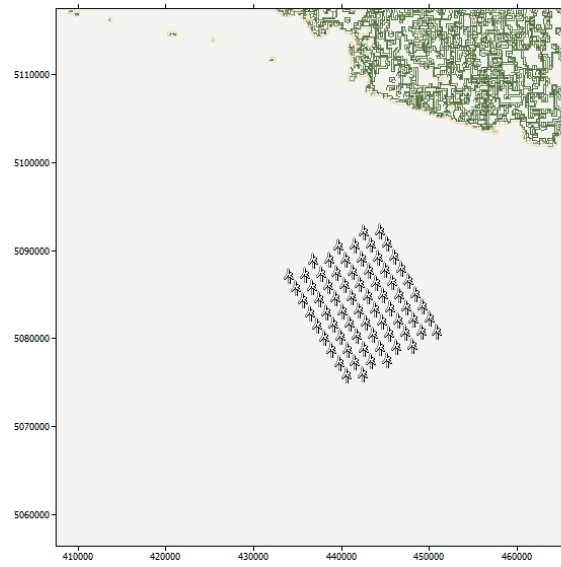


Figure A.2: Roughness map used for Site 1

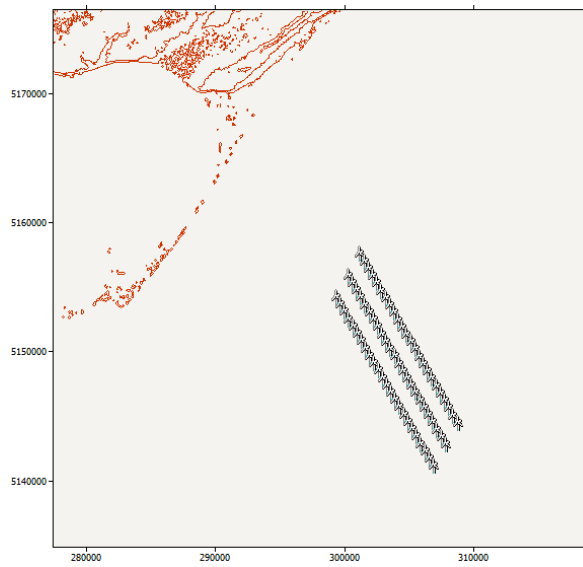


Figure A.3: Elevation map used for Site 2

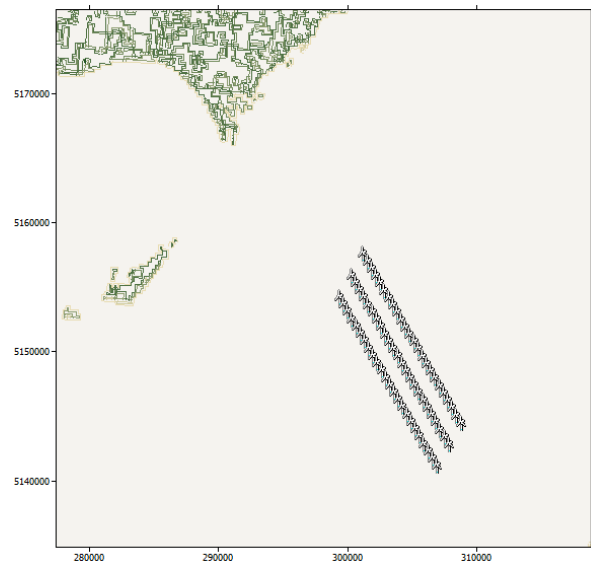


Figure A.4: Roughness map used for Site 2

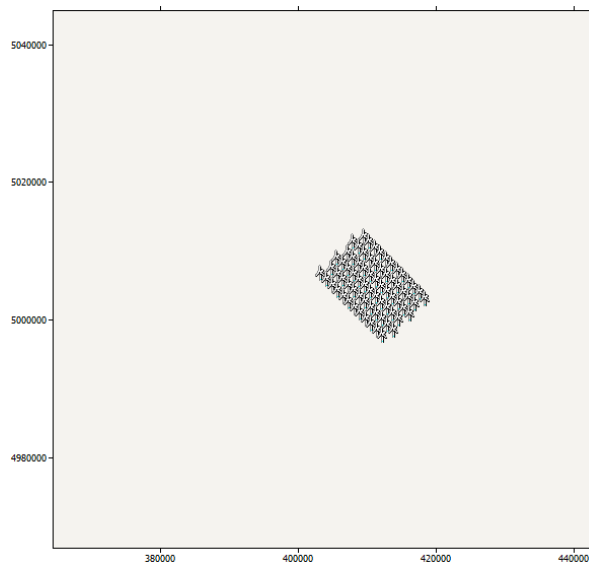


Figure A.5: Elevation map used for Site 3

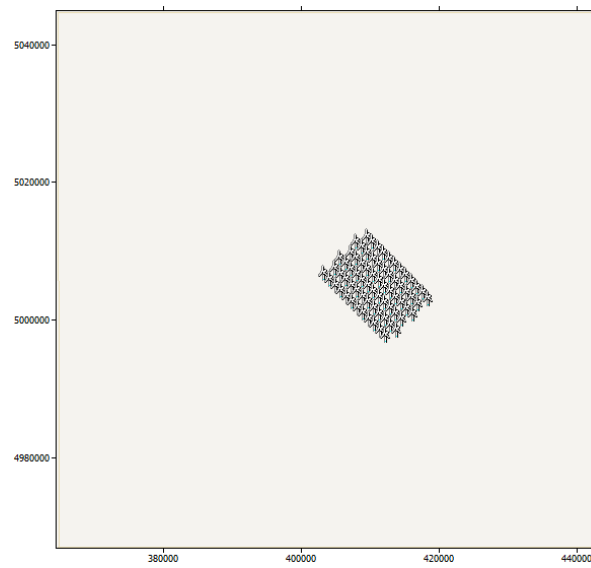


Figure A.6: Roughness map used for Site 3