



**INTERREG ITALY-CROATIA
PROGRAMME 2021 – 2027**

BEYOND - Blue Economy sYnergies fOr sustainable Development

D.1.4.1 Pilot regions preliminary offshore wind energy potential analysis

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1. Introduction

Today, the world stands at a critical crossroads in the energy landscape, facing the growing urgency of climate change while balancing the need for energy security and economic stability. These problems started the discussion about future energy sources where the pivotal role plays renewable energy inside the traditional power sources. Renewable energy is crucial for steering the direction of global energy transmission. These sources represent more than just technical alternatives. They symbolize a significant transformation in how energy is produced and consumed.

There are many advantages of offshore wind energy. Winds above the sea are stronger and more stable. That automatically results in significantly higher production per installed unit of wind turbine. At sea, wind turbines can also be bigger compared to the onshore turbines. From the middle of the 2000s, the offshore wind industry started to grow significantly in Europe. Every 2-4 years the total capacity of the received energy from the offshore wind turbines doubles. Installed offshore wind capacity in the EU in 2020 was around 12 GW. The plan is to reach 60 GW by 2030 and 300 - 400 GW of electricity power from wind offshore until 2050 so offshore wind may represent up to 15% of total power consumption. Besides the North Sea and Baltic Sea which have high and widespread natural potential for offshore wind energy, the EU has other suitable places for installing offshore wind farms such as the European Atlantic Ocean, Mediterranean Sea and Black Sea. To achieve the EU's strategy for energy production from renewable sources by 2050, it will be necessary to develop more offshore locations in Europe. This means that the existing offshore infrastructure in the EU will need to be expanded.

This is precisely the focus of the BEYOND Interreg project, which aims to initiate steps toward potential offshore wind farm (OWF) construction in the Adriatic Sea. This report will include a detailed analysis of preliminary offshore wind energy potential for four chosen pilot locations in Croatia and Italy. The process for calculating wind power and annual energy production will be presented. Furthermore, the selection of wind turbine type needs to be conducted based on the site specifics, therefore, three wind turbine types will be selected for each of the four locations. For each pilot location, three target OWF nominal capacities (500 MW, 700 MW, and 1000 MW) have been explored. The following analysis





in this report will determine the required number of each of the three selected wind turbine types, as well as the necessary area to achieve these power outputs. Additionally, results will be consolidated with a graphical comparison of analyzed scenarios. Finally, a conclusion will be drawn, including a joint summary and recommendations.



2. Methodology

Within this chapter, the wind power potential and nominal output capacity of OWFs at four pilot locations in the Adriatic Sea will be analyzed (*Figure 2.1*). Two of these locations, the Istria region and Split-Dalmatia region, are within Croatian territorial waters, while the other two, Apulia and Veneto, are in Italian territorial waters. Of the four, two are situated in the northern, shallower part of the Adriatic, while the remaining two are in the southern, deeper region.

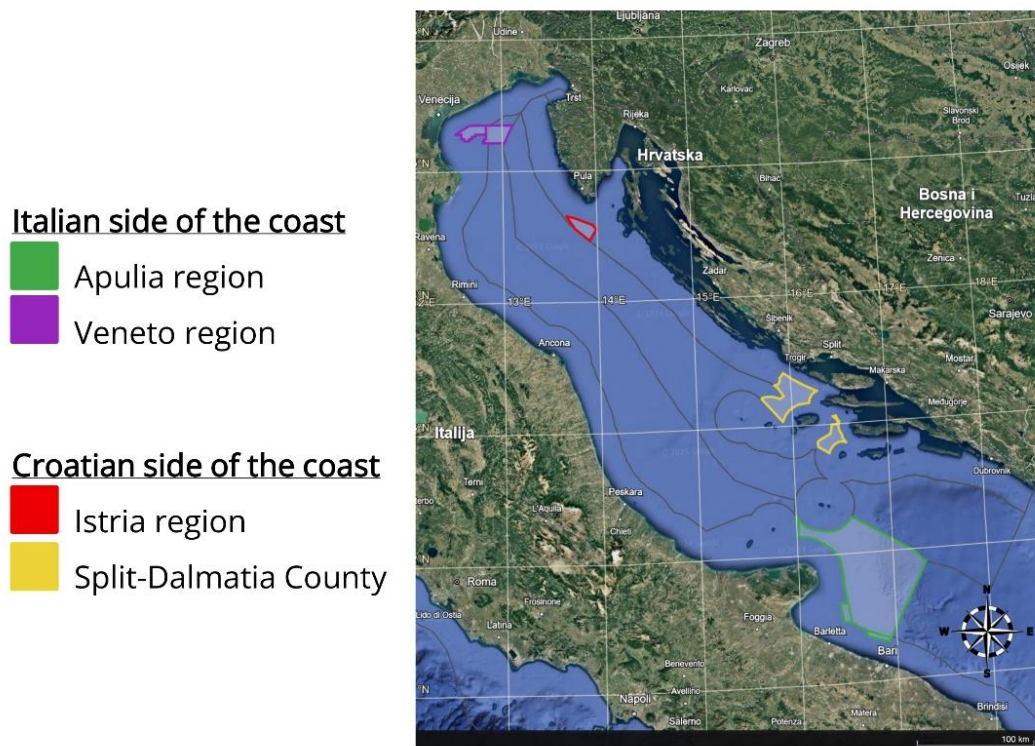


Figure 2.1. Locations of the test regions [1]



2.1. Pilot areas average wind speed

According to the available average wind speed data for each location (*Figure 2.2*), calculations related to OWF power output will be conducted. The analysis was conducted for 10 year period (2009-2018) based on wind speed from the New European Wind Atlas [2]. For several selected wind turbines power output will be calculated. More specifically, the analysis will include OWF power output estimation and annual energy production.

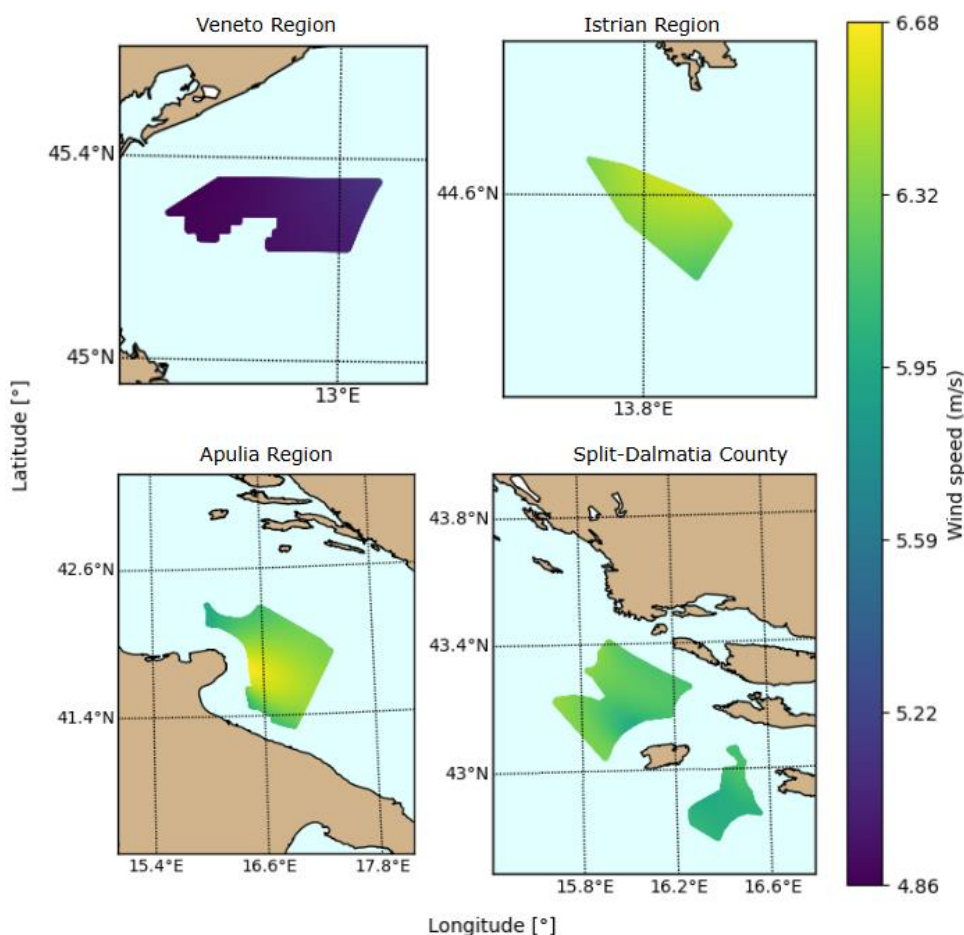


Figure 2.2. Average wind speeds for all four test regions



2.2. Wind turbine model selection

The amount of electricity generated by a wind turbine primarily depends on the rotor diameter, specifically the rotor swept area. Commercial wind turbines are defined with parameters depicted in Figure 2.3. A larger rotor leads to a proportional increase in the amount of energy the turbine can produce. It is important to note that extending the blade length results in a quadratic increase in rotor swept area, significantly boosting energy production. For example, if the blade length increases by 20%, the rotor swept area will increase by 70%.

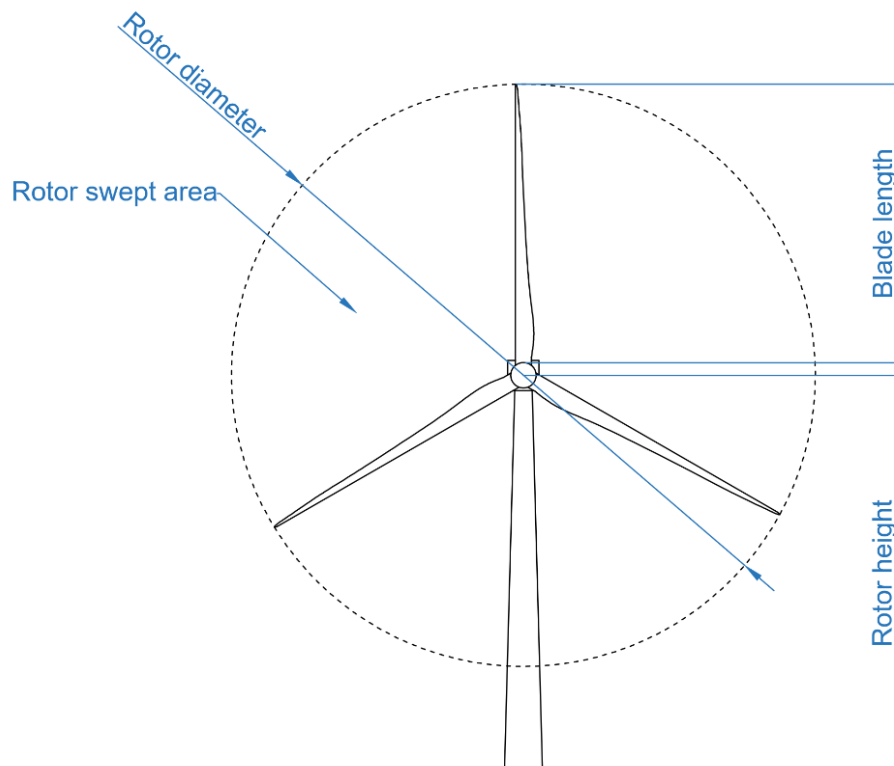


Figure 2.1. *Basic technical drawing of a wind turbine*

Rotor swept area can be calculated as:

$$A = \left(\frac{d}{2}\right)^2 \cdot \pi \tag{2.1}$$

where:

d – rotor diameter (m).

Consequently, there is a trend of using turbines with larger diameters to capture more wind energy. Global average rated power of offshore wind turbines reached 1.5 MW in 2000. By 2009, the average rated power of offshore turbines in Europe was approximately 3 MW. In 2019, the average turbine rated power for new installations in Europe exceeded 7.2 MW. From 2010 to 2020, the global average rated power increased by 150%, rising from 3 MW to 7.5 MW [3]. The increase in rotor size and rated power of wind turbines over time is depicted in Figure 2.4.

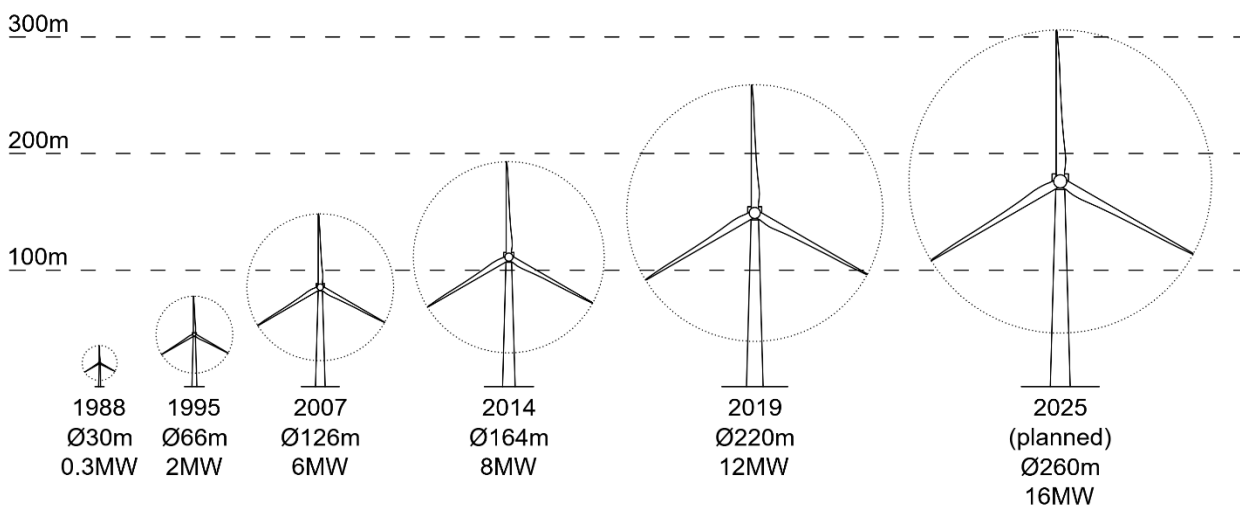


Figure 2.2. Increase in wind turbine rotor size and rated power over time (data source [3])

Offshore wind turbines are installed in two variants: floating wind turbines and fixed wind turbines as shown in Figure 2.5. Fixed wind turbines are directly connected to the seabed, while floating



wind turbines remain on the water's surface and are anchored to the seabed with chains, allowing limited movement. Each wind turbine can be installed in either variant, as a floating or fixed turbine. It is an established rule that fixed foundations are used for water depths up to 50 meters, while floating foundations are used for depths greater than 50 meters [4].

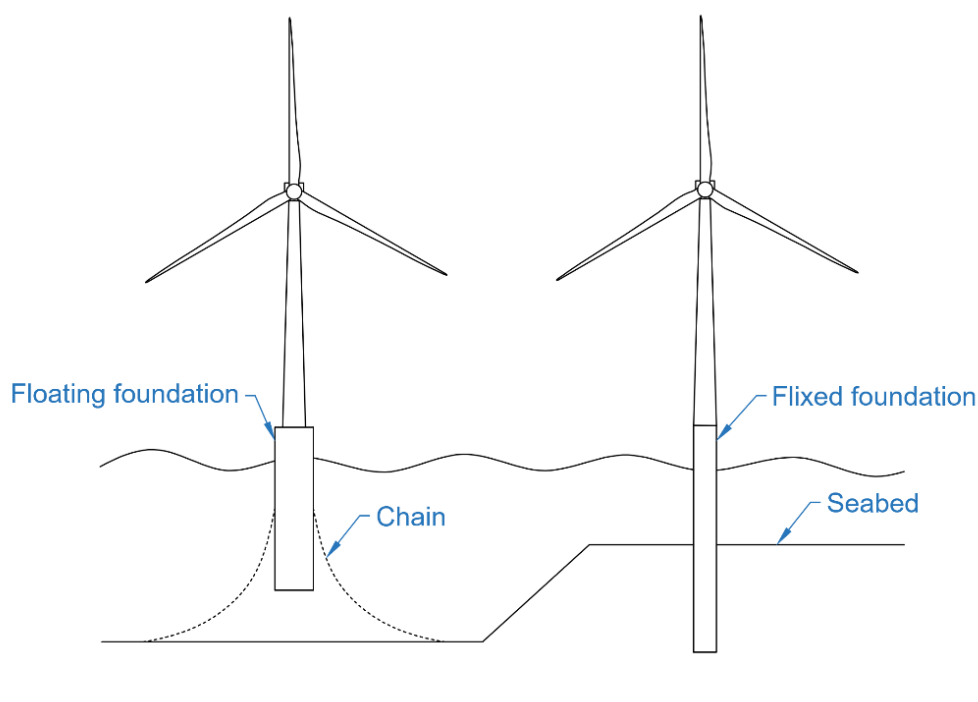


Figure 2.3. *Offshore wind turbines foundations*

Wind turbine IEC classes are determined based on annual average wind speed and turbulence intensity as shown in Table 2.1. IEC stands for International Electrotechnical Commission which issued the international standard on wind turbines design requirements IEC 61400-1:2019 [5]. IEC classification is commonly used and is updated to cover fixed and floating offshore wind turbines applications due to advances in technology and gain of experience.



Table 2.1. Basic parameters for wind turbine classes [5]

Wind turbine class		I	II	III	S
V_{ave} (m/s)		10	8.5	7.5	Value specified by the designer
V_{ref} (m/s)		50	42.5	37.5	
A+	I_{ref} (-)	0.18			
A	I_{ref} (-)	0.16			
B	I_{ref} (-)	0.14			
C	I_{ref} (-)	0.12			

where:

V_{ave} - the annual average wind speed,

V_{ref} - the reference wind speed average over 10 min,

A+, A, B and C - correspond to the categories for very high, higher, medium and lower turbulence characteristics, respectively

I_{ref} - a reference value of the turbulence intensity.

The wind turbine power curve describes the amount of electrical power output the turbine can produce at a certain wind speed. Theoretical power curves are usually given by the manufacturer assuming ideal conditions. Figure 2.6 shows a typical wind turbine power curve. Power production is possible only if the wind speed is within the wind speed interval of the power curve. The minimum wind speed value at which the turbine can start to operate is called the cut-in speed and the maximum wind speed the turbine can operate at is cut-out speed. Shutting down the power generation of the wind turbine when the speed exceeds the cut-out speed is crucial in order to prevent damage. The wind speed at which the turbine generator is producing its rated power is called the rated speed.



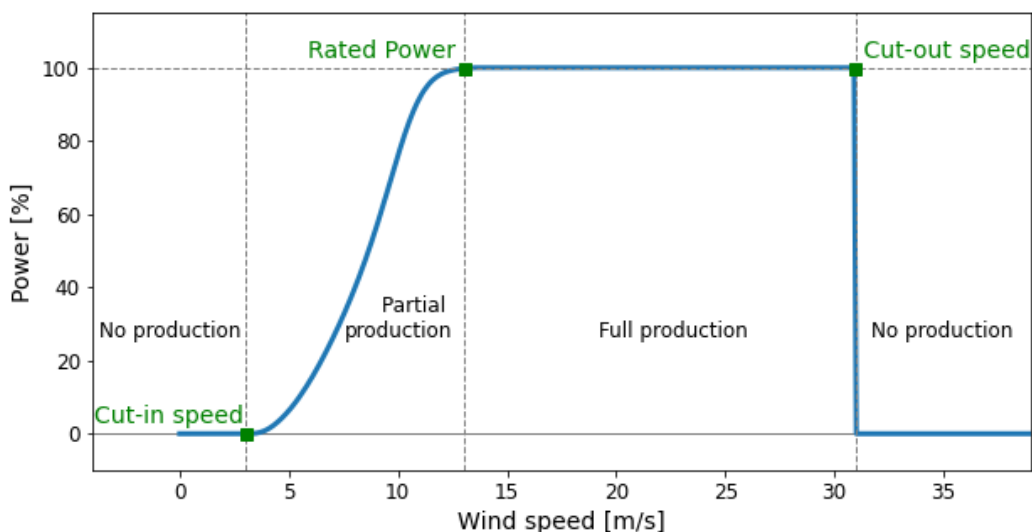


Figure 2.4. Power curve example

Average annual wind speed can give an idea of the potential amount of wind energy at that location. However, this amount of energy is not evenly distributed throughout the year but has certain variations. The change in the amount of energy can be shown over months or hours, where some months or hours will have a higher average wind speed, while some months or hours will have a lower average wind speed. Figure 2.7 shows a graph of the Monthly Wind Speed Index, in which the index shows how much higher or lower the average wind speed in that month is, compared to the annual average wind speed. Similarly, Figure 2.8 shows a graph of the Daily Wind Speed Index, in which the index shows how much higher or lower the average wind speed in that hour is compared to the annual average wind speed. By studying these two graphs, it can be determined in which time periods a higher or lower amount of energy can be expected to be produced.

By knowing the movement of average wind speed over certain periods of time and market demand at certain times, wind turbine selection can be adjusted to obtain higher efficiency for specific wind speeds. This may reduce the total amount of energy produced but will increase energy production during periods when it is more needed by the market.



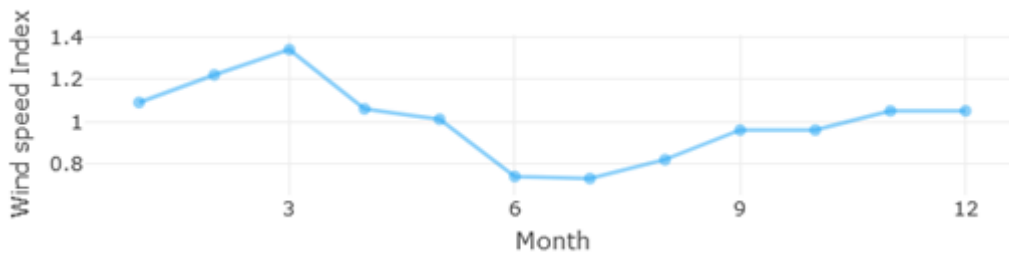


Figure 2.5. Example of Monthly Wind Speed Index for Istrian region [6]

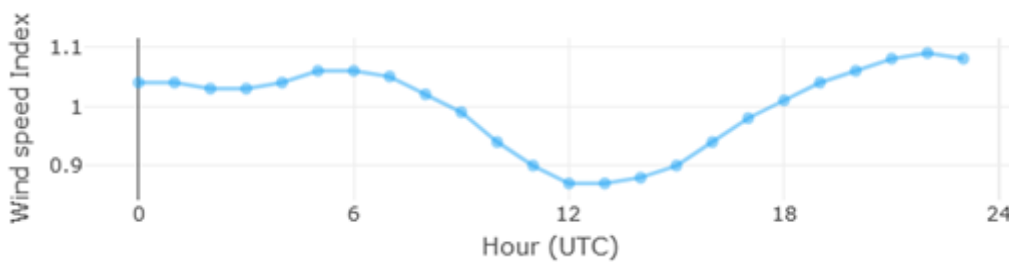


Figure 2.6. Example of Daily Wind Speed Index for Istrian region [6]

2.2.1. Selected wind turbines

For the purposes of this project, three wind turbine models with different rated power and rotor sizes were selected. The energy production of these three models was calculated based on the wind potential in the examined regions. This will allow for a comparison of the energy output of different wind turbine types.

The selected wind turbines are manufactured by Vestas and Siemens Gamesa, two of the world's leading wind turbine producers. Vestas has its global headquarters in Aarhus, Denmark. The company manufactures wind turbines in several countries, including Denmark, Germany, Spain, China, etc. On the other hand, Siemens Gamesa has its global headquarters in Zamudio, Spain. The company manufactures wind turbines in several countries, including Spain, Germany, Denmark, China, etc.

The selection includes two models already in commercial operation: the Vestas V164-8.0 MW and the Siemens Gamesa SG 10.0-193 DD. These turbines have been successfully deployed for several



years, demonstrating their reliability and efficiency. The third model, the Vestas V236-15.0 MW, has undergone extensive testing and is now gradually entering commercial deployment.

The Vestas V164-8.0 MW is an offshore wind turbine with a maximum power output of 8 MW. Its 164-meter rotor is equipped with three blades, each 80 meters long, ensuring high energy efficiency. The turbine starts operating at a wind speed of 3.5 m/s, reaches its rated power at 13 m/s, and shuts down at 25 m/s. The prototype was installed in 2014 in Østerild, Denmark, with commercial production beginning in 2016. Currently, it is also used at the Buro Bank wind farm in the United Kingdom where 32 wind turbines V164-8.0 MW are installed at an average sea depth of 10 m and a distance of 9 km from the coast [7]. The V164-8.0 MW is designed for IEC S class. The annual output of a single turbine is enough to supply electricity to approximately 7,500 households.

The Siemens Gamesa SG 10.0-193 DD is an offshore wind turbine with a maximum power output of 10 MW. Its 193-meter rotor is equipped with 94-meter-long blades [8], ensuring high energy efficiency. The turbine starts operating at a wind speed of 4 m/s, reaches its rated power at 12 m/s, and shuts down at 28 m/s. The prototype was installed in 2019 in Brande [9], Denmark, with commercial production beginning in 2022. The SG 10.0-193 DD is designed for IEC Class I conditions, meaning it is built to withstand high wind speeds and harsh offshore environments. The annual output of a single turbine is enough to supply electricity to approximately 10,000 households.

The Vestas V236-15.0 MW is an offshore wind turbine with a maximum power output of 15 MW. Its 236-meter rotor is equipped with three blades, each 115.5 meters long, ensuring high energy efficiency. The turbine starts operating at a wind speed of 3 m/s and shuts down at 31 m/s. The prototype was installed in 2022 in Østerild, Denmark, with serial production planned. The V236-15.0 MW is designed for IEC S class. The annual output of a single turbine is enough to supply electricity to approximately 20,000 households. This model is representative of the wind turbines that are starting to be installed, and it is expected that future wind farms will be built with wind turbines with similar characteristics. Currently, two wind farms are under construction with this wind turbine [10]. The first is the EnBW He Dreiht wind farm in Germany, which will consist of 64 wind turbines V236-15.0 MW at an average water depth of 38 meters and a distance of 95 km from the coast. The second wind farm is Inch



Cape in the United Kingdom, which will consist of 72 wind turbines V236-15.0 MW at an average water depth of 50 meters and a distance of 20 km from the coast [11].

Table 2.2 presents overview of the main technical specifications of the selected wind turbines.

Table 2.2. *Technical specifications of the selected wind turbines*

Manufacturer	Vestas [12]	Simens Gamesa [9]	Vestas [13]
Model	V164-8.0 MW	SG 10.0-193 DD	V236-15.0 MW
Rotor (m)	164	193	236
Rated power (MW)	8	10	15
Wind class	IEC S	IEC S/IB	IEC S
Cut-in speed (m/s)	3.5	3.5	3
Cut-out speed (m/s)	25	25	31

Figure 2.9 shows the power curves for the three selected wind turbines. Publicly available power curve data for the Vestas V164-8.0 MW and Siemens Gamesa SG 10.0-193 DD turbines has been published by their respective manufacturers. For the Vestas V236-15.0 MW turbine, Vestas has not publicly released power curve data, therefore, for this project, an approximation was developed based on the previous research [14]. These power curves will be used to estimate actual electricity production based on wind characteristics in all four examined regions.



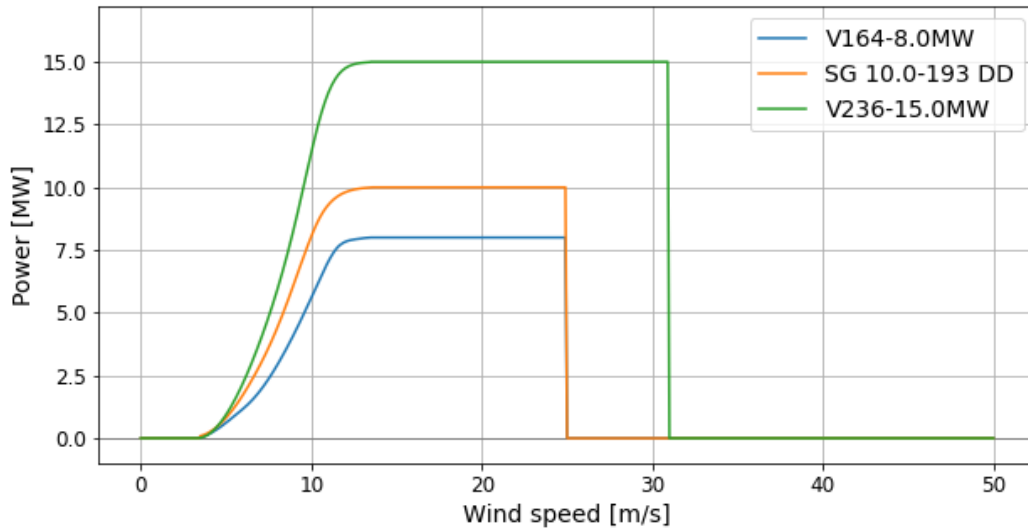


Figure 2.9. Power curves for tested wind turbines

Figure 2.10 shows the wind energy efficiency of three selected wind turbines. These curves indicate how efficiently each turbine utilizes wind energy at different wind speeds, highlighting the wind speed range for which each turbine is designed.

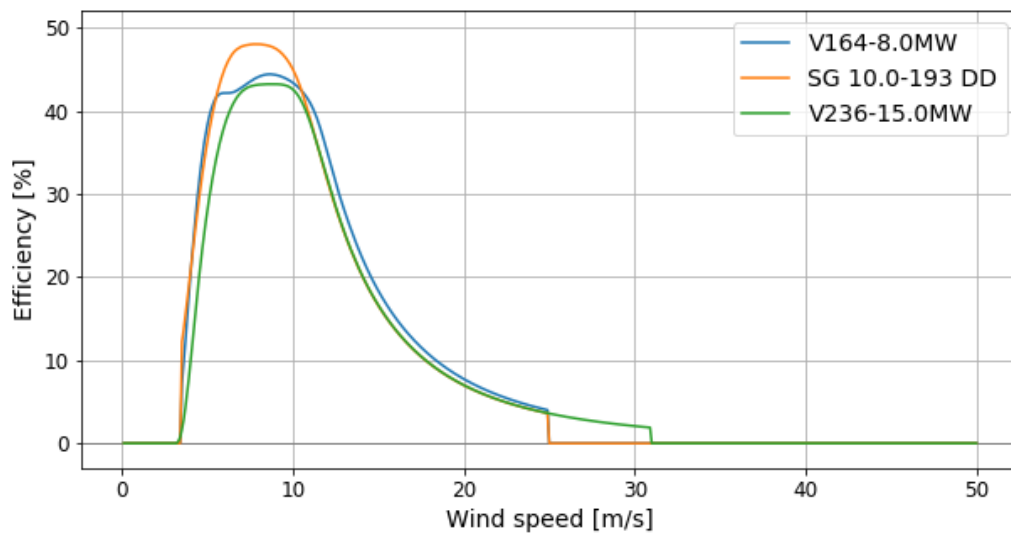


Figure 2.10. Efficiency for selected Wind Turbines



The efficiency curve of a wind turbine is obtained using the efficiency equation (2.2) [15], where the power of the wind turbine at a given wind speed is divided by the power of the wind at that wind speed.

$$\eta = \frac{P_{turbine}}{P_{wind}} \cdot 100\% \quad (2.2)$$

Where:

η - efficiency of turbine (%),

$P_{turbine}$ – power of turbine (W),

P_{wind} – power of wind (W).

Wind power can be calculated as:

$$P_{wind} = \frac{1}{2} \cdot \rho \cdot v^3 \cdot A \quad (2.3)$$

where:

ρ – air density (1.225 kg/m³),

v – wind speed (m/s),

A – rotor swept area (m²).

Air density depends on temperature, pressure and humidity. In order to obtain data on the actual air density, it would be necessary to conduct measurements of temperature, pressure and humidity at the studied locations. Therefore, for the purpose of this project, the universally accepted air density constant of 1.225 kg/m³ is used.



2.3. Calculation of the OWF power output

2.3.1. Power calculation

When an offshore wind farm is installed, its rated power can be calculated by multiplying the rated power of a single wind turbine by the total number of turbines:

$$P_{R_windfarm} = P_{R_turbine} \cdot N \quad (2.4)$$

where:

- $P_{R_windfarm}$ - Rated power of the wind farm (MW),
- $P_{R_turbine}$ - Rated power of the wind turbine (MW),
- N - Number of wind turbines in a wind farm.

However, wind turbines operate at their rated power only for a portion of the time; during the remaining periods, they generate reduced power or may not operate at all. The power output of a wind turbine depends on wind speed, which is variable. Multiplying the wind turbine power (achieved at the average wind speed within one hour) by the time interval of one hour, the wind turbine's electricity production for that hour is obtained:

$$E_{h_turbine} = P_{turbine}(v_h) \cdot \Delta t \quad (2.5)$$

where:

- $E_{h_turbine}$ - Electricity production of one wind turbine in one hour (MWh),
- $P_{turbine}(v_h)$ - Wind turbine power at wind speed v_h (MW),
- v_h - Average wind speed within one hour (m/s),
- Δt - Turbine operating time (1 hour).



To calculate the annual energy production of a wind farm, wind speed data for each hour must be multiplied by the corresponding turbine power output at that wind speed. Summing all these hourly energy outputs over a year results in the total annual energy production of a single wind turbine:

$$E_{AEP_turbine} = \sum_{n=1}^{8,760} P_{n_turbine}(v_n) \cdot \Delta t \quad (2.6)$$

where:

- $E_{AEP_turbine}$ - Annual energy production of a single wind turbine (MWh),
- $P_{n_turbine}(v_n)$ - Wind turbine power for average wind speed in the n-th hour (MW),
- v_n - Average wind speed in the n-th hour (m/s).

For this project, data on average hourly wind speeds over a ten-year period was collected. To achieve greater accuracy in the results, the total electricity generation will be calculated for the entire ten-year period and then divided by ten to obtain the average annual energy production of a single wind turbine:

$$E_{mean_AEP_turbine} = \left(\sum_{n=1}^T P_{n_turbine}(v_n) \cdot \Delta t \right) \div 10 \quad (2.7)$$

where:

- $E_{mean_AEP_turbine}$ - Average annual energy production of a single wind turbine (MWh),
- $P_{n_turbine}(v_n)$ - Wind turbine power for average wind speed in the n-th hour (MW),
- v_n - Average wind speed in the n-th hour (m/s),
- T - total number of hours per 10 years period (87,648).

When hourly wind speed data is available, it is best to use the above method to calculate annual energy production. However, sometimes this data is not available, and in that case the Weibull distribution can be used, which gives an approximation of the frequency of occurrence of a particular wind speed. In that case, the power of the wind turbine at a particular wind speed is multiplied by the



time that wind speed is present in a year. By summing all the energy produced for all wind speeds, an approximation of the annual energy production for a single turbine is obtained. This calculation is less accurate than the more specific calculation of energy production per hour, but it is faster to calculate.

Equation (2.7) provides the average annual energy production for a single wind turbine within the wind farm. This calculation must be repeated separately for each wind turbine using the wind speed data specific to its location. By summing the average annual energy production of all wind turbines, the total average annual energy production of the wind farm is obtained:

$$E_{mean_AEP_windpark} = \sum_{i=1}^N E_{mean_AEP_i_turbine} \quad (2.8)$$

where:

- $E_{mean_AEP_windpark}$ - Average annual energy production of a wind farm (MWh),
- $E_{mean_AEP_i_turbine}$ - Average annual energy production of the i-th wind turbine (MWh),
- N - Number of wind turbines in a wind farm.



3. Results for pilot locations

Using the available wind speed data and the described calculation methodology, the OWF power output has been determined for three selected turbines: Vestas V236-15 MW, Siemens Gamesa SG 10.0-193 DD, and Vestas V164-8.0 MW.

For the wind turbine with the highest nominal power output (Vestas V236-15 MW), an OWF turbine layout was created, and is shown in the next Subsections for each pilot region. This layout visually represents the spatial distribution of the planned OWF at the selected location and the total area it will occupy. Additionally, the OWF layout has been designed for three nominal power outputs (500 MW, 700 MW, and 1000 MW), with larger rotor diameters requiring more space within the test region. The distance between the turbines is determined as $5D$ [16], where D is the rotor diameter. The placement of wind turbines is based on locations with the highest wind speeds. For example, the first wind turbine is placed in the position with the highest wind speed within the pilot area, the second in the position with the next highest wind speed, and so on. The wind speeds used are the average hourly speeds for the 10-year period, specifically from January 1, 2009 to December 31, 2018.

For the other turbine types, a data summary is provided in subsection 3.5., allowing for a direct comparison between all three analysed turbine types. Specifically, it presents the number of wind turbines required to achieve the planned nominal power output and the total area they will occupy. A table for each pilot region presents the annual energy production values for each selected wind turbine model and each OWF nominal power capacity.

3.1. Veneto Region

Within the Veneto pilot region highest wind speed areas are located in the northeastern corner of the region, and as such are chosen for placement of OWF. The layouts of OWF-s for chosen nominal powers with evenly distributed turbines are depicted in Figure 3.1. It must be noted that this placement



is not suitable in terms of proximity to the mainland, therefore, installing the OWF at this location would maximize the wind potential utilized at the site, but at the same time, it would increase the costs of construction and maintenance.

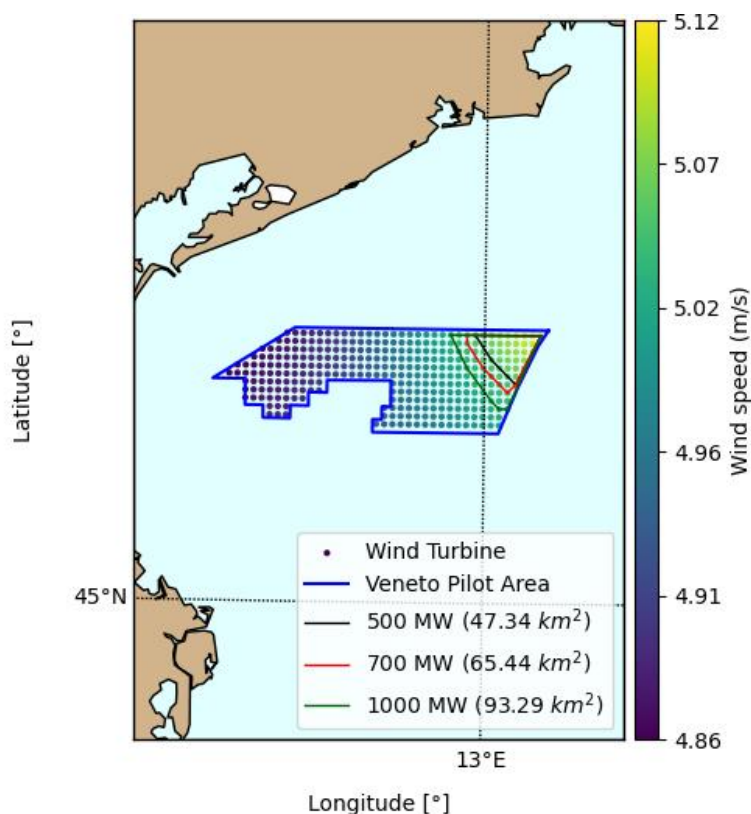


Figure 3.1. *Spatial turbine layout of OWF's with 500, 700 and 1000 MW capacities*

The annual energy production (AEP) was calculated according to equations (2.7) and (2.8) to provide additional information on the characteristics of the selected OWF configurations. The results for the Veneto region are summarized in Table 3.1, with AEP presented in GWh. As expected, AEP increases proportionally with the rise in the OWF's nominal capacity. It can be observed that wind turbine (WT) model SG 10.0-193 DD has greatest AEP, which can be explain by turbine efficiency which is more suitable for lower wind speeds, which are present in this area. Namely, it can be observed from Figure 2.10 that for wind speeds below 10 m/s, this turbine has greater efficiencies than remaining turbines.



Although turbine V236-15.0 MW produces greater amount of energy for smaller wind speeds compared to other turbines (*Figure 2.9*) it must be noted that for achieving, for example, targeted nominal power of 500 MW it is required 34 V236-15.0 MW turbines while for SG 10.0-193 DD, it is required 50 turbines. Due to this difference, ultimately OFW with SG 10.0-193 DD turbines has greater AEP.

Table 3.1. Annual energy production (GWh) for various OWF configurations in the Veneto Region

OWF nominal power		500 MW	700 MW	1000 MW
WT model	V164-8.0 MW	858 GWh	1194 GWh	1688 GWh
	SG 10.0-193 DD	928 GWh	1295 GWh	1841 GWh
	V236-15.0 MW	883 GWh	1216 GWh	1724 GWh

3.2. Istrian Region

For the Istrian test region, the northeastern area has the highest wind potential. Therefore, in this region the OWF has been placed and spatial distribution of turbines is depicted in Figure 3.2. This area, in addition to being the best in terms of wind energy, is also the most favourable in terms of distance from the coast. Installing the OWF in this area will be suitable, due to the wind potential and the reduced costs related to OWF construction and maintenance.



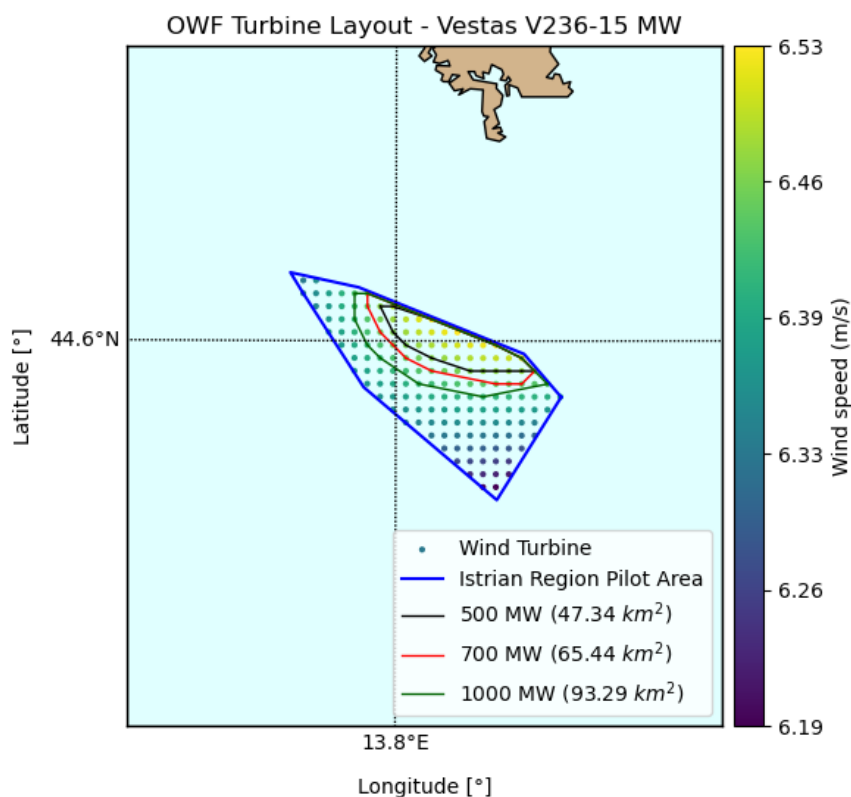


Figure 3.2. Spatial turbine layout of OWF's with 500, 700 and 1000 MW capacities

The results of the AEP for the selected OWF configurations in the Istrian Region are summarized in Table 3.2. The same trend of increasing AEP values with larger OWF capacities can be noticed as in the Veneto Region. Based on the calculations, the WT model SG 10.0-193 DD results in the highest AEP for each OWF nominal power capacity.

Table 3.2. Annual energy production (GWh) for various OWF configurations in the Istrian Region

OWF nominal power		500 MW	700 MW	1000 MW
WT model	V164-8.0 MW	1281 GWh	1785 GWh	2526 GWh
	SG 10.0-193 DD	1381 GWh	1929 GWh	2746 GWh
	V236-15.0 MW	1327 GWh	1830 GWh	2600 GWh



3.3. Split-Dalmatia County

As with the Veneto and Istria regions, the process of collecting wind data and calculating the required area for the OWF to meet three nominal outputs follows the same methodology. In Split-Dalmatia County the higher wind speeds are found in the northern polygon, more precisely in its northwest area. Placement of OFWs is presented in Figure 3.3. The results indicate that the required area, based on giving priority to areas with maximum wind energy, is not a single, unified space for all three nominal outputs. Instead, it is divided into two parts due to the specific boundaries of the Split-Dalmatia County area. Additionally, the larger required surface for the OWF is located in the northwest corner, while the remaining surface is situated in the northeast corner. Furthermore, regarding the distance from the mainland, this location for the OWF is not the most ideal, especially the part in the northwest corner, which is the farthest from the shore. This spatial dispersion of the OWF, combined with the less favourable distance to the coast, would increase both construction and maintenance costs.



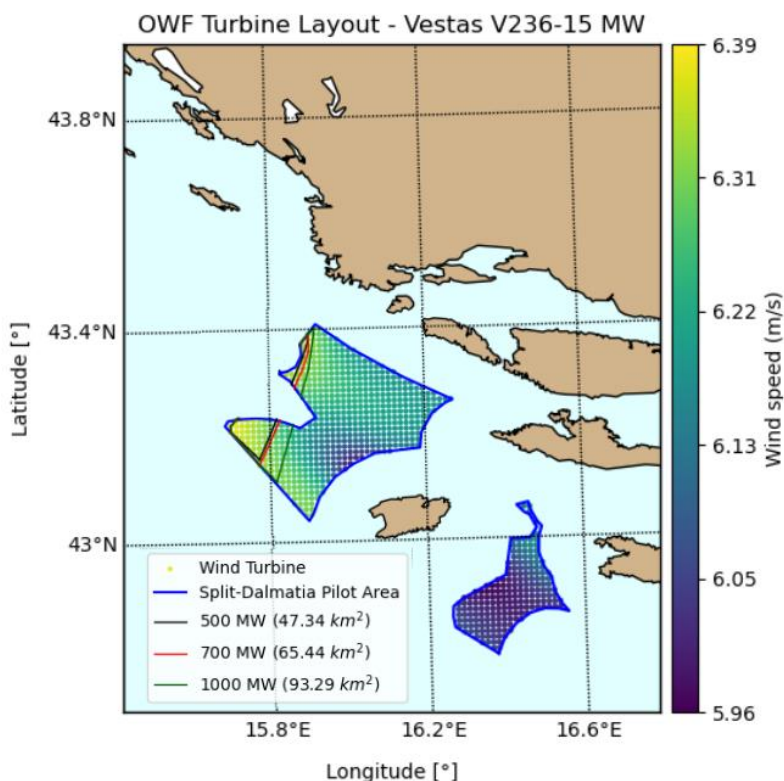


Figure 3.3. Spatial turbine layout of OWF’s with 500, 700 and 1000 MW capacities

The wind turbine model SG 10.0-193 DD, with a nominal power of 10 MW, once again yields the highest AEP in the OWFs with nominal capacities of 500, 700 and 1000 MW, among other wind turbine models, as observed in the Veneto and Istrian Regions. Table 3.3. summarizes the AEP values for the selected OWF configurations in the Split-Dalmatia County.

Table 3.3. Annual energy production (GWh) for various OWF configurations in the Split-Dalmatia County

OWF nominal power		500 MW	700 MW	1000 MW
WT model	V164-8.0 MW	1280 GWh	1784 GWh	2529 GWh
	SG 10.0-193 DD	1379 GWh	1928 GWh	2747 GWh
	V236-15.0 MW	1326 GWh	1829 GWh	2601 GWh



3.4. Apulia Region

In the Apulia region, the highest wind potential is located about one-third of the way along the polygon, near the northwest border, and from there it spreads towards the southeast, gradually weakening. The proposed locations of OWFs can be observed in Figure 3.4. The most suitable wind area is also the most favourable in terms of distance from the coast, as it is one of the closest points to the shore. This proximity should make construction and maintenance easier and more cost-effective.

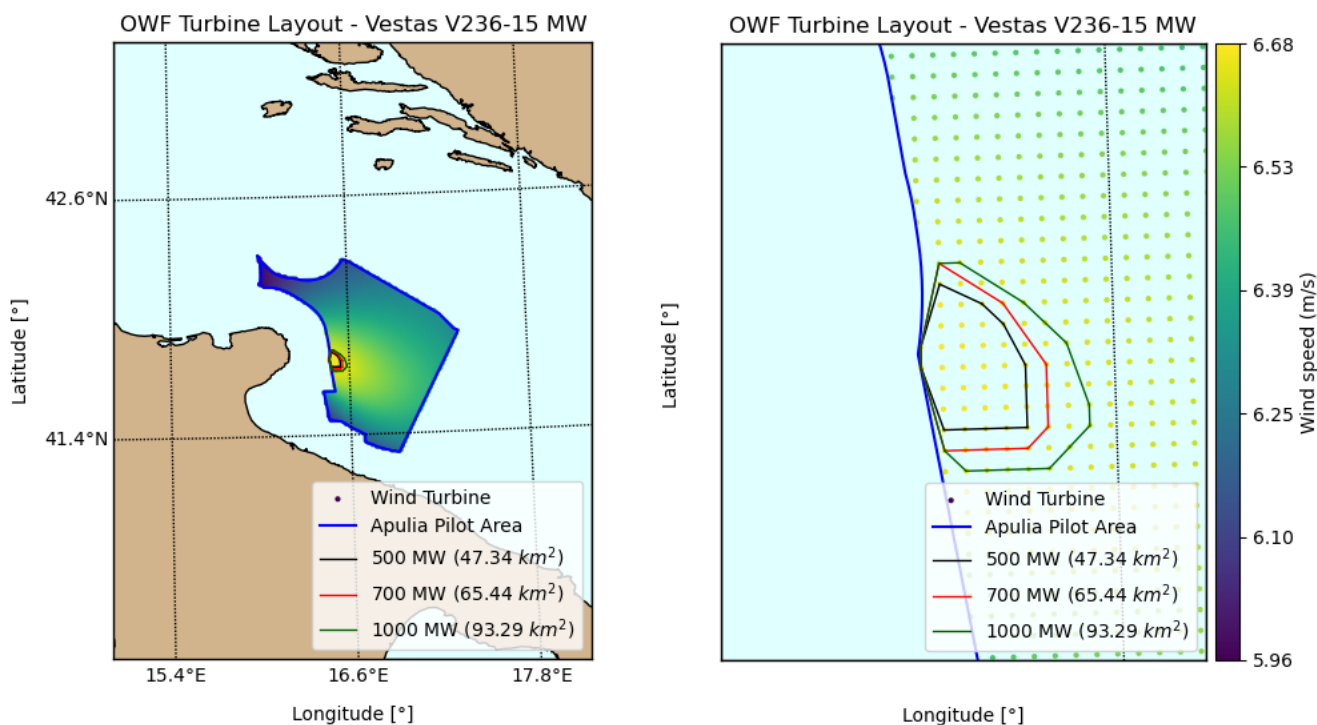


Figure 3.4. Spatial turbine layout of OWF's with 500, 700 and 1000 MW capacities

The AEP results for the selected OWF configurations in the Apulia Region are summarized in Table 3.4. The highest AEP is also achieved using the SG 10.0-193 DD turbine model, as in the other pilot regions. Although the SG 10.0-193 DD turbine model can produce the largest amount of energy, the number of required wind turbines must also be taken into account when analysing the profitability.



Table 3.4. Annual energy production (GWh) for various OWF configurations in the Apulia Region

OWF nominal power		500 MW	700 MW	1000 MW
WT model	V164-8.0 MW	1414 GWh	1973 GWh	2798 GWh
	SG 10.0-193 DD	1533 GWh	2144 GWh	3060 GWh
	V236-15.0 MW	1471 GWh	2032 GWh	2893 GWh

3.5. Pilot region wind energy potential comparison

After analyzing all four OWF test regions in the Adriatic, a data summary of the results is provided in Figure 3.5. This summary includes, alongside the wind turbine type with the highest nominal power output (Vestas V236-15 MW), for which the OWF layout and spatial distribution were created for each of the four test regions, an analysis of the remaining two selected wind turbine types (Siemens Gamesa SG 10.0-193 DD and Vestas V164-8.0 MW). The data summary provides a visual comparison between each wind turbine type for the three analysed nominal power outputs. Furthermore, the data summary graph illustrates how many wind turbines of each type are required and the corresponding area needed for their installation. From Figure 3.5, it is noticeable that increasing the nominal power output influences the increase in the number of required wind turbines, as well as the area needed. It should be mentioned that wind turbines with the highest nominal power output require a larger area than those with smaller nominal power outputs, although they require, at the same time, fewer wind turbines. Specifically, for the wind turbine type with the highest nominal power output (Vestas V236-15 MW), the smallest number of wind turbines is required for each of the three analyzed nominal power outputs, but they require the largest area for installation. In contrast, for the Vestas V164-8.0 MW, which has the smallest nominal power output, a larger number of wind turbines is required, but they require the smallest area. In numerical terms, the required number of Vestas V164-8.0 MW wind turbines at the 500 MW nominal power output is 63, while the number of required Vestas V236-15 MW



is nearly half that, or 34 wind turbines. This difference increases almost linearly with the nominal power output of the OWF, reaching 125 required Vestas V164-8.0 MW turbines at a 1000 MW nominal power output, compared to 67 Vestas V236-15 MW turbines. For the required area at a nominal power of 500 MW, the Vestas V164-8.0 MW turbines require an area of approximately 42.5 km², while the Vestas V236-15 MW turbines require about 47 km². This difference of about 5 km² is not significant, but it increases also almost linearly with increasing nominal power outputs of the OWF, leading to a difference of around 10 km² at the 1000 MW nominal power output. Furthermore, the Siemens Gamesa SG 10.0-193 DD wind turbine type falls somewhere in between these two Vestas turbines in terms of area and number of turbines required.

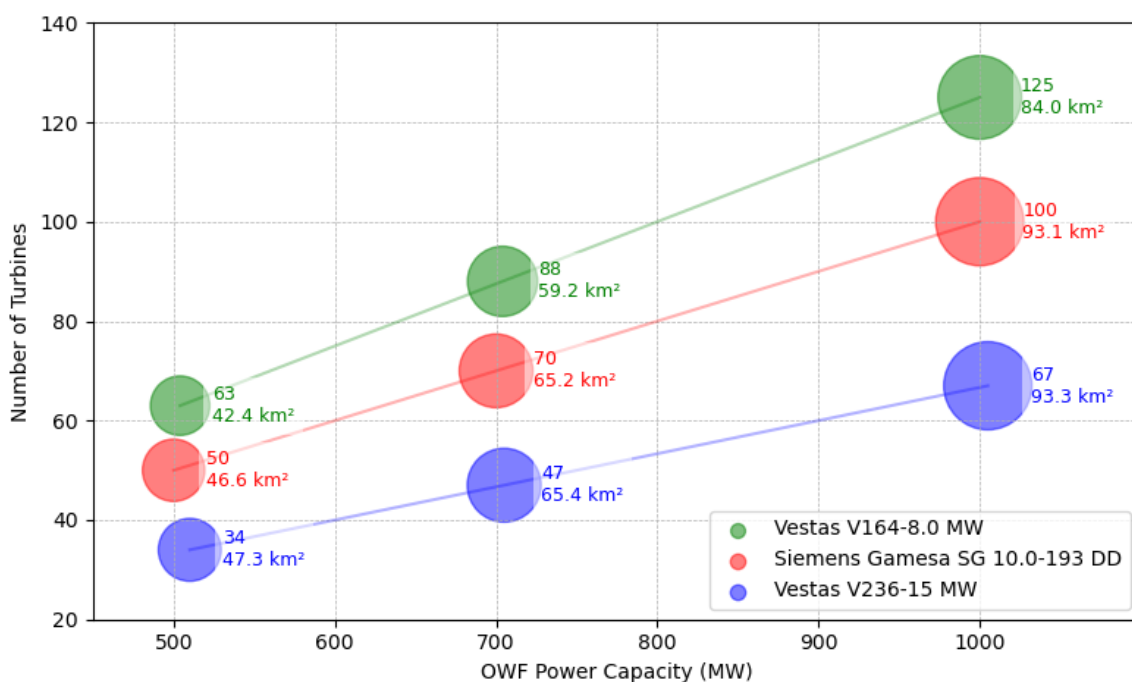


Figure 3.5. Comparison of the number of wind turbines by power and wind farm area

The capacity factor (CF) provides information on the actual OWF energy output over a given period of time, in this case, one year, to the theoretical maximum electrical energy output over that period. It is calculated using the formula:



$$CF = \frac{E_{mean_AEP_windpark}}{P_{R_turbine} \cdot N \cdot 8760} \cdot 100\% \quad (3.1)$$

For OWFs with capacities of 500, 700 and 1000 MW and wind turbine model SG 10.0-193 DD, CF was calculated. The highest energy output was observed for the Apulia Region, with the maximum CF of 35%. The next pilot regions with the highest CFs are the Split-Dalmatia County and the Istrian Region, both with the capacity of 31.5%. The lowest CF was calculated for the Veneto Region, with values of 21.2 %.



4. Wind farm optimization

Wind farm layout optimization problem is the task of OWF engineers and designers who must decide where to locate each turbine, also called micro-siting. The optimization of turbine location, electrical cable routing and foundation are the most important optimization tasks to encompass in the preliminary offshore wind park design to increase energy production and reduce costs. In a large number of research optimization is oriented at maximizing the wind farm energy production or minimizing the cost of energy to get a lower levelized cost of energy (LCOE) of the wind farm [17].

Considering wake effects is crucial to mitigate wind speed reduction, which results in power production losses [18]. A wind turbine wake is the volume of air downwind of the turbine, characterized by lower wind speeds and higher turbulence compared to the freestream. The effects of wakes not only include reduced power output of the wind farm, but also increased structural loads on turbine components such as blades and tower [19]. Wake modelling is typically performed using computational fluid dynamics (CFD) or analytical models such as the Jensen model [17]. The wake effect produced by upwind turbines is taken into account by calculating the reduced wind speed at specific downwind distances from the turbines. The average power loss due to turbine wakes in large OWFs is around 10 to 15% [17], and can reach up to 20% of the total annual energy production, according to Barthelme et al. [19].

After determining wind turbine position, turbine foundation optimization is carried out considering sea bed conditions and water depth. Turbine towers, support structures and foundations systems are optimized in order to reduce cost while ensuring no damages in the overall structure [18]. Heuristic algorithms such as genetic algorithm (GA) and particle swarm optimization (PSO) are most commonly used to overcome these important optimization tasks. Regardless of invested effort, WF layout is usually designed manually in practice, with respect to the proper distance between the wind turbines.



Cable routing optimization consists of finding the minimum cost connection of all offshore turbines using different types of cables, with different capacities, electrical resistances and prices. An optimized selection of the cable structure and type can reduce the electrical current losses during the operation of a wind farm [18].



5. Joint summary

A preliminary offshore wind energy potential analysis was carried out for the four pilot regions to identify favourable positions of wind turbines within each pilot region, to examine the suitability of selected wind turbine models, and estimate their annual energy production based on long-term hourly wind speed data.

The methodology for performing the preliminary offshore wind energy potential analysis was presented. The hourly wind speed dataset over a 10-year period, acquired from the New European Wind Atlas, was the base for the further analysis. The average wind speeds across each pilot region were computed, with the purpose of determining the wind turbine positions with the highest values of wind speeds. Next, several wind turbine models were selected for evaluation of turbine power output. The nominal power and the rotor diameters of three selected turbines - Vestas V236-15 MW, Siemens Gamesa SG 10.0-193 DD, and Vestas V164-8.0 MW, were used to determine the necessary number of wind turbines for offshore wind farm configurations with nominal capacities of 500, 700 and 1000 MW, as well as the respective area of the pilot region they would occupy. Another important factor, that provided additional information on the characteristics and profitability of the selected OWF configurations, was the annual energy production.

After the selection of wind turbine layouts within the pilot regions based on highest wind speeds, in the Istrian Region and the Apulia Region, it can be observed that the selected WT positions are closest to the mainland, in comparison with other possible WT positions, which is favourable in terms of the OWF construction and maintenance costs. On the other hand, more suitable WT positions, in terms of energy production, are more distant from the coast in the Veneto Region and the Split-Dalmatia County, which would result in higher expenses related to the construction of OWF in those pilot regions. Number of required wind turbines grows with the increase in OWF nominal power capacity, although it is possible to reduce their total number by choosing the WT model with higher nominal power. The annual energy production results for each OWF configuration with different WT models and different power capacities, indicate that the model SG 10.0-193 DD yields the highest AEP in every pilot region



even its nominal power is not the highest considered power, but its power curve characteristics are the most suitable for the given pilot regions and their wind speeds. For the considered turbines, the capacity factor for pilot regions ranges from 21.2% to 35% with a maximum value for the Apulia region. This indicates that turbines more suitable for lower wind values should be considered in future.

Distance from the mainland, the number and type of wind turbines and the annual energy production are some of the factors that should be taken into consideration when performing the optimisation and economic analysis to determine which option is the most profitable from the possible OWF configurations. Wake effect must also be considered in the planning and optimisation process due to the fact that power losses can reach up to 20% of the total annual energy production of an OWF.



6. Literature

- [1] Google Earth (2024) Google Earth. Available at: <https://earth.google.com/web/> (Accessed: September 2024).
- [2] New European Wind Atlas (2025) New European Wind Atlas. Available at: <https://map.neweuropeanwindatlas.eu/> (Accessed: 12 February 2025).
- [3] Bilgili, M. and Alphan, H., (2022) 'Global growth in offshore wind turbine technology'. *Clean Technologies and Environmental Policy*, 24(7), pp.2215-2227.
- [4] Roddier, D., et al. (2010) 'WindFloat: A floating foundation for offshore wind turbines', *Journal of renewable and sustainable energy*, 2(3).
- [5] IEC (International Electrotechnical Commission) (2019), *Wind energy generation systems - Part 1: Design requirements*, IEC 61400-1:2019, IEC, Geneva.
- [6] Global Wind Atlas (2024) Methodology. Available at: <https://globalwindatlas.info/en/about/method> (Accessed: 17 September 2024).
- [7] The Wind Power (2025) Vestas V164-8.0 MW Wind Turbine. Available at: https://www.thewindpower.net/turbine_en_867_vestas_v164-8000.php (Accessed: 4 February 2025).
- [8] Siemens Gamesa (2025) New Siemens Gamesa 10 MW Offshore Wind Turbine SG 10.0-193 DD. Available at: <https://www.siemensgamesa.com/global/en/home/press-releases/new-siemens-gamesa-10-mw-offshore-wind-turbine-sg-10-0-193-dd.html> (Accessed: 4 February 2025).
- [9] The Wind Power (2025) Siemens Gamesa SG 10.0-193 DD Wind Turbine. Available at: https://www.thewindpower.net/turbine_en_1662_siemens-gamesa_sg-10.0-193-dd.php (Accessed: 4 February 2025).



- [10] Vestas Wind Systems A/S (2023) Vestas secures a 960 MW firm order of V236-15.0 MW wind turbines. Available at: <https://www.vestas.com/en/media/company-news/2023/vestas-secures-a-960-mw-firm-order-of-v236-15-0-mw-wind-c3845287> (Accessed: 4 February 2025).
- [11] The Wind Power (2025) Vestas V236-15.0 MW Wind Turbine. Available at: https://www.thewindpower.net/turbine_en_1798_vestas_v236-15.0-mw.php (Accessed: 4 February 2025).
- [12] Vestas Wind Systems A/S (2012) V164-8.0 MW Offshore Wind Turbine. Available at: <https://pdf.archiexpo.com/pdf/vestas/vestas-v164-80-mw/88087-134417.html> (Accessed: 4 February 2025).
- [13] Vestas Wind Systems A/S (2025) V236-15.0 MW Offshore Wind Turbine. Available at: <https://www.vestas.com/en/energy-solutions/offshore-wind-turbines/V236-15MW> (Accessed: 4 February 2025).
- [14] Saint-Drenan, Y.M., Besseau, R., Jansen, M., Staffell, I., Troccoli, A., Dubus, L., Schmidt, J., Gruber, K., Simões, S.G. and Heier, S. (2020) 'A parametric model for wind turbine power curves incorporating environmental conditions', *Renewable Energy*, 157, pp. 754-768.
- [15] Lu, L., Yang, H. and Burnett, J. (2002) 'Investigation on wind power potential on Hong Kong islands - an analysis of wind power and wind turbine characteristics', *Renewable energy*, 27(1), pp. 1-12.
- [16] Jung, C. and Schindler, D., (2023) 'The properties of the global offshore wind turbine fleet', *Renewable and Sustainable Energy Reviews*, 186, p.113667.
- [17] Hou, P., Zhu, J., Ma, K., Yang, G., Hu, W. and Chen, Z. (2019) 'A review of offshore wind farm layout optimization and electrical system design methods', *Journal of Modern Power Systems and Clean Energy*, 7(5), pp. 975-986.



- [18] Fischetti, M. and Pisinger, D. (2019) 'Mathematical optimization and algorithms for offshore wind farm design: An overview', *Business & Information Systems Engineering*, 61, pp. 469-485.
- [19] Barthelmie, R.J., Hansen, K., Frandsen, S.T., Rathmann, O., Schepers, J.G., Schlez, W., Phillips, J., Rados, K., Zervos, A., Politis, E.S. and Chaviaropoulos, P.K. (2009) 'Modelling and measuring flow and wind turbine wakes in large wind farms offshore', *Wind Energy: An International Journal for Progress and Applications in Wind Power Conversion Technology*, 12(5), pp. 431-444.

