„Dunărea de Jos” UNIVERSITY OF GALAȚI

Doctoral School of Mechanical and Industrial Engineering

DOCTORAL THESIS

Extended Abstract

STUDIES ON ONSHORE AND COASTAL WIND ENERGY EXTRACTION

Scientific leader
Prof. eng. Eugen Victor Cristian RUSU PhD

Corresponding member of the Romanian Academy

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STUDIES ON ONSHORE AND COASTAL WIND ENERGY EXTRACTION

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Eng. Victoria Caranfil (Yildirir)

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Summary

Chapter I

1.1 General Objective of the Thesis and Specific Objectives

The current rapid growth of population and the fast development of technology clearly determine the need for renewable energy demand to be utilized on a much larger scale [1]. Global warming, climate change and the extraction of energy from renewable energy resources are an important topic in today's policy domain, both from an economic and engineering point of view.

In 2018, a new target to reduce energy consumption by at least 32.5% by 2030 was set in the “Clean Energy for All Europeans” package [2]. The global technical potential of wind energy can provide 5 times more energy than is currently consumed by the entire global population.

In Romania, based on the registered assessments, wind installations with a capacity of 14000 MW can be installed, which means a contribution of 23000 GWh/year [3].

In the framework of this thesis, conducted research using MERRA-2 and ERA5 reanalysis data, as well as *in situ* data collection, comparison and processing of *in situ* data from inland and coastal areas in Europe and Romania, based on data provided by the Romanian National Meteorological Administration (ANM), as well as data according to the European Centre for Medium-Range Weather Forecasts (ECMWF).

The specific objectives of the thesis on onshore and coastal wind energy extraction are the following:

- evaluation of ERA5 and MERRA-2 data for several *onshore* and *offshore* reference points specific to the Black Sea and coastal zone*;*
- analysis of *in situ* measurements processed for the 20-year time interval for the points Galați, Tulcea and Sulina, as well as identification of mean and maximum values, specific to wind speed;
- calculation of the hourly wind speed distribution specific to the reanalysis data (ERA5 and MERRA-2) for Galați, Tulcea and Sulina;
- research on the energy potential of local wind and solar resources near the Galați area, regarding the renewable energy resources in the area of Lake Brateș;
- evolution of wind resources for nine points in the Black Sea, using the ERA5 dataset, including wind data reported directly at 100 m height for 20 years, the dataset being defined by a spatial resolution of 0.25º of four values per day;
- forecasting the seasonal distribution, quantifying the quality of wind resources by identifying wind classes, the performance of certain turbines by calculating the power factor (Cf), calculating the V_{max} (maximum wind speed) to identify wind turbines suitable for a given reference point, and the annual electricity production of a given turbine;

There are a number of advantages to wind energy extraction, both onshore and offshore:

- the main advantage of investing in wind energy is the 'zero emission' of pollutants and greenhouse gases, because no fuels are burned;
- wind power generation is waste-free and 90% of turbine components can be recycled;
- low costs per unit of produced energy;
- low decommissioning costs, with the possibility of extending the lifetime through the implementation of *repowering* concepts;
- government stimulating job growth, but also increasing the number of consumers using renewable sources has benefits for increasing renewable energy production, but also for protecting the environment;
- it is recommended that small and medium-sized enterprises participate in awareness campaigns for the adoption of these renewable energy sources.

From these data collections, ERA5 and MERRA-2, area-specific data have been extracted to be used in detail to analyze wind speed and direction in the Black Sea area, with the aim of studying its potential for renewable energy and climatological research. Backcast analysis, also known as "*reanalysis*", is a relatively new field that emerged in 1979 with the use of meteorological data collected under the First GARP Global Climate Experiment (FGGE) [4].

I will evaluate future data scenarios for 100 years, this long-term assessment of wind conditions shows the impact of climate change and its effects on the evolution of the dynamics of areas with wind potential, which in turn is a particularly important aspect in the assessment and planning of investments in wind energy extraction.

1.2 Current State of Renewable Energy in Land and Coastal Areas

Promoting the production of electricity from renewable energy sources (RES) is a crucial and topical issue in the European Union, driven by: environmental protection, but also increasing energy independence from imports from Russia, by tapping the energy potential, but also by diversifying energy supply sources, as well as other economic, political and social cohesion reasons.

With a share of 24.7% in 2015, Romania has already reached its 2020 target (24%) for renewable energy, mainly due to the size of its hydropower sector, which is responsible for about one third of the installed electricity generation capacity, but also to the evolution of wind energy (9.4% of the energy generated in 2014) and the use of biomass for heating (16.6% of final energy consumption) [5].

Using only 4% of the *offshore* area*,* around 10 km of coastline, and taking into account the restrictions imposed by navigation, oil and gas platforms, military zones, Natura 2000 areas, Romania can increase the potential by more than 90% (from 2,800 TWh in 2020 to 3,500 in 2030) [6]. *Offshore* wind turbines are an important wind energy technology and have several advantages over *onshore* wind turbines. One of these is their ability to produce more energy due to their advantageous offshore location, where they are exposed to more constant and higher wind strength, allowing them to generate larger amounts of energy compared to *onshore* turbines. Figure 1.2 represents the wind map of Romania, the average wind speed in m/s, at 100 m.

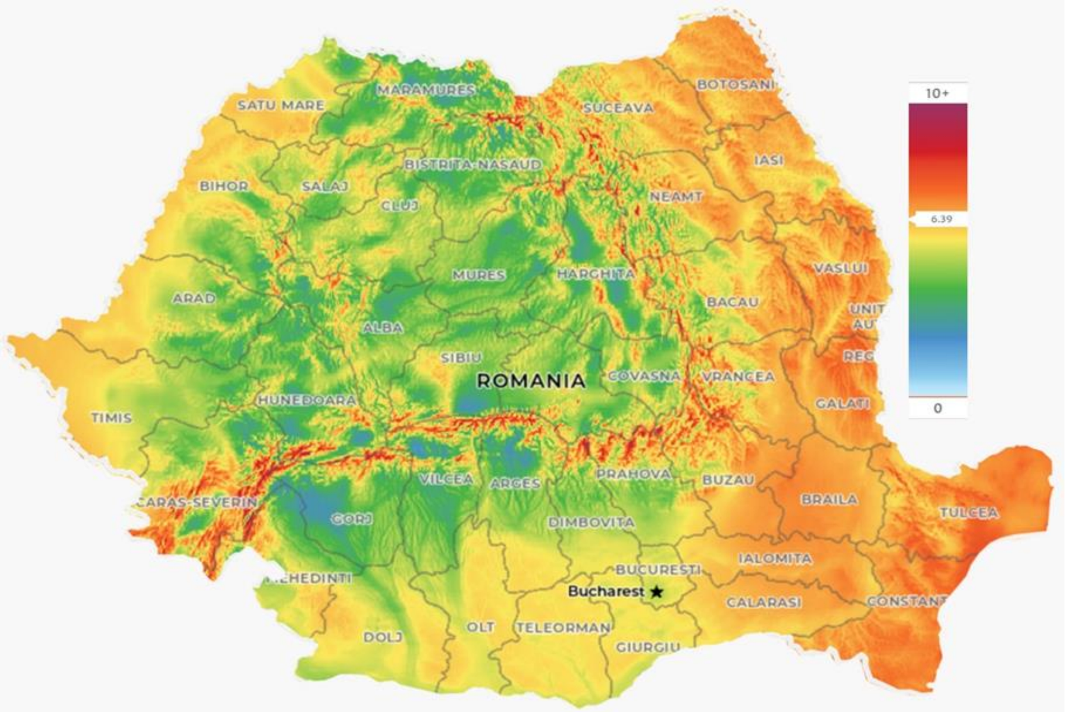

Figure 1.2. Wind map of Romania, average wind speed in m/s, at 100 m, year 2024 Source: Wind Atlas Map GWA 3.3 [7]

On the Romanian Black Sea coast, from north to south, there is an uneven distribution of wind speed intensity. The highest wind intensities are recorded in the directions of the northern sector, based on the records from the Gloria offshore platform [8]. Regional statistics of solar resources and specific photovoltaic output (PVOUT) are calculated from long-term averages over the period 1994-2007 (depending on the region) to 2018; in Romania, PVOUT is 2.89 - 3.71 kWh/kWp.

In Romania, the wind potential, both onshore and offshore, is significant from an energy point of view, being twice as large as the total electricity consumption today.

Romania's wind sector has invested in: CEZ (Czech Republic) with the Fântânele-Cogealac wind farm, with over 240 wind turbines of 2.5 MW, with a capacity of 600 MW, Energia de Portugal (Portugal) the third largest investor worldwide, has invested in Cernavodă a wind farm of 48 turbines of 3 MW, with a capacity of 138 MW and Enel (Italy) the Sfânta Elena wind farm, in Caraș-Severin, and Agighiol, in Tulcea, comprising 21 wind turbines of 2.3 MW with a total peak capacity of 48 MW, and the wind farm built north of the city of Tulcea, with a total installed capacity of 140 MW and 35 turbines of 2 MW each [9].

1.3 Conclusions

Climate change will alter energy demand and production. Electricity consumption in southern Europe, but also in the Mediterranean region, will increase due to projected temperature increases and the associated rising demand for cooling space. Due to changes in river flows, hydropower production will increase in northern Europe and decrease in the south. In Europe, summer droughts will be more severe, limiting the availability of cooling water and thus reducing the efficiency of thermal power plants. Both impacts can lead to changes in emissions of air pollutants and greenhouse gases from energy, which are, however, difficult to estimate [10].

The city of Galați looks like it could become the next *"Hydrogen Valley*" and a pole of *GREENSTEEL* investment in renewable energy, as well as the infrastructure needed to realize these goals. "Galați-Green Valley" represents one of the greenest investments in the European Union [11].

Chapter II
Basics of Wind Turbine Operation and Trends in the Wind Industry

2.1 Wind in Terrestrial and Coastal Areas

In Romania, in areas such as Moldova, Dobrogea, southern and eastern Muntenia, during the winter, the "crivăț", is a particularly strong wind that blows from the northeast to the southwest, sometimes with speeds exceeding 30-35 m/s. In combination with snow, it often causes the worst blizzards in our country during the cold season.

The wind speed in Romania reaches its highest values in the eastern part of the country, especially the south-eastern part. The average speed in the region is over 8 m/s, measured at 100 m altitude. The direction of the wind is determined in relation to the cardinal point from which it propagates.

Figure 2.1 shows the days with wind speeds suitable for wind energy exploitation, more constant values, without extremes, are recorded in the summer and fall seasons, but also in spring, fall, in September, for example, with values above 12 m/s for 14 days, and in July, 15 days at the same wind speed.

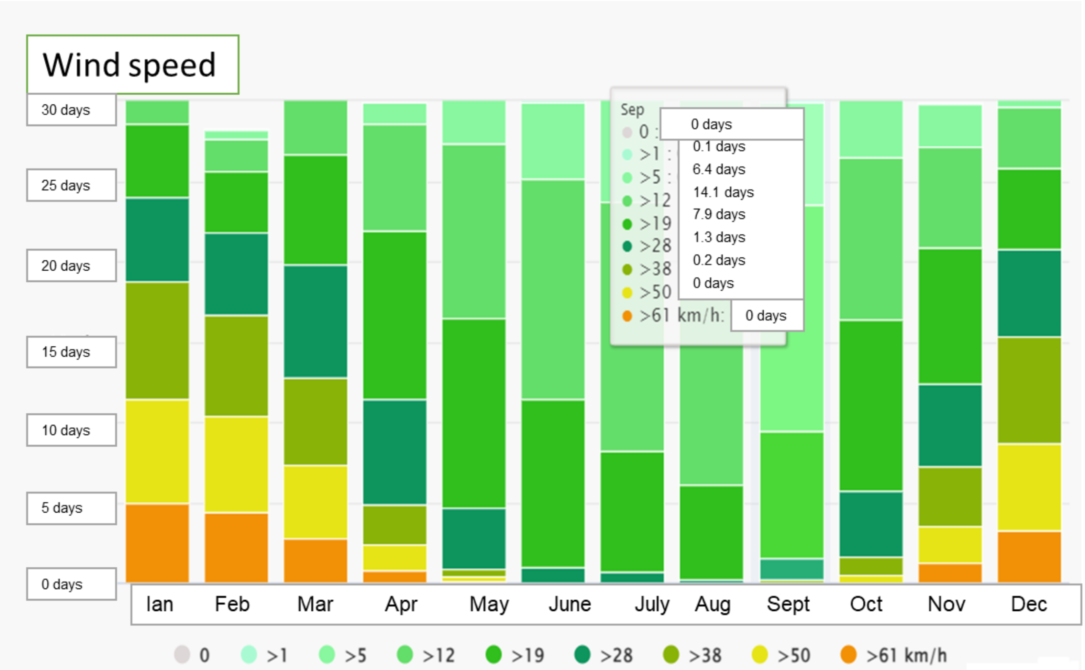

Figure 2.1. Wind speed diagram in Romania (km/h), averaged over a 30-year period (1990-2020) [12].

2.2 Wind Turbines and Their Classification

There are three main types of wind turbines, according to their power output:

- ***utility-scale wind turbines:*** wind turbines with capacities between 100 kW and 250 MW;
- ***small wind turbines*** under 100 kW;
- ***offshore wind turbines***: wind turbines above 2.5 MW that are installed in the marine environment.

By design there are horizontal-shaft turbines and vertical-shaft turbines.

The mechanical power of the wind generator is directly proportional to the air density. As the air density increases, the available power also increases. The mechanical power (P) is harnessed due to the wind speed (V). Wind speed is a measure of wind turbine generator activity and has the greatest effect on mechanical power. Air density has an important effect on mechanical power and wind stations operating under air clarify the variation of density with constant wind speed. Generator mechanical power is directly proportional to air density. As air density increases, the available power also increases.

Wind power increases at higher turbine shaft heights, so the higher a turbine is, the more electricity it produces. Variation of wind speed v with height h is [13] :

$$\frac{V}{V_0} = \left(\frac{h}{h_0}\right)^{\alpha} \qquad (2.1)$$

v_0 - speed [m/s] at ground level ($h = 0$),
α - area characteristic coefficient, $\alpha = 0{,}1 \div 0{,}4$,

$$P = \left(\frac{1}{2}\right) \rho \cdot S \cdot v^3 \qquad (2.2)$$

where ρ, is the air density, ρ - 1.25 kg/m³, under normal conditions of temperature and pressure at sea level; v - wind speed [m/s]; S - area [m²] covered by the turbine blades.

Given Betz's limit, which is 0.593, relation (2.2) can be multiplied by this coefficient to obtain the actual power delivered by the turbine.

However, not all of this power can be harnessed, as some of it is needed to exhaust air that has performed mechanical work on the turbine blades [14].

The capacity factor characterizes the efficiency of the wind turbine. The capacity factor is a measure of the overall efficiency of the whole turbine system, as it represents the combination of the efficiency of different turbine components, such as: blades, shaft bearings, generator, but also the power. It can be expressed as [15]:

$$Cf = \frac{Instant\ turbine\ power}{Nominal\ power} \qquad (2.3)$$

Where, *Cf* is the capacity factor.

The power coefficient was introduced in Betz's theory. The Betz limit indicates the maximum energy that can be recovered by even the most efficient wind turbines. It can only be 59% of the wind energy. For a real wind turbine, *Cf* is at most 0.3 ÷ 0.4.
Betz's theory models the passage of air through the turbine blades as through an airflow tube with velocities [16]:

- v1 - wind speed before the turbine;
- v - the wind speed at the wind turbine blades; it is in the order of a few m/s (~ 10 m/s);
- v2 - wind speed after the wind turbine blades have taken up kinetic energy.

The velocities are considered to be parallel to the wind turbine axis, where V1 > V > V2. The highest energy capture efficiency is 59.3%, known as the Betz limit. According to Betz's law, determined in 1919 by Albert Betz, no turbine can capture more than 59.3% of the kinetic energy of the wind. The factor 16-27 (0.593) is known as the Betz coefficient. This is the theoretical upper limit, a value that cannot be reached in practical installations.

2.3 Repowering Concept and EU Regulations

Repowering is the concept of replacing older wind turbines, or parts of them, with newer, generally larger and more efficient models. New innovations in wind energy technology have dramatically increased the production capacity of new wind turbines compared to older turbines. Partial repowering means replacing parts of old wind turbines with new parts or improving existing parts, changing their size and efficiency. These modified turbines would increase the amount of energy that can be generated from a wind farm.

There are several types of repowering: total/full or partial. The manager of a wind farm can select to deal with these assets at the end of their life cycle:

- complete repowering: wind turbines are completely dismantled; the new wind turbines are installed on industrial and/or agricultural land,
- partial repowering: by extending the lifetime, i.e. dismantling some of the components of an existing wind turbine, which are upgraded (e.g. generator, blades) and improved; the overall external structure of the farm remains unchanged (e.g. hub height, location, size). Life extension differs from normal operation and maintenance activities.

WindEurope estimates that the annual volume of repowering increases from 1-2 GW in 2017 and stabilizes at 5.5-8.5 GW by 2027. The main markets will be Germany, Spain, Italy, Denmark, Portugal and France.

On average, the application of repowering has led wind projects to reduce their number of wind turbines by about 30%, but to improve their production capacity by about 130%, and there are a number of other benefits such as reduced noise pollution and reduced deforestation for new turbines.

2.4The Benefits of Repowering and The Need for its Implementation

Among the main benefits of the concept of repowering, applied to existing wind farms, are the following is very important: reducing wind energy costs;

Repowering wind in the post-2020 period is a clear opportunity to modernize the European wind fleet with the latest available technology. The provision of measures and regulatory frameworks for repowering will unlock further cost reductions in wind generation by 2030 and achieve the EU's decarbonization goals at least cost to society by:

- integrating wind energy resources into the national and regional electricity grid;
- improving social acceptance and benefits for local communities;
- providing lower energy prices for consumers;
- sustainable waste solutions;
- reduced waste generation, as 90% of the components of a turbine are recyclable; in addition, no new construction and demolition waste will be generated for existing or new turbines.

2.5 Wind Analysis and Partial Repowering Concept Applied to the Fântânele-Cogealac Project

Rising energy demand and climate change have forced rapid decisions and the development of efficient solutions. One of the solutions may be repowering and significant changes in transmission systems to deliver it through the electricity grid.

It will be analyzed the largest existing onshore wind farm in Romania, the Fântânele-Cogealac wind farm. This wind farm has been in existence since 2012, so, in at least 10 years, the farm will be assigned improvements. Repowering is the best way to improve wind turbine technology. From this perspective, the current wind power generated by the 240 turbines, each wind turbine has a capacity of 2,5 MW, was analyzed. Reanalysis data for 20 years, provided by ERA5 data, were compared to *in situ* data for this time span.

The objective of this study is to demonstrate the project management concepts of repowering systems after the 20-25 year life cycle of a wind farm. Repowering Strategic Project Management (RSPM) to extend the lifetime of a wind farm will be analyzed [17].

The study area is Fântânele-Cogealac, the largest wind farm in Romania, located in Dobruja, Romania, at latitude 44°36′54″N and longitude 28°34′34″E (Figure 2.2); it is only 17 kilometers from the Black Sea coast, with 240 operational units, with an output of 2.5 MW and a total installed capacity of 600 MW.

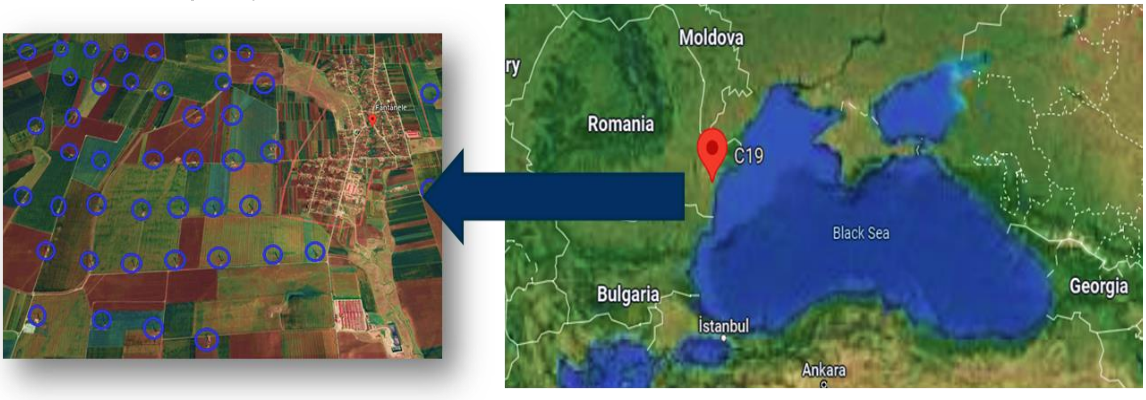

Figure 2.2 Structure of the Fântânele-Cogealac wind farm [18]

The wind farm has been in existence since 2012, so in at least 10 years it is necessary to modernize the existing wind turbines. The CEZ wind farm's output in 2019 was 1,185 GW/h, higher than in 2018 by 80 GW/h. The ideal wind speed for a wind turbine is~14 m/s. It has been calculated how much power can be added just by replacing new generations of wind blades. This improvement is possible because the new blades are much larger and are theoretically able to capture more wind energy. Repowering can increase the net power generated by a wind turbine by more than 20%.

In the Fântânele-Cogealac area, the prevailing wind blows from the north in the coastal area and from the northwest in the continental area. The wind direction in the northern sector accounts for 40.3% of the annual total. The highest mean annual wind speeds of 7.4 m/s for the north, 6.7 m/s for the NE and 4.7 m /s for the NW are also recorded in these directions [9]. The NE winds have the highest mean wind speed in November and the NE winds have the highest mean wind speed in the three winter months. During the year, the mean wind speed and calm duration periods have a cyclic evolution. The multi-year average monthly mean speed has a maximum in February of 6.75 m/s and a minimum in July of 5.10 m /s. In August are the calmest days, 15.8% of the total, and in February and December 8.4%, it is~ 56 hours and 62 hours respectively. The frequency of storms lasting more than 12 hours per year ranges from 16 in 1990 to 37 in 1983, with an annual average of 29. The same directions also record the longest average wind durations. From the NE direction, 33 hours, 31 hours from the N, the maximum duration of 138 hours with wind speed greater than 10 m/s between February 16-22, 1979. The mean wind speed per month in 2005 at 10 m was 4.7 m/s, class 2 power density. This means a wind power density of 100-150 W/m^2. The reanalysis data gives a result for the average wind speed of 5.86 m/s at 100 m for the period 2000-2020.

The farm's best production months for gross electricity production were recorded in January 2019, February 2018 and December 2017. In 2019, the Fântânele-Cogealac wind farm completed the misalignment degree at 40% of the number of turbines. Modular desalination produces a bending moment on each of the coupled shafts. A single turbine will be able to produce 13 MW of power, enough to light a city of about 12,000 houses. ERA5 data was used for comparison. The *European Centre for Medium-Range Weather Forecasts* (ECMWF) covers various reported atmospheric parameters (land, land surface and sea areas). Repowering has proven to be a good land-based solution for increasing energy production while reducing the number of wind turbines [19]. In the case study, a partial *"repowering"* system will be applied to the existing turbines by replacing new blades covering a larger diameter. Based on the results obtained from the reanalysis data for 20 years, an average annual wind value of 6.13 m/s in 2017, in 2001 and 2015 the following values 6.08 m/s and 6.00 m/s are found. The highest values were recorded in December 2018, reaching a maximum of 21.44 m/s.

The amount of energy that a wind turbine can utilize from the wind depends mainly on three factors: wind speed, air density and the area of the circle created by the blades [17]. Therefore, the power coefficient for existing turbines has to be taken into account in the equation, and the power from the wind is given by the following equation [20]:

$$P = \frac{1}{2}\rho A V^3 Cp \tag{2.4}$$

ρ - air density (1.123 kg/m³), A - area covered by turbine blades;

$$A = \pi r^2 \tag{2.5}$$

V= 5.86 m/s, Cp= 0.43, r - turbine radius.

The turbine power coefficient, *Cp*, provides an estimate of how much power the turbine can extract from the wind [12]. The actual blade length for the wind turbine is 47 m. A longer turbine blade length means that the turbine can capture more energy from the wind. Applying the concept of partial repowering to existing turbines can increase energy production with 39%. For two decades, the power coefficient of wind turbines has been in the 23-35% range. However, the average power coefficient for Europe over the last five years is below 21% [21].

Wind power density (WPD) is a parameter that can reflect the particularity of wind potential in terms of seasonal, diurnal/nocturnal or directional variations [22]. Most studies indicate values for power coefficient in the range of 19-60%, more commonly between 20% and 40% [23]. The global average power coefficient for new turbines has increased from 27% in 2010 to 34% in 2018. The resulting power coefficient values in the present work can reach the highest value of 31.06%. From the wind power density (WPD) calculation the wind classes will be determined in the Table 2.1. There are 3 wind classes, starting with class 1 and ending with class 4, recorded in 2017 [24]. The maximum power coefficient value used is 0.593. Currently, no wind turbine can convert more than 59.3% of the wind kinetic energy into mechanical energy according to the Betz limit.

Table 2.1. *Wind power density, capacity factor and electric power of wind turbines determined from wind reanalysis data over the time interval 2000-2020* [25]

Period	**Wind speed (m/s)**	**WPD (w/m²)**	***Cp* (MW)**	***Cp* (%)**	**Electrical power MW/year**
2015	6,004	211	0,711	28,44	6228,36
2016	5,869	206	0,696	27,85	6099,15
2017	6,133	230	0,776	31,06	6802,14
2018	5,745	198	0,667	26,69	5845,11
2019	5,716	176	0,594	23,76	5203,44

2.6 Conclusions

The concept of repowering has proven to be a very good onshore solution for increasing electricity production while reducing the number of wind turbines and maintenance costs.

In my research, the hourly wind variation is also crucial. For example, in the analyzed case, an increase of up to 20% can be observed between 20:00 and 17:00. Also, better values were obtained starting in October and ending in December.

By applying the concept of partial repowering to existing turbines, an increase in energy production of 39% can be achieved. For this applied partial repowering concept at the Fântânele-Cogealac wind farm, a turbine with very long blades and very low rated electronics can be chosen to generate maximum rated power when there is a higher wind speed and thus would result in a higher power coefficient.

The resulting power coefficient in the present work can reach the highest value of 31.06%, according to the reanalysis data for the average values, at the Fântânele-Cogealac wind farm. Another solution can be the total repowering for the Fântânele-Cogealac wind farm, by implementing new more efficient turbines, such as General Electric, a new GE Haliade-X 13MW prototype GE Haliade-X 13MW, with 220 m blade diameter, could increase the maximum power output with 19%. Another valuable resource in wind turbine dismantling can be recycling and reuse in the circular economy, 85-90% of the dismantled wind turbine can be recycled. And the remaining space can be used for agricultural activities or the company can invest and export renewable electricity. According to the global climate change model, the percentage increase in annual average wind speeds will increase and range from 20% to 80% on a global scale.

Chapter III. Renewable Energy in the European Context and in Romania

3.1 Renewable Energy in a Global and European Context. Main Features and Objectives of the European Green Deal

The European Union, the European Green Pact commits member states to a clean and circular economy; according to the Global Wind Report 2022, the wind industry enjoyed its second-best year on record, with growth in 2021 up just 1.8% on the previous year. Some 94 GW of capacity was added to the power system, despite the second pandemic year caused by the COVID-19 virus. The 93.6 GW of new installations in 2021 brings the global wind power capacity to 837 GW, an annual increase of 12%. The EU's plan to become the first carbon-neutral continent by 2050 was endorsed by the European Council at the end of 2019 by all Member States, except Poland [26].

EU legislation to promote renewable energy sources has evolved significantly over the last 15 years. In 2009, EU leaders set a target of 20% of EU energy consumption to come from renewable energy sources by 2020. In 2018, a target of 32% of EU energy consumption to come from renewable energy sources by 2030 was agreed. In July 2021, in light of the EU's new climate ambitions, a revision of the target to 40% by 2030 was proposed for legislative consideration. In 2014, the REmap 2030 - Roadmap for doubling the share of renewable energy by 2030 was launched. The total electricity consumption registered in Romania was 56,222,860 MW in 2022 [27].

More than 200 GW of wind power has been installed in the EU, including 16 GW *offshore*. These installations supplied 16% of the EU's electricity generation in 2022. Other targets under the European Green Deal are:

- 40% energy production from renewable energy sources. The proposals promote the uptake of renewable fuels, such as hydrogen in industry and transport, with additional targets, but also reduce energy consumption, which is essential to lower both emissions and energy costs for consumers and industry;
- 36-39% energy efficiency by 2030 for final and primary energy consumption;
- renovating around 35 million buildings;
- cutting car emissions by 55% by 2030;
- 50% cut in emissions from vans by 2030;
- 0 emissions from new cars by 2035.

As part of the European Green Pact, the European Commission proposed, in September 2020, to raise the 2030 greenhouse gas emission reduction target to at least 55% below 1990 levels.

3.2 Renewable Energies and the Romanian Energy System

In 2020, Romania reached its target of 24% of total energy consumption from renewable energy sources. For 2030, the new target set by the Romanian government is 30.7%, achievable by adding 7 GW of renewable energy capacity. In terms of energy consumption, according to Eurostat data, in 2013, just over 24% of energy consumption came from renewable energy sources, putting Romania in the 10th place in the EU and above the EU average.

The share of renewables in gross final consumption that could be considered when revising the relevant legislation in the light of the *Fit for 55* packages for solar and wind was 4,273 MW for 2021 and 10,309 MW for the baseline scenario of 2030. According to the estimates of the Ministry of Energy of Romania, an increase of 4,656 MW of total solar + wind (including *off-shore)* capacity could be expected, compared to the values assumed in the current version, thus reaching a total renewable energy capacity of more than 22 GW in 2030 (including here also 25 MW geothermal and 85 MW biomass [27].

In 2022, the EU produced 2,641 TWh (terawatt-hour) of electricity. Almost 40% of this came from renewable energy sources.

I note that, in Romania, the share of renewable energy is above the EU average, but it is still dependent on coal for electricity generation, which leads to an energy price more than

50% higher than that of market energy [28]. At the same time, according to an analysis of greenhouse gas emissions in Romania, emissions related to the energy sector category account for about 70% of total national greenhouse gas emissions [29].

According to the monthly statistical bulletin of the National Statistical Institute, No. 5 of 2023, the main primary energy resources recorded in the first quarter of 2023 - May 31, 2023, totaled 13544.5 thousand Tons of Oil Equivalent (TOE), of which 7687.8 thousand TOE from domestic production, down by 0.9% compared to the same period of 2022, for the same quarter. As a result of a 6% decrease in imports, primary energy production increased by 3.4%. Electricity production amounted to 25432 kWh, for the first quarter of 2023, there was an increase of 5.4% compared to the same period of 2022. Final electricity consumption to 20563.

According to data published by the National Institute of Statistics and the National Commission for Strategy and Forecasting, in 2021 there was an increase compared to 2020, accumulating 43.2 million Tons of Oil Equivalent (TOE), both primary production and imports increased by 0.6 million TOE and 1.9 million TOE, respectively. For 2022, a total energy resource level of 42.7 million TOE was recorded, while imports decreased by 0.4 million TOE. Solar energy can be harnessed throughout the country. In the south the potential photovoltaic energy (PVOUT) can reach 3.8 kWh/day. European statistics show that Romania's energy production decreased by 9% from 19,733 MW to 18,000 MW. Since 2019, Romania has become an electricity importer. If investors sustain further investment, Romania is forecast to complete new projects with a capacity of 13,000 MW in 2030, from wind, solar, gas-fired power plants, small modular reactors (SMRs) with NuScale technology. A new project of about 1292 MW is estimated for Galați by 2030, according to the notice of operation and connection contracts issued valid as of January 31, 2023. According to ANRE authority, at the end of 2022 the accredited installed capacity in E-SRE production units was 4700 MW, a decrease compared to 2021, taking into account the electricity capacities for which the validity of the accreditation decision expired.

Figure 3.1 shows the electricity production in 2022 from all currently available energy extraction sources.

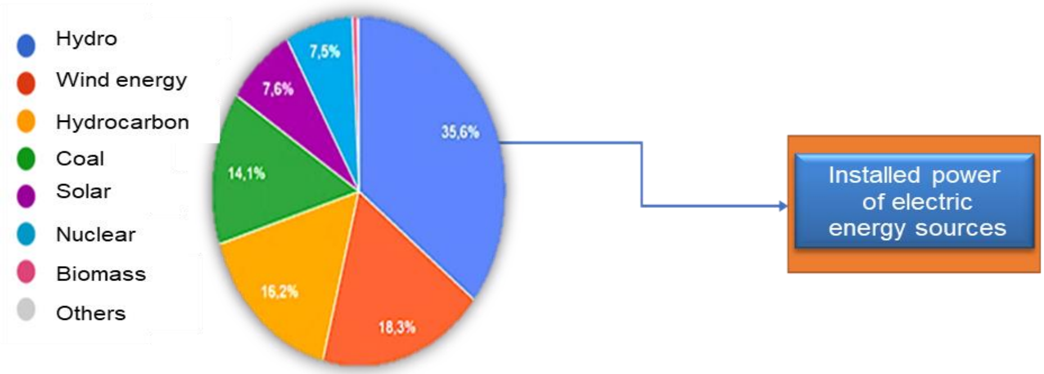

Figure 3.1. Installed production in electricity generated capacities in real time by ANRE on January 2, 2023 [30].

Analyzing the evolution of the components of the energy balance, in 2022, there were decreases in net domestic consumption and net energy production by 8% and 6%, respectively, compared to the same period of the previous year. The highest recorded consumption is in the winter months: December and January. For example, for the year 2022, 8658 MWh/h was recorded in January. Compared to 2020, there were also decreases by 4% and 1% respectively. Cross-border export exchanges in 2022 showed an increase of 51% compared to 2021, (44% compared to 2020) and cross-border import flows showed an increase of 16% (2% compared to 2020).

3.3 Physico-geographical Characteristics of the Southeastern Part of Romania

The municipality of Galați is located in the south-east of the country, between 45º25' and 46º10' north latitude, 27º20' and 28º10' east longitude, it borders to the north with Vaslui and Vrancea counties, to the south with Brăila and Tulcea counties, to the east with the Republic of Moldova, and to the west with Vrancea county [31]. It is located at a distance of 240 km from the capital of Romania, Bucharest, according to the information provided by the Romanian Road Map. The geographical position of the county on the internal plan is projected on the ancient land of Moldavia, bordering Dobrogea and Muntenia. The climate is temperate-continental.

The municipality of Galați, is included in the network of municipalities as a first-rank municipality was based on the fact that it has a population of 667629, according to the census of July 1, 2021, diversified universities and higher education institutions and a rich cultural life. The municipality can develop international trade relations, thanks to its location about 11 km from the Giurgiulești customs point and 57 km from the Oancea customs point, which connect with the Republic of Moldova, and 88 km from the Ismail customs point, which connects with Ukraine. Galați is the administrative capital of Galați County and the main economic, political, administrative and cultural center of the county. The physio-geographical characteristics of the area are as follows: the average annual temperature, calculated over a period of 70 years, is 10 degrees Celsius, the average summer temperature is 21.3 ºC. The climate in the area is temperate-continental. In winter, cold air masses come over Galați county from the north and north-east, producing temperature drops, ranging from 0.2ºC to 3 ºC. The average monthly temperature is lowest in January, when it reaches -3ºC to 4ºC. The average temperature in July is 21.7 ºC.

During the year there are approx. 210 days with temperatures above 10 ºC. The predominant wind is the ,,*Crivăț''*, which accounts for 29% of the annual wind frequency. The second predominant wind is the rather dry south wind Austral, with a frequency of 16% and blowing more in summer.

According to Figure 3.2 for the analysis from January 30, 2023 to February 13, 2023, we observed a minimum temperature not exceeding -7ºC and a maximum of 6ºC, with more frequent values between 0 ºC and -4ºC. The wind speed is quite high, with extremes above 40 km/h being recorded, with the most frequent values falling between 10-35 km/h.

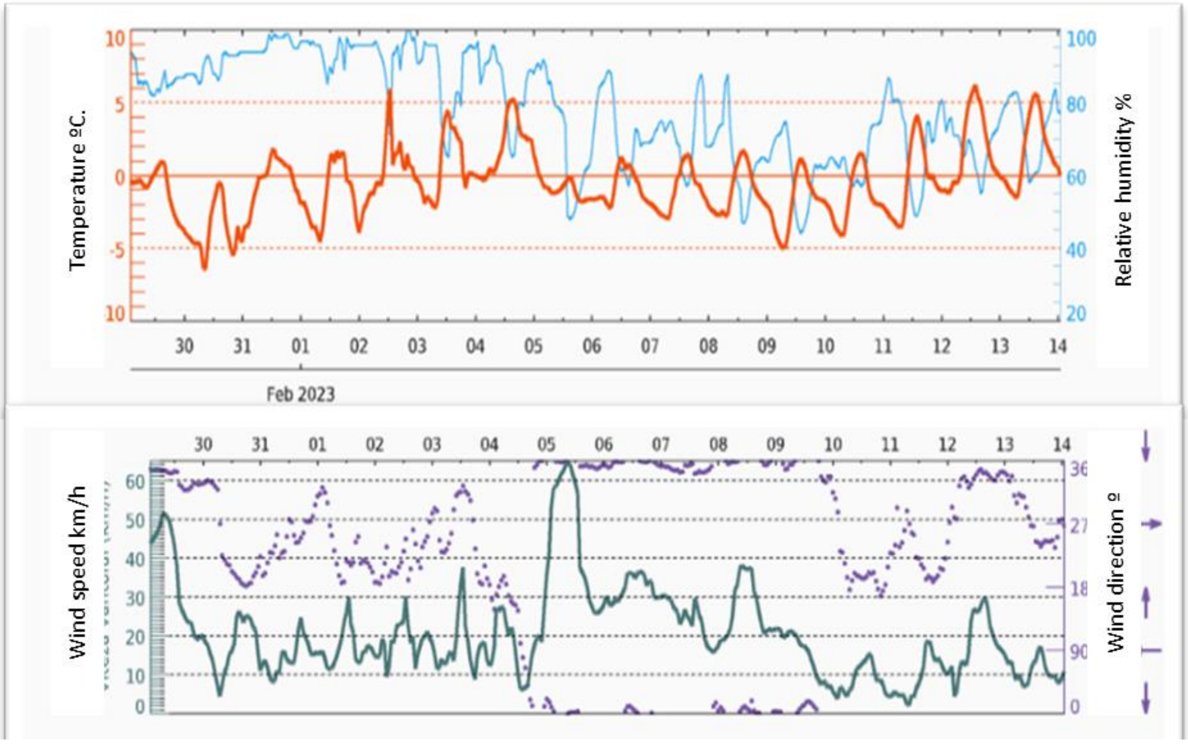

Figure 3.2. Temperature and wind speed in the city of Galați for a 2-week period in winter, January 30 - February 13, 2023 [12].

The installed capacity in Galați in 2020 was 580,881 MW. Average energy production in 2018 was 1,701 GWh. Average energy consumption in 2018 was 1848 GWh. According to the institution of Electric Energy Distribution Romania, 752,188.751 MWh of electricity was distributed in the county of Galați, to a number of 247,251 consumers.

The electricity supply in the city of Galați is carried out by the National Energy System through Smârdan (400/220 kV) and Barboși (220/110 kV) system stations, 6 110 kV stations are connected to the 110 kV lines of these stations, which are connected to the 110 kV substations of Galați. The company in charge of electricity distribution in the municipality of Galați is S.C. Eletrica Furnizare S.A. - Galați Electricity Distribution Branch.

3.4 Characterization of Renewable Energy Sources in Romanian Coastal Areas

The intermittent nature of renewable energy sources provides a major challenge for the use of renewable energy sources such as wind, solar, even wave energy [32].

The huge amount of energy received from the sun in the form of light and heat causes heating of land, seawater and the earth's atmosphere, with differences in temperature, humidity and pressure leading to air currents. It is estimated that globally 2.5% harvesting of solar energy (1.2 billion kWh/s) is converted into wind energy.

In Romania, the climate is favorable for both solar and wind energy. The map in Figure 3.3 shows a map of wind energy resources, annual average wind speed data at 80 m above the ground and at a spatial resolution of 5 km based on measurements over the last 10 years created by 3TIER for Megajoule. In high mountainous areas the average wind speed is above 5 m/s and 7 m/s in the Black Sea and coastal areas the average wind speed is 7 m/s.

Romania's wind energy market capacity in terms of installed capacity is expected to grow from 3.33 GW in 2024 to 4.12 GW by 2029, at a CAGR of 4.35% during the forecast period (2024-2029). According to the Energy Institute Statistical Review of World Energy 2023, wind power generated about 12.56% of Romania's electricity, ranking second among renewable energy sources after hydropower. According to statistics from the International Renewable Energy Agency (IRENA), the installed capacity of *onshore* wind power in Romania reached 3015 MW in 2022 [33].

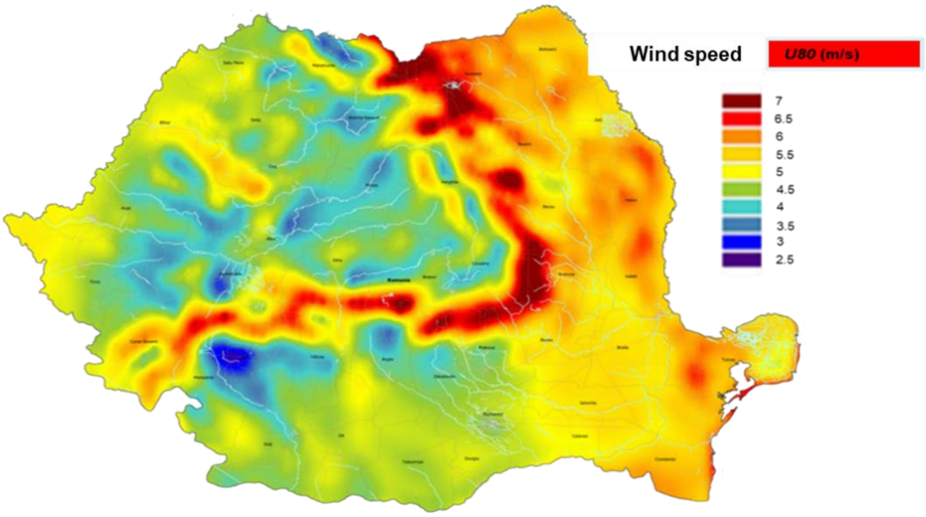

Figure 3.3. Wind energy resources map of Romania in 2014 [7]

The study identifies two potential clusters with the most favorable conditions for a first-stage *offshore* wind development, based on fixed turbines: one with capacity factors between 33-35%, at water depths below 50 m, at 40-60 km offshore - an area that strikes the right balance between wind resources and the costs of the required *offshore* grid, given the possibility of output injection into the Constanța Sud power station and the proximity to the Port of Constanța [34].

At the sea, the wind is stronger than onshore, so *offshore* wind farms, i.e. those located at sea or immediately close to shore, will produce more power per unit area than onshore wind farms.

Due to its geographical position on the seashore, the Dobrogea area has the highest potential for wind energy production in Romania. The region is home to one of the most important wind power plants in Romania, built in 2011 by Petrom in Dorobanțu, a town about 39 km north-west of Constanța. The wind farm has 15 turbines with a total installed capacity of 45 MW. By the end of 2012, the company expects to reach a net annual production of almost 144,000 MWh.

A major private investment in renewable energy in Romania has been implemented about 50 km from Constanta; in November 2012, the largest coastal wind farm in Europe, located at Fântânele-Cogealac, became operational. The €1.1 billion project was developed by CEZ, a major energy producer and supplier in Central and Eastern Europe. The wind farm has an installed capacity of 600 MW. It has 240 turbines with an installed capacity of 2.5 MW each. The coastal wind farm can provide energy for one million households annually.

The analyzed data show that wind speed increases with distance from shore, with only the central part of the deep-water sector having higher average wind speeds (close to 7 m/s). A large part of Romania's Exclusive Economic Zone (EEZ) consists of an area of deep water (>50 m), more suitable for floating platforms. However, several *offshore* wind farms in Europe have recently been built about 60 km offshore, a distance that is right in Romania's transition zone from shallow to deep water.

3.5 Conclusions

Based on the evaluation and interpretation of the recorded data, the wind energy potential in Romania is most favorable on the Black Sea coast, in the mountainous areas and foothills of Moldova or Dobrogea. The coastal area of the Romanian littoral is exposed to winds, which contribute to both wind and wave energy. Due to its calm regime, compared to other geographical areas of the globe, the value of the gross energy potential of the waves around the Romanian coastline is relatively low. Although from the wave energy point of view, the Black Sea cannot be considered as having a high potential, especially in comparison with ocean coasts, in terms of wind energy resources, the potential of this coastal environment is in line with other coastal areas where such offshore wind farms are already successfully operating [35].The city of Galați looks set to become the next ,,Hydrogen Valley" and a pole of greensteel investment in renewable energy, as well as the infrastructure needed to realize these goals. "Galați - Green Valley", could be one of the "greenest" investments in the European Union [11]. Is planned to be builded a hydrogen plant in Galați on the platform of the Steelworks, an investment for the future. It is a complex project that means economic development, innovation, new jobs and a cleaner environment.

Chapter IV
Climatological Studies on the Evolution of Europe's Wind Resources

4.1 Meteorological Analysis of Wind Resources

For this analysis, 17 locations in Europe, shown in Figure 4.1 and Table 4.1, both offshore and onshore areas, were selected to point out the effects of climate change according to RCP (Representative Concentration Pathways) data. Were evaluated RCP’s in different parts of Europe and the influence on wind energy potential. The pathways describe different climate change scenarios, all of which were considered possible depending on the amount of greenhouse gases (GHG) emitted in the years to come. For RCP4.5, range of global mean temperature increase with 2.5 to 3 ºC and for RCP8.5 with 5 ºC till 2100.

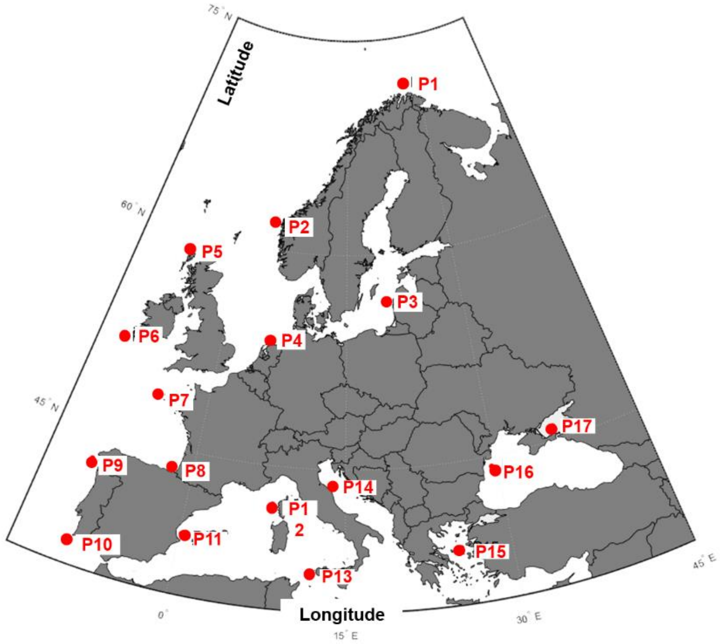

Figure 4.1. Map of Europe, landmarks and analyzed location

Table 4.1 *Geographical position of the 17 points in Europe*

Nr. points	Latitude (º)	Longitude (º)	Location name	Water depth (m)	Distance shore (km)
P1	71.85	27.60	Scandinavia	330	83
P2	61.95	4.06	Norway	237	46
P3	56.76	20.24	Baltic Sea	96	53
P4	53.81	5.45	North Sea	18	47
P5	58.65	-7.04	United Kingdom	122	40
P6	51.56	-11.34	Ireland	245	75
P7	48.355	-5.47	France	76	50
P8	43.66	-2.19	Spain	482	42
P9	42.59	-9.68	Spain-Atlantic	1632	49
P10	36.70	-9.54	Portugal	1798	65
P11	39.27	0.21	Spain - Mediterranean Sea	588	40
P12	42.32	8.08	Corsica	2739	42
P13	37.75	11.84	Sicily	248	51
P14	43.83	13.61	Ancona	56	30
P15	39.00	25.44	Turkey - Mediterranean Sea	253	43
P16	44.28	29.49	Romania	63	58
P17	45.96	36.41	Sea of Azov	12	57

The analysis will also use future climate simulation data on wind speed from the MERRA-2 database, at 10 m height, for a 7-year interval and at 100 m height, for a 95-year interval for different times of the year. These points cover coastal areas of Europe, for example P3 is located in the Baltic Sea, an important area for future *offshore* wind developments. Point P14, Ancona, is located near Rimini, where a major *offshore* wind project is to be developed.

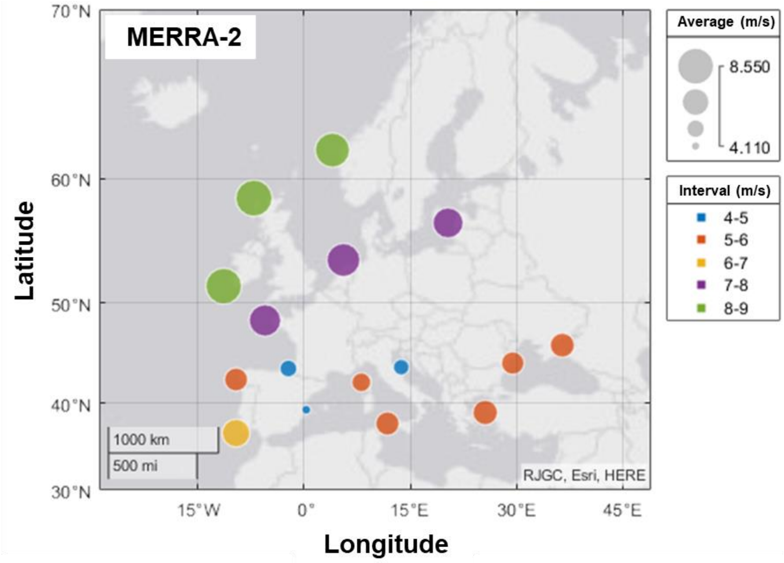

Figure 4.2. MERRA-2 (*U10)* mean values for the time interval January 2006 - December 2022

Figure 4.2 shows the mean values of the parameter *U10*, which are in the range of 4.11 m/s and 8.55 m/s. Most values are located in the range 5-6 m/s (in the south), while higher wind speeds are associated with points in the north. According to the MERRA-2 data, for the time period January 2006-December 2022, with green are recorded the highest values in the northern part of Europe, values between 8-9 m/s, while the lowest are represented with blue, with values of 4-5 m/s, in some regions of Spain and Italy.

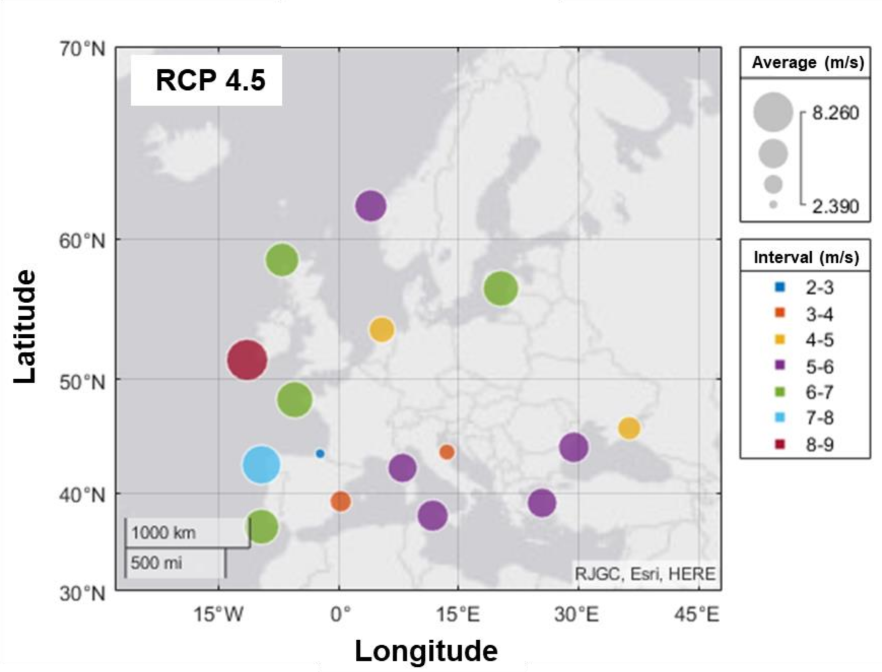

Figure 4.3. Mean RCP 4.5 (*U10)* values, for the time interval January 2006-December 2022.

Figures 4.3 and 4.4 show the average values associated with RCP 4.5 (*U10)* and RCP8.5 data indicated, for the time interval January 2006-December 2022, with most of the selected points showing values between 6-8 m/s.

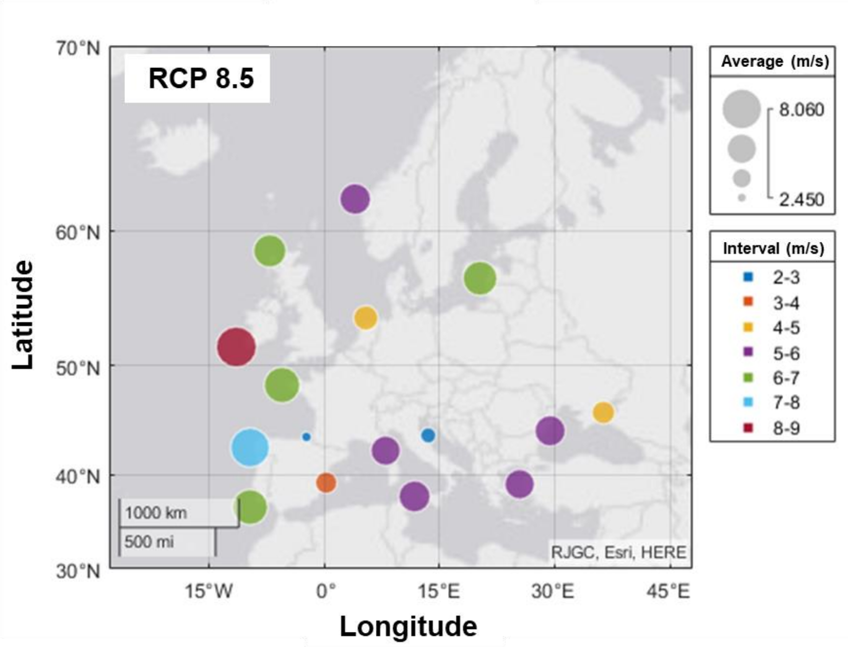

Figure 4.4. Average RCP 8.5 (*U10)* values for the time interval January 2006-December 2022.

MERRA-2 is a more robust database, so RCP data were compared to values extracted from the MERRA-2 database [36]. Figure 4.5 presents direct comparisons between MERRA-2 and CPR data, for the parameter *U10*. Results specific to the time interval 2006-2022, show that negative values are associated with an underestimation, and for plus values, they are associated with an overestimation of the CPR data compared to MERRA-2. The differences are expressed in percentages and as can be seen, the RCP4.5 data do not differ greatly from the RCP8.5 data.

Since there can be differences of up to 50%, each point in each database was adjusted by a coefficient. Most are negative, meaning that the RCP data are smaller than the MERRA-2 data. If a particular point had a difference of 0.5, its time series was adjusted by 1.5 to compensate for this variation. The following results will be obtained using this adjusted data.

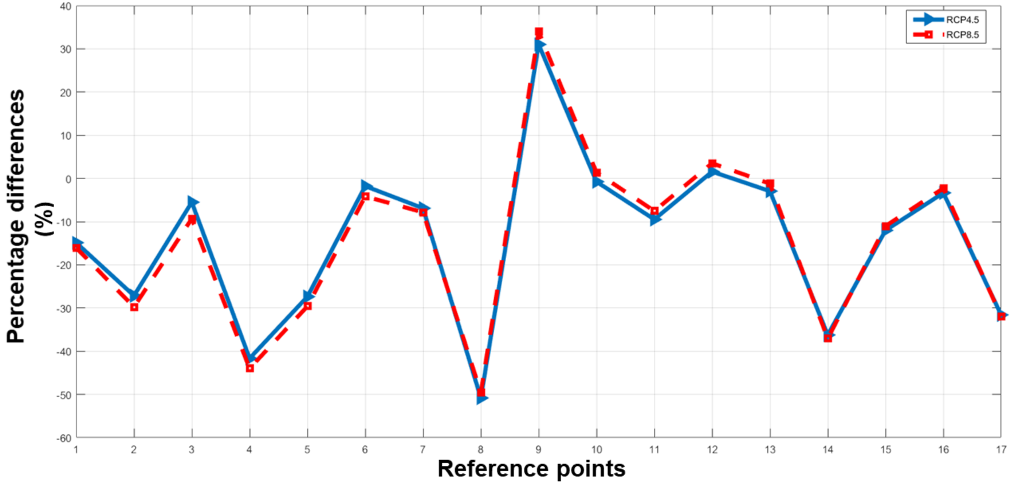

Figure 4.5. Direct comparisons between MERRA-2 data and RCP data, indicated for parameter *U10*. Results specific to the 2006-2022 time range, where negative values are associated with an underestimation of the RCP data compared to MERRA-2.

For the present study, RCP4.5 and RCP8.5 were selected because they are associated with the most relevant scenarios. Differences were calculated for one historical period only (2006-2022), using the formula below [37]:

$$\mathrm{PFC} = \left(\frac{\mathrm{Urcp} - \mathrm{UMerra-2}}{\mathrm{Urcp}}\right) * 100\ (\%) \tag{4.1}$$

where, U_{RCP} - wind speed associated with RCP data, $_{\mathrm{UMerra\text{-}2}}$ - wind speed associated with MERRA-2 data.

The results show different changes in wind productivity under each scenario. The values can be positive and others negative. For the positive ones, it means that the RCP data are higher than MERRA-2, and for the negative ones the RCP values are lower. Next, Figures 4.6 and 4.7 illustrate the evolution of parameter *U10* for points P2, P6, P9 and P14, the time series being specific to the interval 2006-2100.

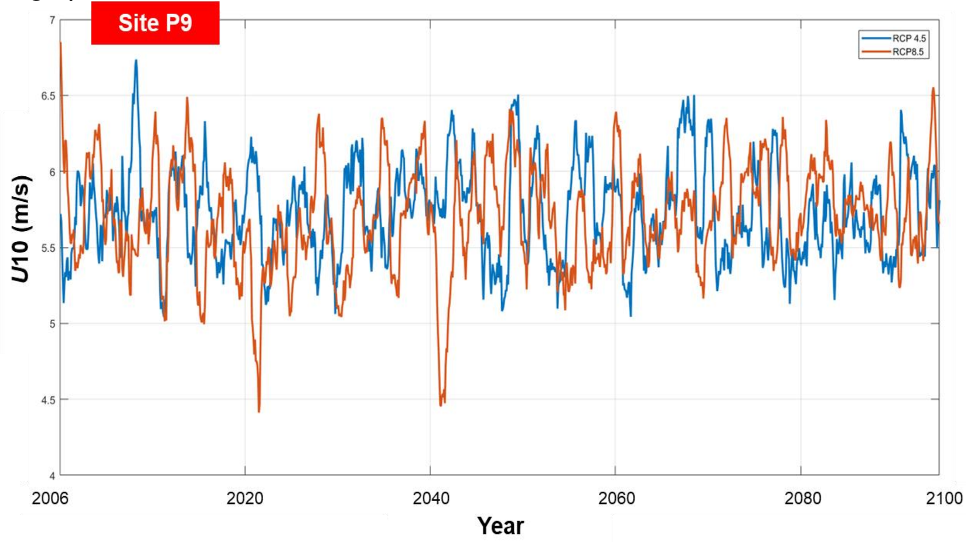

Figure 4.6. Annual mean values (*U10)* indicated by RCP 4.5 and 8.5 data for reference point P9 (Spain-Atlantic), considering the time interval 2006-2100.

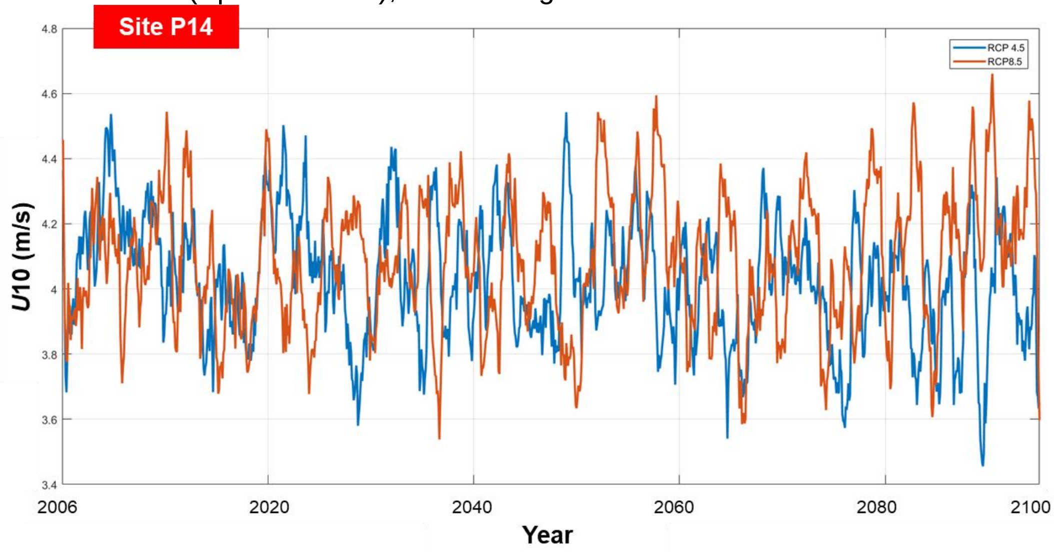

Figure 4.7. Annual mean values (*U10)* as indicated by RCP 4.5 and 8.5 data, for reference point P14 (Ancona), considering the time interval 2006-2100.

For point P9, in north-western Spain, RCP8.5 values show steeper decreases between 2021 and 2042, after which the values normalize. For the RCP4.5 data, the values are more constant in this time period, but with an increasing trend.

Point 14 (Ancona) is located in the north-eastern part of Italy, with a steeper increasing trend after 2050 for the RCP8.5 data, and a gradual decrease over the same period, for the RCP4.5 data, with a sharp decrease in 2094.

In the following figures I compare the RCP4.5 and RCP8.5 time data, considering each season, separately.

Figure 4.8 and 4.9 give the mean values of RCP4.5 and RCP8.5, respectively, in spring. Point P2 has a lower wind speed value in the RCP4.5 scenario of 6-7 m/s, while the RCP8.5 scenario gives a value of 7-8 m/s.

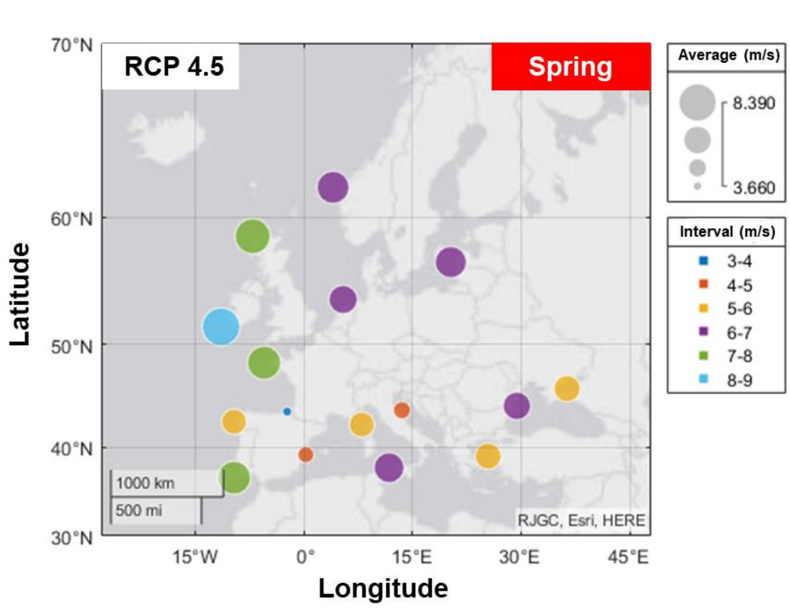

Figure 4.8. Spring - mean RCP 4.5 (*U10)* values indicated for the interval January 2006 - December 2100

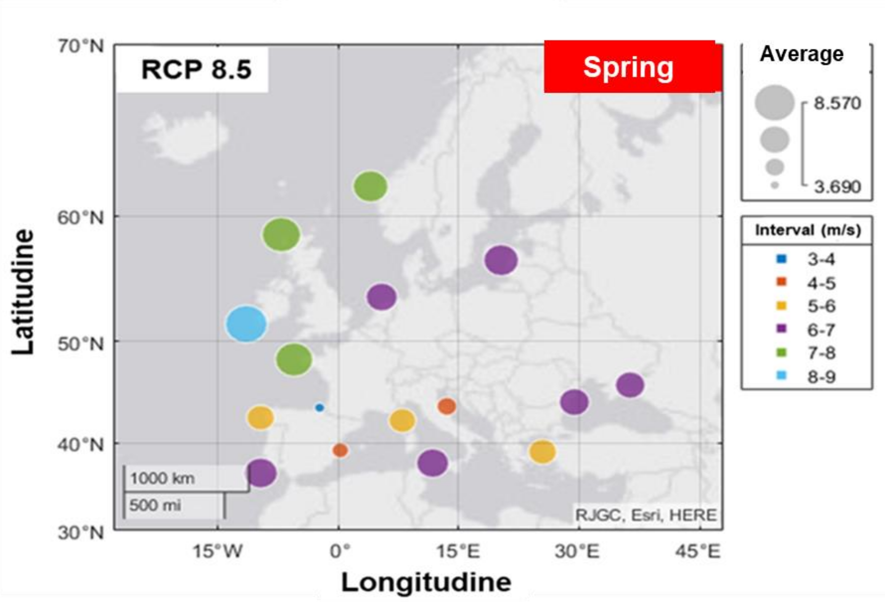

Figure 4.9. Spring - mean RCP 8.5 (*U10)* values indicated for the interval January 2006- December 2100

Figures 4.10 and 4.11 show the mean RCP4.5 and RCP8.5 values, respectively, in summer; point P10 has a lower wind speed value in the RCP8.5 scenario of 7-8 m/s, and a modified value of 8-9 m/s in the RCP4.5 scenario. Another insignificant difference is recorded at point P13 on the map, in the RCP8.5 scenario of 3-4 m/s, and in the RCP4.5 scenario, there is a modified value of 4-5 m/s.

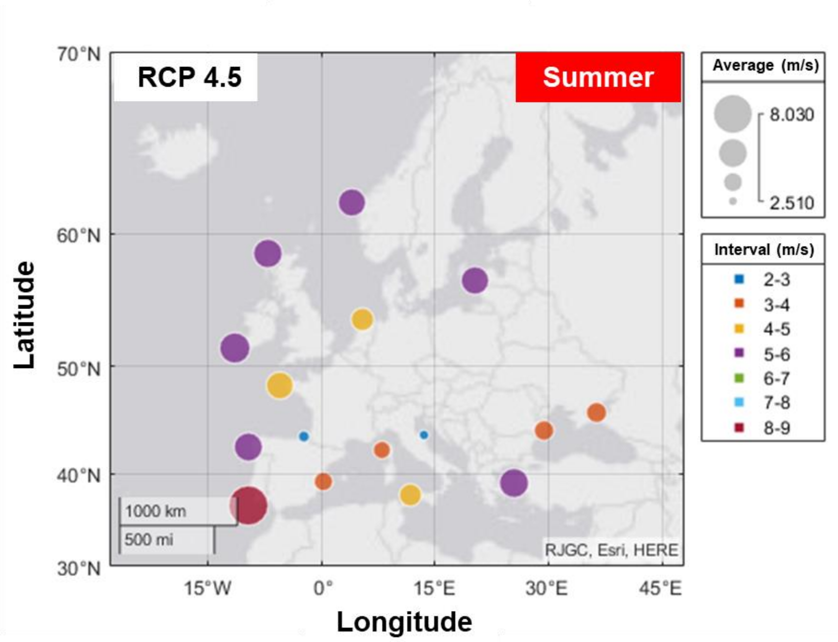

Figure 4.10. Summer - RCP 4.5 (U10) mean values indicated for the interval January 2006 – December 2100

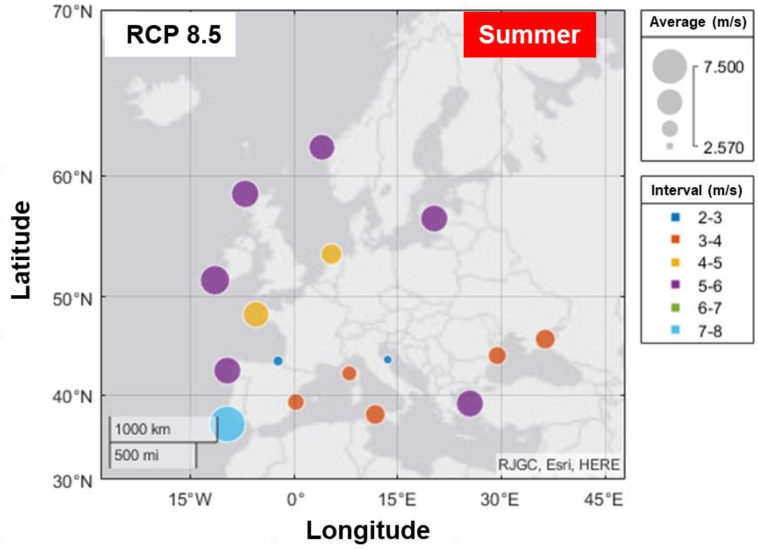

Figure 4.11. Summer - RCP 8.5 (U10) mean values indicated for the interval January 2006 – December 2100.

In Figures 4.12 and 4.13, the mean values of RCP4.5 and RCP8.5, respectively, are plotted in the fall; differences are recorded at points P2, P9 and P10.

Point P2 (Norway) has a higher wind speed value in the RCP8.5 scenario of 8-9 m/s, and a lower wind speed value of 7-8 m/s in the RCP4.5 scenario.

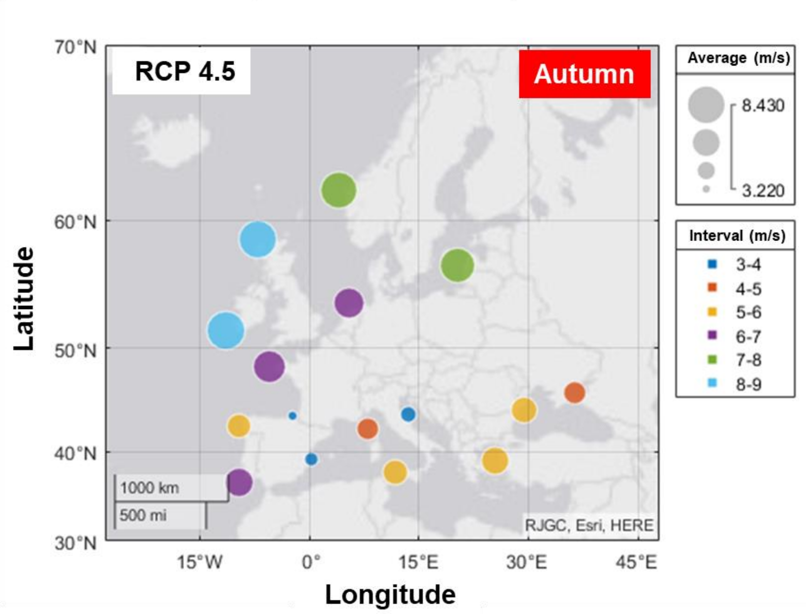

Figure 4.12. Autumn - mean RCP 4.5 (*U10)* values for the interval January 2006 - December 2100.

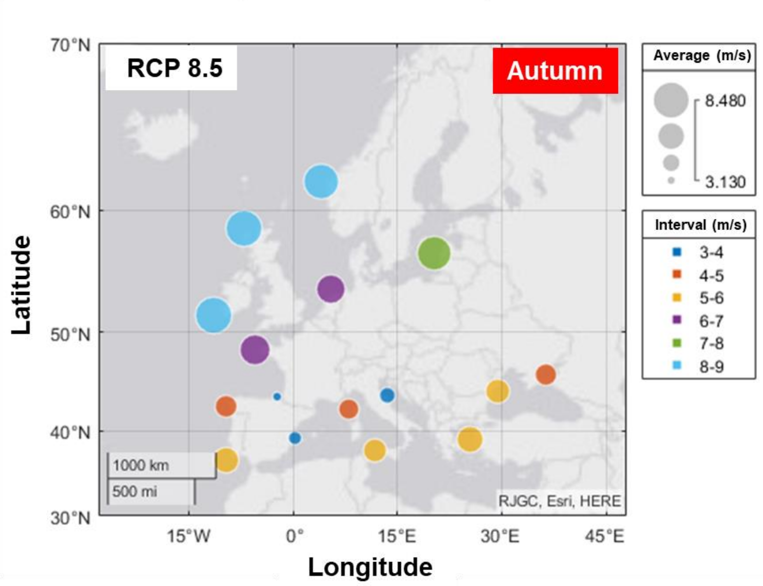

Figure 4.13. Fall - mean RCP 8.5 (*U10)* values, indicated for the interval January 2006 - December 2100.

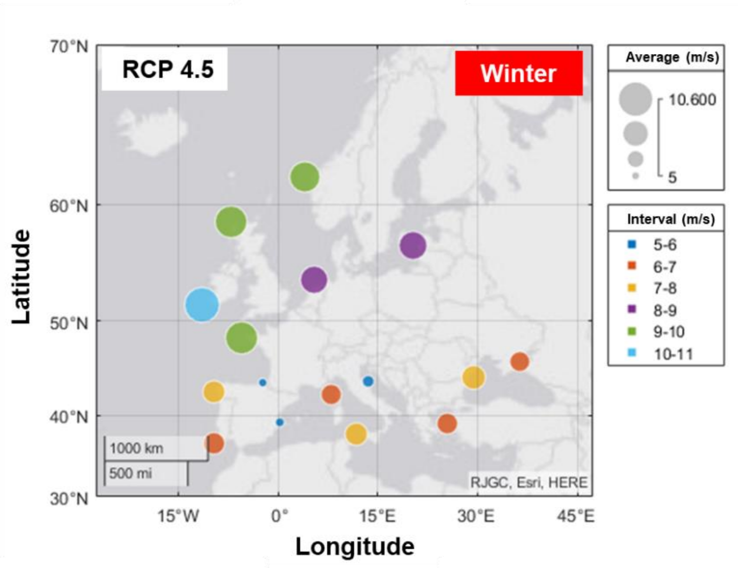

Figure 4.14. Winter - mean values of RCP 4.5 (*U10)* indicated for the interval January 2006 - December 2100

Another difference is recorded at point P9 on the map, in the RCP8.5 scenario there is a decrease compared to the RCP4.5 data, thus, 4-5 m/s is recorded, and in the RCP4.5 scenario it has a higher value of 5-6 m/s.

Figures 4.14 and 4.15 also show the mean values of RCP4.5 and RCP8.5, respectively; in winter, slight differences are found at points P8 and P11.

For point P8 (Spain) for RPC4.5 data there is a value of 4-5 m/s, and for RCP8.5 data, there is a slight decrease 4-5 m/s. For point P11 for RPC4.5, data, there is a value of 5-6 m/s, and for RCP8.5 data there is a slight decrease, as for point P8, of 4-5 m/s.

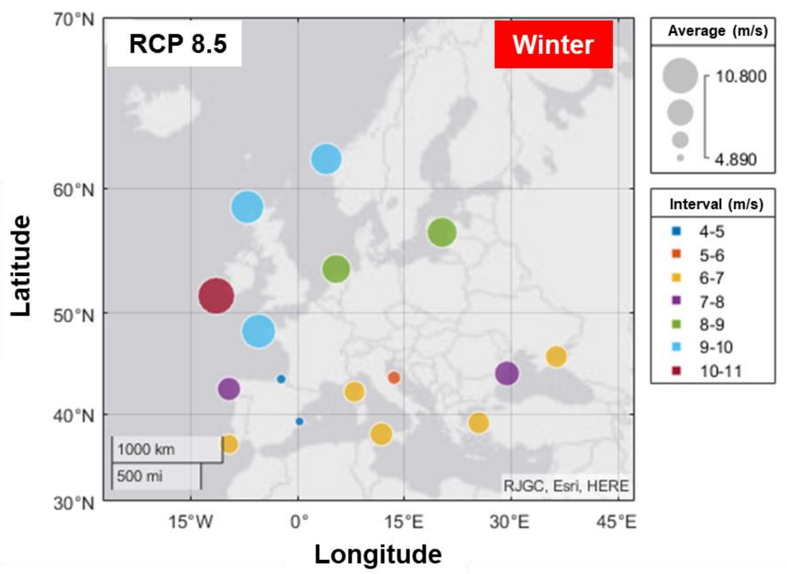

Figure 4.15. Winter - mean values of RCP 8.5 (*U10)* indicated for the interval January 2006-December 2100

4.2 Wind Resource Assessment Using Wind Turbine Specific Parameters

RCP wind data will be considered to assess the wind resource dynamics for the time interval January 2006-December 2100. It was considered useful to process wind fields at available heights of 160.2 m (denoted as *U160*.2), as this is the tower height at which most wind farms currently operate.

Another objective of the present work is to estimate the performance of some *offshore* wind turbines that are expected to be implemented in future projects.

In Table 4.1, the parameters of the studied turbine are specified. The RCP data was reported at a height of 10 m, so far wind has been analyzed in this way with *U10*. But this turbine operates at a height of 160.2 m, and for this height the equations below were used.

The wind speed at 10 m will be adjusted according to the height of the wind turbine *U160.2* m, as follows [38]:

$$\mathrm{Uturbine} = U160{,}2\ \cdot \ln\left(\frac{\mathrm{z_{turbine}}}{\mathrm{z_0}}\right) / \ln\left(\frac{\mathrm{z_{160,2}}}{\mathrm{z_0}}\right) \tag{4.2}$$

where Uturbină - wind speed at 160,2 m, $z_{160,2}$ - initial height (160,2 m in this case), $z_{turbine}$ - initial and adjusted height (160,2 m in this case).

The turbine power will be adjusted. The initial wind speed (*U160*.2) will be calculated [39]

$$\mathrm{Pturbine} = \int_{cut-in}^{cut-out} f(u)P(u)du \tag{4.3}$$

where *f*(u) is the Weibull distribution function; P(u)- the power curve of the wind turbine at coupling and decoupling, the operability limits (see Table 4.1).

The annual electricity production (or AEP) can be obtained by multiplying the power output by the average number of hours per year (8760 hours in this case).

Were calculated the annual energy production (AEP) for a 20 MW turbine with both RCP4.5 and RCP8.5 data for the time interval 2006-2100.

***Table 4.1**. Parameters of the studied turbine 20 MW (U160,2)*

Turbine parameters	Their value
Rated power (MW)	20
Starting wind speed (m/s)	3
Nominal wind speed (m/s)	10.7
Decoupling wind speed (m/s)	25
Tower height (m)	160.2
Rotor radius (m)	135
Rotor orientation	downwind

According to the calculations, represented in Figures 4.16 and 4.17, a change is observed for points P2 and P15, where according to the RCP4.5 data they register an increase, namely P2 of 100-120 m/s and P15 80-100 m/s, but according to RCP8.5 data, 80-100 m/s is recorded for P2 and 60-80 m/s for P15.

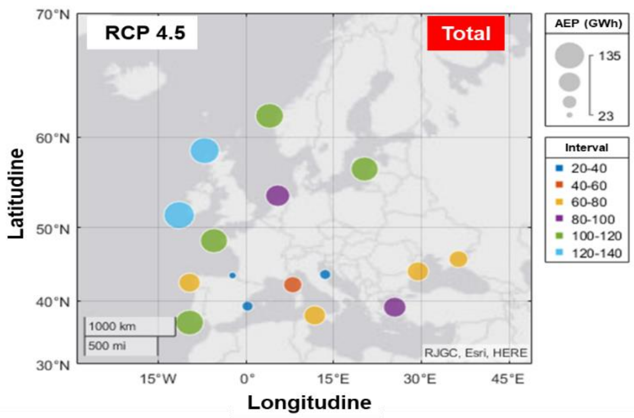

Figure 4.16. AEP values (in GWh) calculated for a 20 MW turbine (U160.2), considering RCP 4.5 data covering the time frame 2006-2100

According to the calculations, a change is observed for points P2 and P15, where according to RCP4.5 data, there is an increase, i.e. P2 at 100-120 m/s and P15 at 80-100 m/s, but according to RCP8.5 data, for P2, there is 80-100 m/s and P15, 60-80 m/s.

Based on equation (4.3), the AEPs (in GWh) of the 20 MW turbine (*U160*.2) were calculated for all seasons, considering all RCP4.5 and RCP8.5 data.

The values specific to the spring season are represented in Figures 4.18 and 4.19; a change is observed at points P7, P10 and P17, where, according to the RCP4.5 data, changes were recorded for Points P7 and P17, namely P7 of 20-30 m/s and P17 of 10-20 m/s, but according to the RCP8.5 data, for Points P7 and P17 an increase is recorded, namely for P7 there are values of 30-40 m/s and P17, 20-30 m/s.

For point P10, more significant values are observed for the RCP4.5 data of 30-40 m/s, whereas AEP for the RCP8.5 data gives 20-30 m/s.

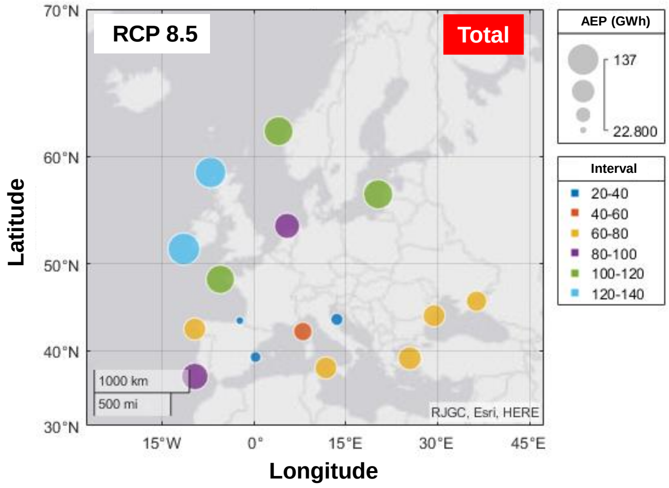

Figure 4.17. AEP values (in GWh) calculated for a 20 MW turbine (*U160*.2), considering RCP 8.5 data covering the time interval 2006-2100

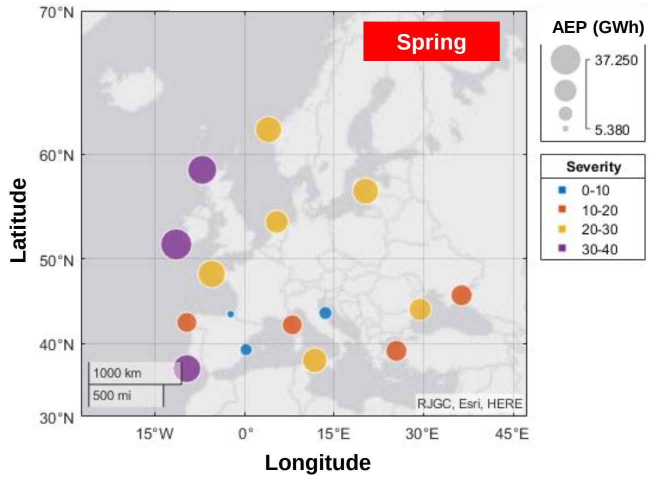

Figure 4.18. Spring - AEP values (in GWh), calculated for a 20 MW turbine (*U160*.2), considering RCP 4.5 data, covering the time interval 2006-2100

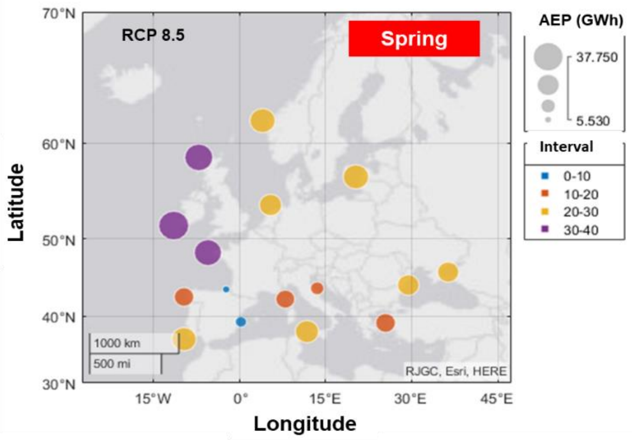

Figure 4.19. Spring - AEP values (in GWh) calculated for a 20 MW turbine (*U160*.2), considering RCP 8.5

data covering the time interval 2006-2100.

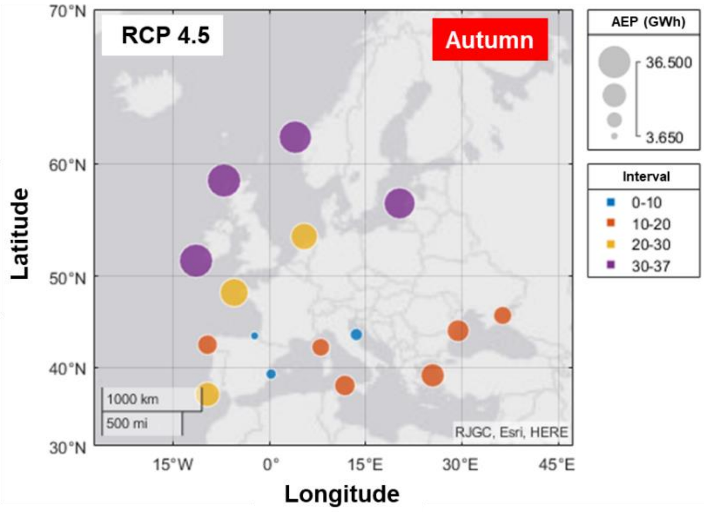

Figure 4.20. Autumn - AEP values (in GWh), calculated for a 20 MW turbine (*U160*.2), considering RCP 4.5 data, covering the time interval 2006-2100

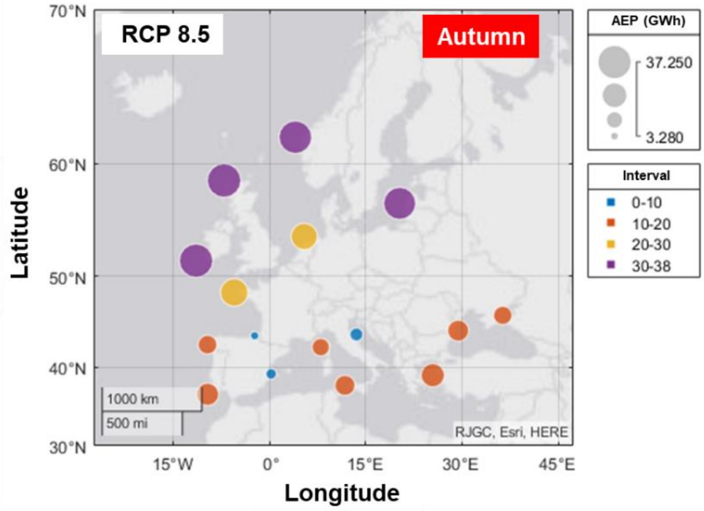

Figure 4.21. Autumn - AEP values (in GWh), calculated for a 20 MW turbine (*U160*.2), considering RCP 8.5 data, covering the time interval 2006-2100

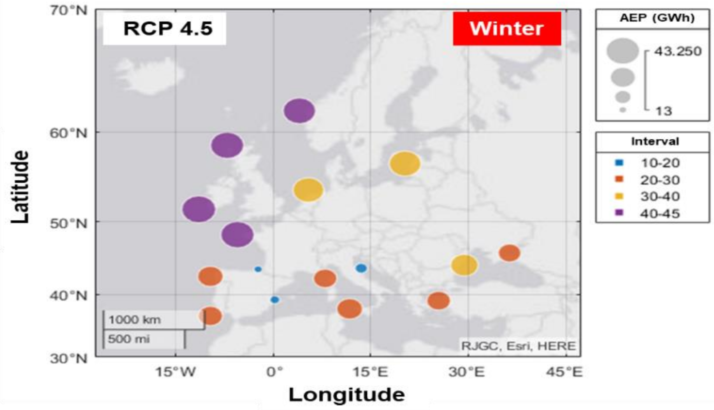

Figure 4.22. Winter - AEP values (in GWh), calculated for a 20 MW turbine (*U160*.2), considering RCP 4.5 data, covering the time interval 2006-2100

The AEP values for the fall season are plotted in Figures 4.20 and 4.21, where a change is observed at Point P10, such that the RCP4.5 data records 20-30 m/s, and the RCP8.5 data records a slight decrease from the RCP4.5 data, which represents values of 10-20 m/s.

The AEP values for the winter season are plotted in Figures 4.22 and 4.23, where a change is observed at Point P3, the RCP4.5 data records 30-40 m/s, and the RCP8.5 data records a slight increase from the RCP4.5 data, with values of 40-45 m/s.

The overall performance of a given turbine can be estimated using the capacity factor index (or Cf), defined as the ratio of the instantaneous turbine power to the rated power of a given wind turbine and can be expressed as [38]:

$$C_f = \frac{P_t}{Pn} \times 100 \quad (\%) \tag{4.4}$$

where C_f - the capacity factor, expressed as a percentage; P_t - the turbine power, associated with a given time interval (in MW); P_n - the rated power output of a given turbine (shown in Table 4.1).

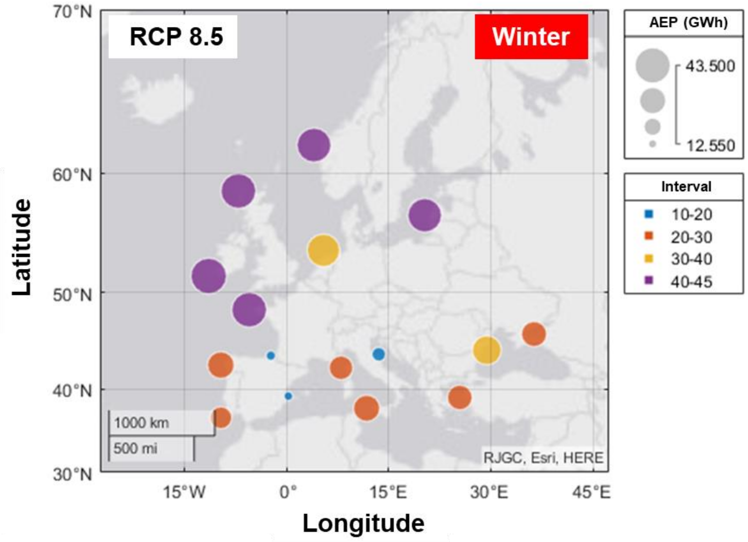

Figure 4.23. Winter - AEP values (in GWh), calculated for a 20 MW turbine (*U160.*2), considering RCP 8.5 data, covering the time interval 2006-2100

Below, the capacity factor in the Figure 2.24 and Figure 2.25, will be calculated for RCP4.5 and RCP8.5 data, taking into account the total period 2006-2100, but also the seasonal evolution. From the presented observations, the capacity factor for both RCP4.5 and RCP8.5, for the time period 2006-2100, show similar results.

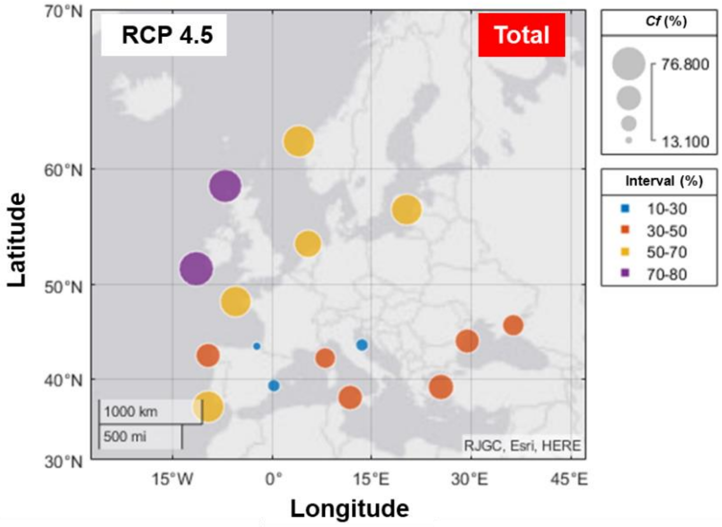

Figure 4.24. Capacity factor (%) calculated for a 20 MW turbine (U160.2), considering RCP 4.5 data covering the time interval 2006-2100

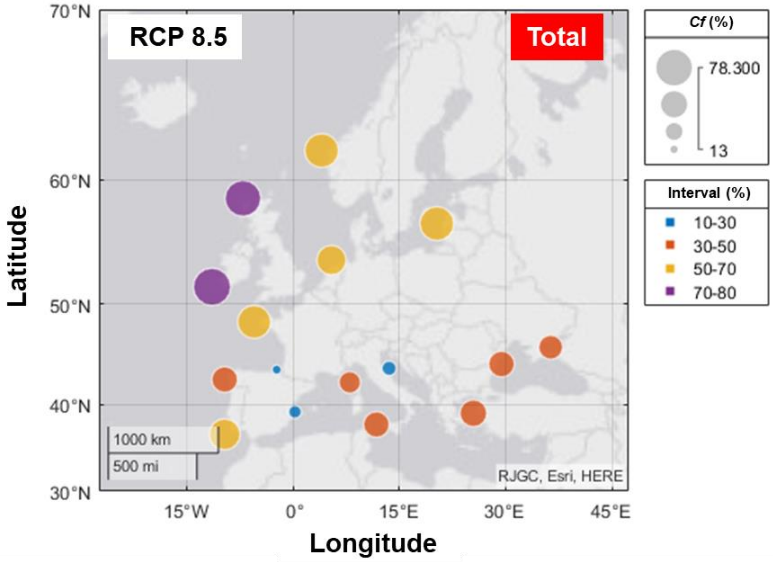

Figure 4.25. Capacity factor (%) calculated for a 20 MW turbine (U160.2), considering RCP 8.5 data covering the time interval 2006-2100

From observations the capacity factor for both RCP4.5 and RCP8.5, for the time period 2006-2100, registers constant results.

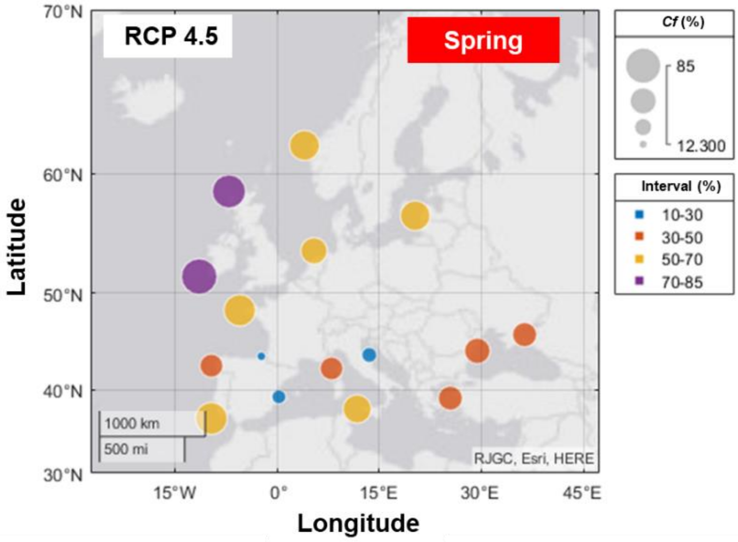

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Figure 4.26. Spring - capacity factor (%), calculated for a 20 MW turbine (*U160*.2), considering RCP 4.5 data, covering the time interval 2006-2100

Figures 4.26 and 4.27 show the capacity factor for the spring season; there is a small change at P7, i.e. for RCP4.5 data, where it shows a value of 50-70%, and an increase for RCP8.5 data, in the range 70-87%.

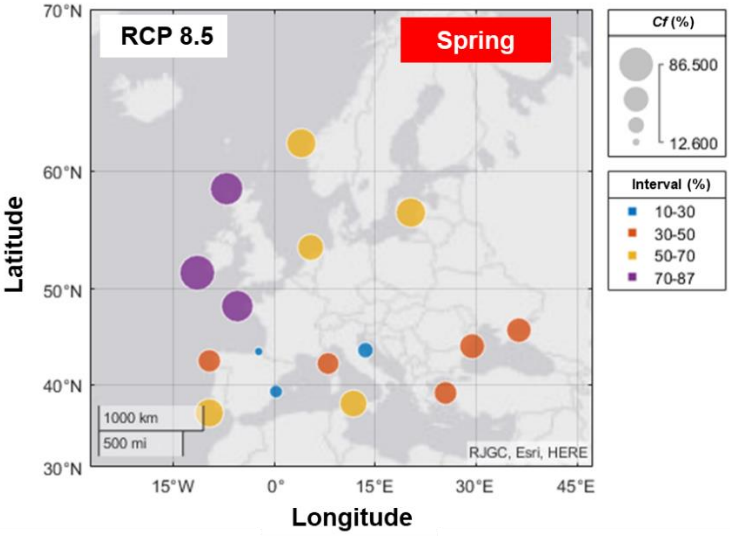

Figure 4.27. Spring - capacity factor (%), calculated for a 20 MW turbine (*U160*.2), considering RCP 8.5 data, covering the time interval 2006-2100

The capacity factor in the summer season for example; there is a slight change at Point P2, i.e. for RCP4.5 data there is a value of 30-50%, and for RCP8.5 data there is a small decrease and the image shows a value of 10-30%.

4.3 An Analysis of Renewable Energy Potential in the Republic of Moldova

In this subchapter, the energy demand and the possibilities to cover the energy needs from renewable energy sources in the territory of the Republic of Moldova were assessed. The assessment of alternative energy resources is extremely important as the Republic of Moldova depends mainly on Ukraine for energy imports.

In December 2023, EU leaders decided to open EU accession negotiations, the thesis describes the directives of the current legislation, and the trend to comply with EU legislation in the field of renewable energy. For this paper, analyzed the data recorded by NASA, in the Chisinau area; thus, for wind energy we investigated the monthly average values of wind speed over a period of 10 years and for solar energy the monthly average direct normal direct monthly radiation over the Chișinău area, over a period of 22 years.

In 2023, only 6% of electricity consumption is renewable energy. 54% of this is wind, 34% - photovoltaics and 6% each - hydro and biogas. The last two are continuous and reliable sources and do not depend on the vagaries of the weather. The largest unused capacity is biogas.

According to the latest energy balance report, natural gas is the most consumed fossil fuel in Moldova, accounting for about 57% of all energy consumed. Natural gas is imported exclusively from Russia. In 2017, the share of renewables in Moldova's gross final energy consumption was 27.8%. However, biomass provides 98% of this share and is mainly used in the heating sector [40]. The main alternative energy resource exploitable in the Republic of Moldova is biomass. Since Moldova is an agricultural country with an agri-food production exceeding 40% of the country's Gross Domestic Product (GDP). In 2021, wind installations produced about 76.3 million kW/h, which represents 1.83% of the country's total electricity consumption. BERD has assessed the wind potential of 1000 MW in the Republic of Moldova [40]. The Republic of Moldova also has 2 hydropower plants. One hydropower plant is in Dubasari district, with a capacity of 48 MW, built in 1954-1966, and the second one is in Costești, with a capacity of 16 MW, built in 1978. The total capacity generated by the hydropower plants is 64 MW. The largest electricity supplier in Moldova is Gas Natural Fenosa [41]. The wind potential measured above sea level at 50 meters above sea level shows that on more than 98% of the country's territory the wind speed is between 4.0 m/s and 7.5 m/s, but at 100 m the wind speed will increase by 25%.

Annual wind speed varies from year to year, being higher than average by about 25.6% and lower than average by about 24.5%. At the same time, these values vary strongly from station to station and a stronger variation is observed at stations located in open places, such as Comrat, Ceadir-Lunga, Soroca [42]. Regarding data from NASA Surface Meteorology and Solar Energy [43], the monthly average wind speed at 50 m above the earth's surface in the Chisinau area, from 1983 to 1993 is 5.84 m/s. Solar energy is not sufficiently exploited in the Republic of Moldova, some research has been done by the EBRD, which emphasized the potential energy through solar thermal applications. According to the profile made by EBRD, there is a potential of more than 150,000 m² for solar thermal applications and about 300 kW for photovoltaic systems [44]. Figure 4.28 illustrates the 22-year average monthly direct normal radiation from 1983 to 2005, averaged around 2.86 kWh/m²/day.

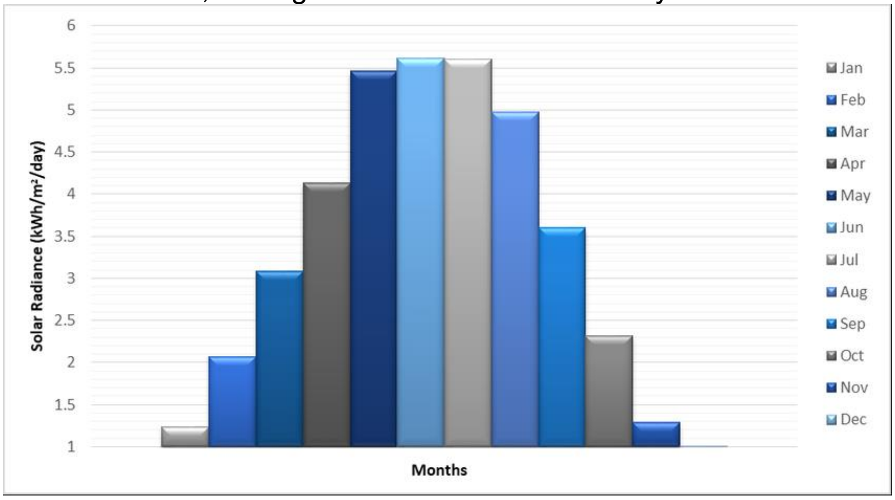

Figure 4.28. Direct normal radiation (monthly mean values) specific to the Chisinau area, covering the time interval 1983-2005 (22 years) [45]

Standard test conditions for quoting cell efficiency for terrestrial applications are: global irradiance=1,000 W/m², AM (air mass) 1.5 for direct normal spectrum and a temperature of 25°C.

4.4 Conclusions

For AEP(total annual energy production) according to RCP 8.5 data, covering the time interval 2006-2100, a change is observed for two of the selected points P2 (Norway) and P15 (Turkey), where according to RCP4.5 data, there is an increase, and for RCP8.5 scenario data, for the same point P2 (Norway), there is a decrease. For several points according to RCP4.5 data, there are changes, which have an increasing trend in the RCP8.5 scenario. The same trend is repeated in the capacity factor calculation, where for RCP4.5 data in spring, there is a value of 50-70%, and for RCP8.5 data, there is an increase, in the range of 70-87%. On the other hand, for the summer and fall seasons, the capacity factor, registers a small change with higher values in the RCP4.5 scenario than in the RCP8.5 scenario. Regarding the high dependence on imported energy, this represents a bottleneck effect for the Moldovan economy and the following aspects should be emphasized:

- the price of electricity from renewable energy sources is stabilizing, with more and more technologies achieving dramatic cost reductions. The average utility-scale costs of utility-scale solar PV and onshore wind have fallen by 73% and 22%, respectively, between 2010 and 2017 [46];
- the wind speed exceeds the minimum level of 3 m/s at which the turbine first starts to rotate and generate power, so we have a result of 5.84 m/s in some areas up to 7 m/s at 100 m, according to the IRENA 2019 study [46];
- wind energy currently has an installed capacity of 27 MW, is the most widely used RES technology in the energy sector in Moldova and is based on second-hand turbines imported from European countries.

Chapter V
Analysis of Solar and Wind Energy Resources in the Southeast Region of Romania

5.1 Solar and Wind Energy Production in the City of Galați in Relation to Coastal Areas

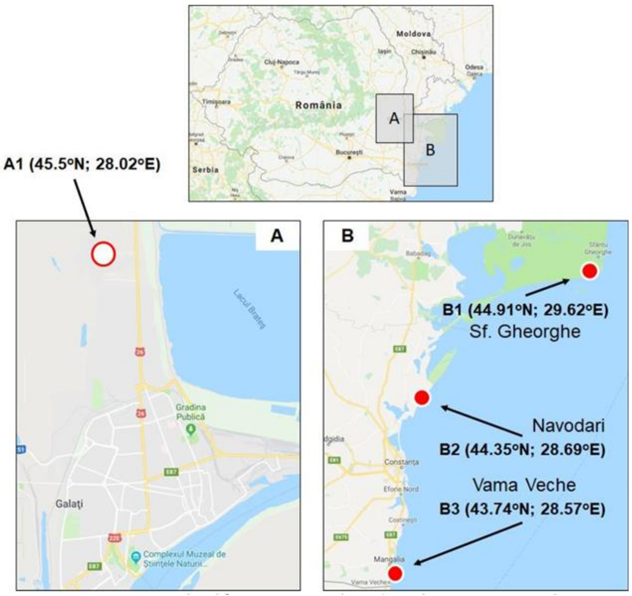

Figure 5.1. Target areas considered for assessment, where: a) solar energy; b) wind energy

The objective of this chapter of the thesis is to estimate the benefits that can be obtained from the implementation of a solar and wind project in the south-eastern part of Romania, by considering several benchmarks, according to the reanalysis data located in the south-eastern part of Romania. In the first case study, the attractiveness of solar energy for a manufacturing plant located in the vicinity of the city of Galați will be assessed. The seasonal and yearly fluctuation of solar energy will be discussed, taking also into account the performance of a photovoltaic panel, which can be installed on the roof of these production halls. Concerning the second case study, the performance of new wind turbines will be evaluated considering three sites located along the Romanian coast, namely Sf. Gheorghe, Năvodari and Vama Veche. According to these results, it has been observed that photovoltaic panels will partially cover the energy needs for the selected factory, and in the case of wind energy, a single wind turbine with a nominal capacity of 3 MW seems to cover the local electricity needs, reported for the localities of Sf. Gheorghe and Vama Veche.

I will focus on studies of photovoltaic technology and electricity generated on the floor area of an existing production plant of Grande Gloria Production SA. Industrial halls are single-story structures and maintain a relatively high roof-to-floor ratio, but also have a large floor area, in this case, they have a total floor area of 8404 m^2 (4 halls x 2101 m^2 each).

Two parameters were considered for the evaluation, namely: ALLSKY- total sky insolation incident on a horizontal surface (kWh/m^2); CLRSKY- clear sky insolation incident on a horizontal surface (kWh/m^2) [47]. The first parameter includes all values, while for the second one only data having an average cloud cover of less than 10% over a given day, averaging over the month.

The reported solar energy output of a PV system can be estimated using the following equation [48]:

$$E = A \times r \times H \times PR \tag{5.1}$$

where, E- electrical energy (kWh); A - total solar panel area, (m²); r- solar panel efficiency; H- average annual irradiance per panel; PR- performance ratio.

The reference points considered for the wind assessment are located along the Romanian coastal areas, being defined near Sf. Gheorghe (point B1), Năvodari (point B2) and Vama Veche (point B3) (Figure 5.1).

The wind speed (reported at 10 m height above the sea surface) corresponds to the ERA- Interim database [25]. Three wind turbines were considered for the research, namely

V90-3.0MW [49], Areva M5000-116 [50] and Senvion 6.2M126 [51] , the power curves of these generators are shown in Figure 5.2.

Since most turbines operate at a hub height of at least 80 m, the ERA-Interim initial wind conditions were adjusted to this reference level by a logarithmic law [38,52,53]. For this work, the time interval between 1.01.1998 and 31.12.2017 will be considered.

Figure 5.3 illustrates the annual variation in solar radiation, shown for the parameters CLRSKY and ALLSKY for Vânători, Galați. The first parameter, CLRSKY shows a much higher value, indicating values around the threshold of 4.9 kWh/m^2, while, for ALLSKY the reported results do not exceed 3.8 kWh/m^2.

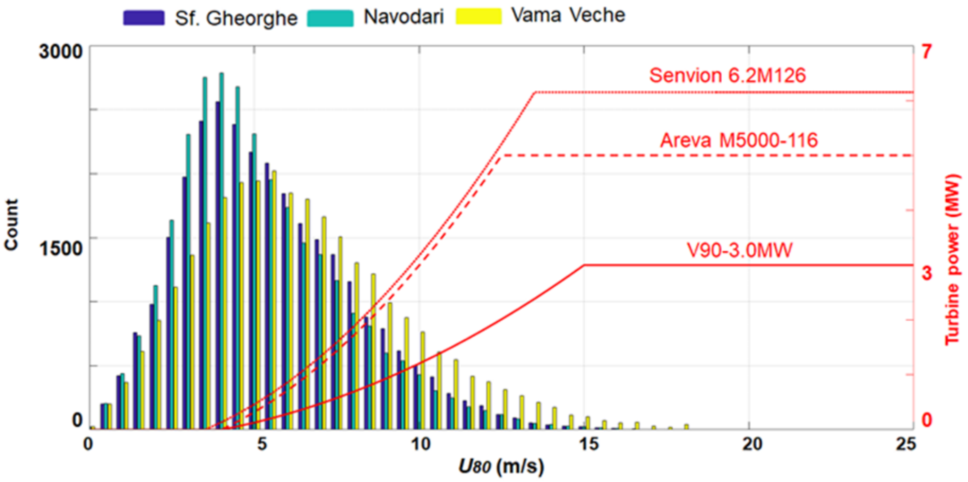

Figure 5.2 Wind histograms and turbine power curves [47]

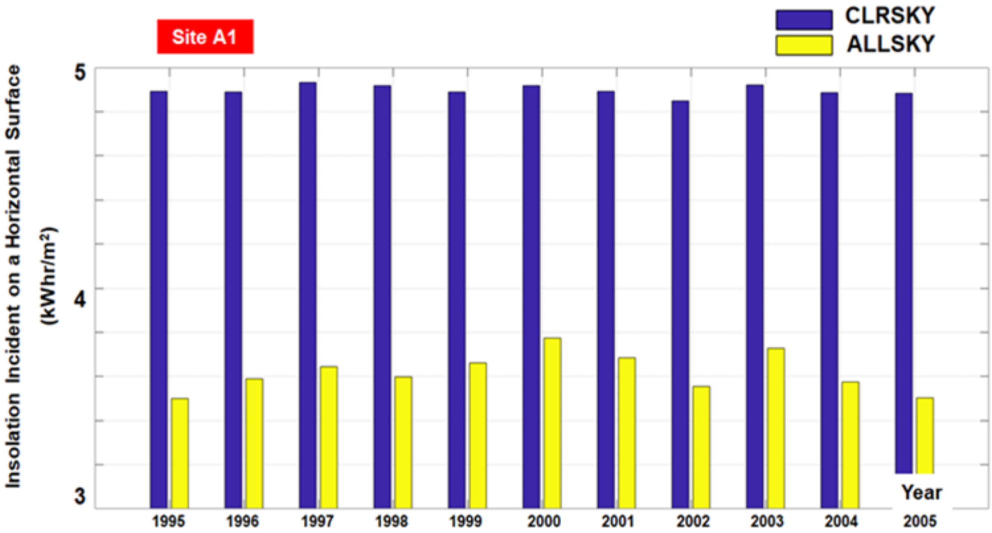

Figure 5.3 Annual evolution of solar radiation (mean values) reported for Site A1 (Vânători, Galați) [47]

The variations are smaller, with a minimum of 3.502 kWh/m being reported during 2005. The seasonal variation of solar energy is shown in Figure 5.4, where the values have been grouped into four dominant ranges: winter - December, January, February; spring - March, April, May; summer - June, July, August; fall - September, October, November. As expected, the most significant results are observed in the spring and summer period, reporting a maximum of 6.98 kWh/m^2 for the CLRSKY data and 5.8 kWh/m^2 for the ALLSKY parameter. Figure 5.4 illustrates the theoretical performance reported by a theoretical PV project (left legend) that can operate on the Grande Gloria Factory roof, considering only the CLRSKY dataset. In this way, the best performance, which can be obtained from such a project and location, will be estimated.

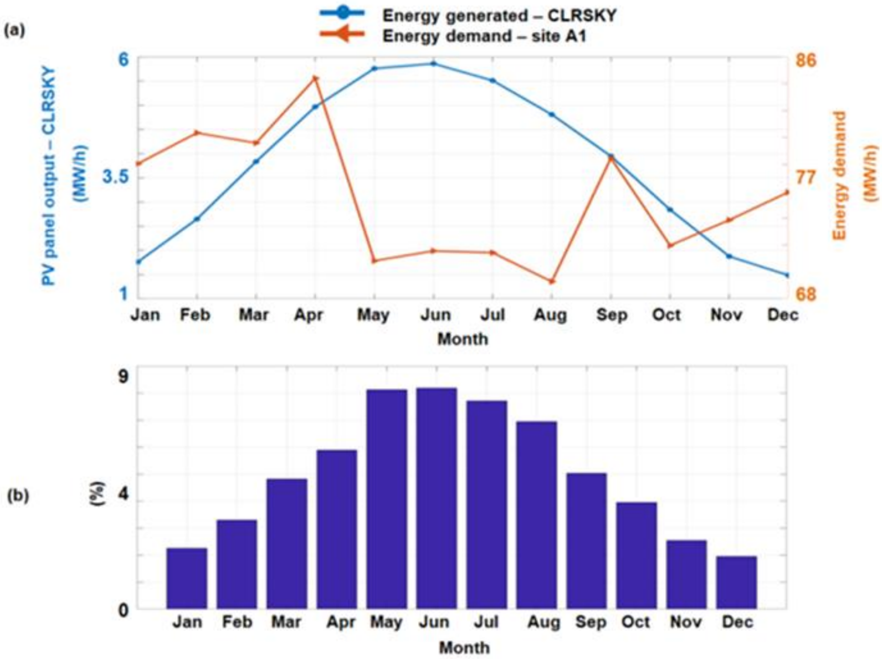

Figure 5.4. Performance of a theoretical PV panel that can be installed on the roof of Grande Gloria on the industrial halls. (a) monthly electricity demand of the factory and energy generated by a PV project; (b) electricity demand covered by the PV project [47]

It can be seen that the electricity demand (right, legend) for this plant is much higher during September-April, which corresponds to moderate solar radiation. Regarding the share of electricity covered by the PV project, values in the range of 4.82% and 8.2% can be expected in the months of April and September, while values close to 2% can be reported in the months of December and January.

For wind power, Figure 5.5 shows the annual energy production (AEP) reported for each turbine and also the capacity factor (CF), which is the ratio of actual power to rated capacity. The power production was estimated using the power curve of each system and the wind distribution associated with each site [54] . As I had already observed from the wind histograms presented in Figure 5.5, the Vama Veche benchmark seems to reveal more consistent wind resources, which is also reflected in the turbine performance. A maximum of 12 MWh can be expected from the Senvion turbine, while a minimum of 2.5 MWh is represented by V90-3.0 MW at the Năvodari site. The CF index reveals values between 9.6% and 24.3%, with the Areva M5000 system (5 MW), showing a better efficiency than the Senvion 6.2M126 (6.2 MW).

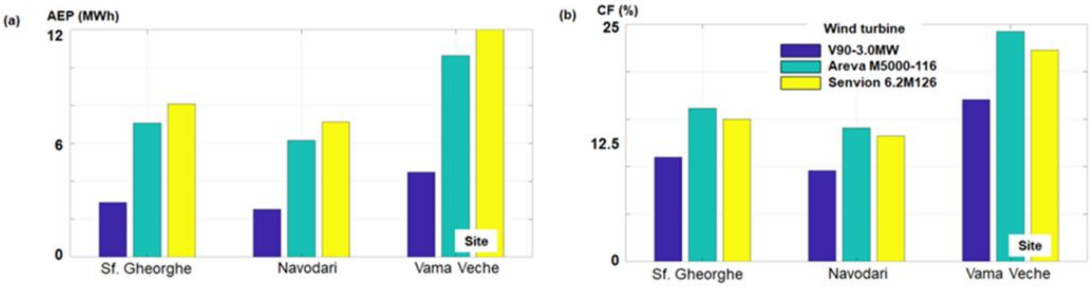

Figure 5.5 Performance of wind turbines that may operate in the vicinity of Sf. Gheorghe, Năvodari and Vama Veche, where a) represents AEP in MWh and b) CF in % [47]

Table 5.1 presents the estimated energy consumption for Sf. Gheorghe, Năvodari and Vama Veche sites, while indicating the value covered by a single turbine.

Table 5.1. *Electricity demand and turbine performance reported for the benchmarks*

Population			**Consumption (MWh)**	
St. Gheorghe		797	St. Gheorghe	1787
Năvodari		31554	Navodari	7075
Vama Veche		178	Vama Veche	399
Turbine power (MWh)			Distribution from turbines (%)	
St. Gheorghe	V90-3.0MW	2885	Sf.Gheorghe	161
	Areva M5000	7062		395
	Senvion 6.2M126	8082		452
Năvodari	V90-3.0MW	2520	Năvodari	3,56
	Areva M5000	6161		8,7
	Senvion 6.2M126	7126		10,07
Vama Veche	V90-3.0MW	4481	Vama Veche	1122
	Areva M5000	10618		2660
	Senvion 6.2M126	11997		3005

According to this estimate, Năvodari, with 31554 inhabitants, requires about 7075 MWh, while the other points reveal a much lower value of 1787 MWh (Sf. Gheorghe) and 399 MWh (Vama Veche). The energy demand is easily covered by the turbines for Sf. Gheorghe and Vama Veche locations, which are remote areas, mostly known for tourist activities, while for the Năvodari point, a maximum of 10% is covered by the Senvion generator.

5.2 Assessment of Wind and Solar Energy Potential in the Brateș Lake Area, Galați

Taking into account the fact that the city of Galați is located in south-eastern Romania, it is considered an attractive point in terms of renewable energies, in this study, I have provided more details on the energy potential of local wind and solar resources, therefore the performance of some efficient wind turbines was considered for evaluation. Following 22 years of data according to ERA5, the fifth generation of ECMWF global climate and weather reanalysis data [55], the data interval 2001-2022 was analyzed, which provides a more comprehensive picture of the renewable energy resources in the Brateș Lake area. Comparing the wind and solar resources with some *in situ* and reanalysis data, a relatively good result was identified, especially in the case of average values. For wind speed conditions at a wind turbine hub height of 100 m, a maximum value of 19.28 m/s can be expected in winter, while for solar radiation the energy level can reach up to 932 W/m^2 in summer. Several 2 MW turbines were considered for the assessment, to which a wind turbine 6.2 MW system was added. The calculated capacity factor of the turbines can reach the range 11.71-21.23%, with better performance expected from Gamesa G90 turbines. Lake Brateș can also be successfully used to run a floating solar project, which is in line with the objective of the REPowerEU plan. Several floating solar units have been considered to simulate these large-scale projects, which can cover between 10 and 40% of the surface of Lake Brateș. In addition to the expected electricity production, the amount of evaporated water saved by these solar panels was also taken into account,meaning, the water demand for at least 3.42 km^2 of agricultural areas, which can be covered on an annual scale. This represent a novelty for this region.

The aim of the European Green Deal, published in 2019, is to promote the use of renewable energy resources (RES) to achieve a significant reduction in carbon footprint. To reach these targets, the envisaged milestones imply a 55% reduction in CO_2 in 2030 (compared to 1990), zero emissions from new cars by 2035 and zero CO_2 by 2050 [56].

Due to the development of technology new opportunities arise, such as the development of FPV projects that can be installed on different water bodies of Europe, such as those in coastal areas, hydropower reservoirs and even urban lakes. An FPV project has the potential to reduce algal growth and water evaporation, performs better than a land-based farm due to lower water temperature, will not compete with land use, while the shading effect will be minimal [57].

By the end of 2018, almost 1.3 GWh of PSP had been installed globally, compared to almost 500 GWh accounted for by the *onshore* market [58]. Being located in the northern hemisphere, Romania is one of the largest countries in the south-eastern part of Europe, covering an area of 240,000 km$^{2.}$ The combination of geographical and climatic characteristics makes this area a suitable candidate for the development of renewable projects, such as solar projects [59,60].

It is estimated that the average insolation period varies between 1,600 h/year and 3,200 h/year, with more important PV projects being developed in lower-lying areas such as the Moldavian and Dobrogean (eastern) plains. For the period 2010-2019, investments in the solar sector covered almost € 2,000 million, with a peak associated with the period 2012-2014, when almost 90% of this budget was allocated.

At the moment, it should be mentioned that there are no FPV projects operating in this south-eastern region. With the exception of the mountainous areas, the most important regions in Romania for the development of wind energy projects are also in the eastern part of the country, more precisely near the Black Sea, the Danube Delta, Northern Dobrogea or even the Bârlad Plateau, where the annual wind speed can reach up to 10 m/s at 50 m height. Consequently, a significant proportion of the wind farms in operation are located in these areas, with a share of 78% for Dobrogea and the southern part of the Barlad Plateau, including the county of Galați, Brăila [61].

Undoubtedly, the Fântânele-Cogealac project (600 MW) is one of the most representative Romanian wind farms, being defined by a total of 240 turbines operating at a height of 100 m. A total of €1.1 billion has been allocated to this project, and it is expected to cover a share of 10% of the total RES production in Romania [61].

For the city of Galați there is still room for analysis and research. The fact being the approval of a 629 MW wind project led by the company Hoopeks International. It will involve a total of 136 turbines (of 6.2 MW), an investment cost of €500 million and a covered area of 13,000 ha.

In the 18th and 19th centuries, this lake had an area of ≈100 km^2, in the meantime it has been drained. Due to various human interventions, its surface area was reduced to 20 km^2 and a maximum water depth of 3 m [62].

From Romania, three specific reference points, noted A, B and C are considered for the analysis, in the Figure 5.6. Point A, corresponds to the position of a meteorological station, maintained by the National Meteorological Administration of Romania in Galați (or ANM), the associated wind measurements (*U10*) being used to verify the accuracy of the reanalysis data. Point B (Lacul Brateș), will be further considered to highlight the profiles of renewable resources (wind and solar), as well as the performance of some onshore wind turbines, but also for floating solar panels. Point C (Bocșa, Caraș-Severin) will be analyzed for knowing how much of the entire energy consumption can be covered by an existing PV installation at a private company, based on actual records and measurements.

Several datasets and variables were considered in this thesis, as presented in Table 5.2. *In situ* wind measurements are only available for point A and are associated with a reference height of 10 m (*U10*). A total of 22 years of data (January 2001-December 2022) were processed, the time series involving daily values of mean and maximum wind speed values. For the same time interval, the ERA5 wind dataset was considered, it includes hourly values (24 values per day) and also the components *u* and *v.* The ERA5 dataset is a project associated with the European Center for Medium-Range Weather Forecasts (ECMWF) that has a spatial resolution of 30 km and is frequently used by researchers to identify renewable energy potential in various geographical environments [63].

The PV installation that I analyze in this paper for point C, Bocșa, is located in Caraș-Severin, at an industrial consumer, which has 160 photovoltaic panels, with a unit power of 270 W, with a total power of 40 kW, with two inverters, a smart power sensor and connection, metering and safety devices [64].

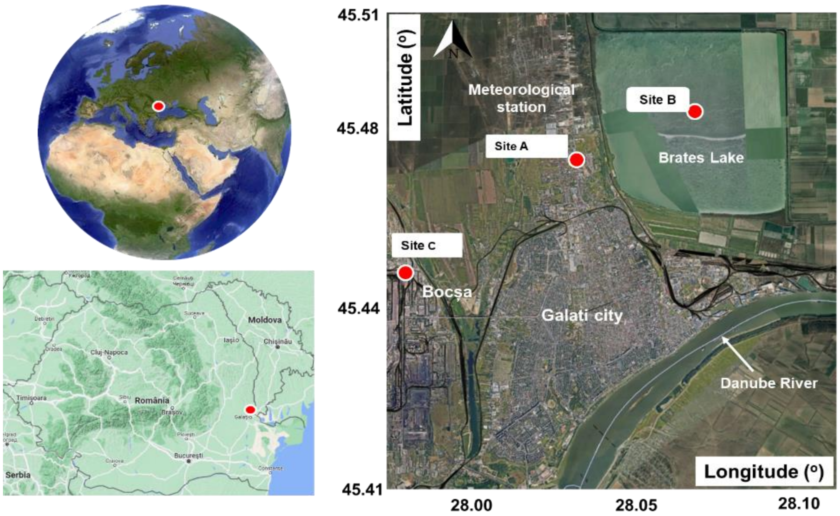

Figure 5.6. Overview of the target area, including the location of site A (meteorological station), site B (in the middle of Lake Brateș) and site C (Bocșa). Information processed from Google Earth 2023 [65].

From a meteorological point of view, the *U10* parameter is more relevant, but for a wind turbine, it is more important to consider the wind conditions that are characteristic of the hub height of a wind turbine (e.g.100 m).

One way of identifying the solar energy potential involves the use of solar radiation incident on a surface (SSRD in J/m^2), which has been processed from the ERA5 package (24 values per day) and is defined as a combination of direct and diffuse solar radiation that has reached a horizontal plane on the Earth. Upon reaching the Earth's surface part of the incident solar radiation (direct and diffuse) is reflected.

Table 5.2. *Main characteristics of the landmarks considered in this paper. Information processed from Google Earth 2023* [65]

Location	ID	Data type	Parameter	Latitude (º)	Longitude (º)
Galați	Point A	*In situ,* ERA5	U10	45,473	28,032
Galați	Point B	ERA5, SARAH	*U10, U100*, SSRD, Temperature, Evaporation	45,483	28,070
Bocșa, Caras-Severin	Point C	Data from report, ERA5	SSRD	48,384	21,777

By dividing this parameter, the direct solar radiation will be calculated. The period (3600 s), can be calculated and new form, can be obtained, which is expressed in W/m^2 [66]:

$$Solar\ radiation = \frac{SSRD}{3600} \tag{5.2}$$

Daily temperature (temperature at 2 meters height) and evaporation rate from the ERA5 database were considered and processed to give a complete picture of the local environmental conditions (daily values, 2001-2022). The magnitude of the flux of reflected radiation depends, in addition to astronomical, meteorological and climatic factors, primarily on the nature of the active surface and its reflectance. The percentage ratio between reflected and incident radiation is called the albedo. The presence of an FPV project can significantly reduce the amount of evaporated water [67], another objective of this work is to estimate the prevention of water evaporation for the area of Lake Brateș. The *in situ* measurements used in this work are only available for wind conditions and, consequently, the SARAH data logging will be used to verify the accuracy of other parameters (e.g. temperature and solar radiation). These data are also available in the paper [68], being associated to Point B (Lake Brateș) for the interval January 2005-December 2016. Figure 5.7 shows the main characteristics of the on-shore turbines accounted for the study. These systems are defined by nominal powers of 2 MW, with the exception of the General Electric turbine (2.5 MW), with the mention that similar generators are operating in wind projects in this region. Doing an analysis for the future *onshore* wind farms that are expected to be deployed in this area, we noted that they will include higher capacity systems that can reach up to 6.2 MW per turbine. Looking ahead to the wind turbine market, it is possible that it will also implement a Vestas V162-6.2 MW Vestas V162-6.2 MW system, which can be also installed in other regions of Romania.

According to the technical details provided by Vestas for this turbine, the coupling value is set at 3 m/s, while the cutoff is similar to the other generators (25 m/s). However, the nominal wind speed is not provided, which means that this will be further identified by comparison to similar wind generators (e.g.Senvion 6.2M152).

Although the profile of the 2 MW turbines may look similar, the main differences are in the coupling values and nominal wind speed, with T3 and T4 turbines being the best performers in this respect. Moreover, the tower height for the system can be adjusted, with values ranging from 67 m (T4) to a maximum of 138 m (T3). Depending on this height, the performance of each turbine will be adjusted by changing the *U100* parameter to a certain level, as follows [38]:

$$U_{hub} = U_{100} \cdot \ln\left(\frac{z_{hub}}{z_0}\right) / \ln\left(\frac{z_{100}}{z_0}\right) \tag{5.2}$$

where, U_{hub} - wind speed associated with a given shaft height, z_{hub} - reference turbine shaft height and z_{100} - reference turbine shaft height at 100 m; z_0 - turbine roughness factor chosen for site B (water surface = 0.0002 m).

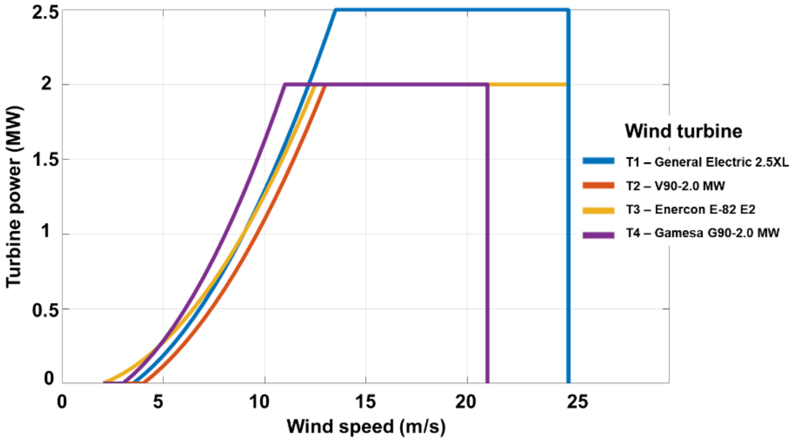

Figure 5.7. Power curves of *onshore* wind turbines considered [65].

The annual electricity production (AEP) of a given wind turbine can be estimated as follows [38]:

$$AEP = 8760 \cdot \int_{cut-in}^{cut-out} P(u) f(u) du \tag{5.3}$$

where, 8760 - the number of hours per year, P*(u)- the* wind turbine power curve, *cut-out/cut-in* cut-out/cut-in - the turbine operating limits. As for the Weibull probability density function, it can be defined as follows [38]:

$$f(u) = \left(\frac{k}{c}\right)\left(\frac{u}{c}\right)^{k-1} \exp\left[-\left(\frac{u}{c}\right)^{k}\right] \tag{5.4}$$

where, u - wind speed; k, c - shape and scale parameters.

As the Galați area presents adequate solar resources for the development of renewable projects, another objective of this thesis is to identify how a floating solar farm can work for the Brateș Lake area. This can be considered a novelty considering that there is no such project in Romania. Table 5.4 shows the characteristics of the floating modules considered for evaluation. Their power ranges from 280 W to 540 W, while the JRH 540 system has a maximum efficiency of 21.35% and a panel area of 2.58 m^2.

Table 5.4. *Specifications of floating PV solar panels* [69]

Parameter	**Q-Power-G5 280 (P1)**	**GCLM6/60H-325 (P2)**	**Trina Solar (P3)**	**JRH 540 W (P4)**
Power (W)	280	325	375	540
Efficiency (%)	17,10	20,00	19,30	21,35
Surface area (m)^2	1,94	1,62	1,95	2,58

Based on these characteristics, the estimated power of a solar panel can be simply estimated as follows [38]:

$$AEP = Solar\ radiation * A_s * T_{r}* \eta \qquad (5.5)$$

where solar radiation is in W/m^2, A_s - solar panel surface area, T_r - solar irradiance hours, η- solar panel efficiency.

In addition to electricity production, another advantage of an FPV project is that it can reduce the amount of water evaporated by blocking the sun's rays. For the present work, several scenarios of covering the surface area of Brateș Lake with solar panels (10 %, 20%, 30% and 40%) were considered. A 40% scenario can be considered to be a realistic one, considering that there are studies in which a 50% scenario has been associated with a lake surface area of 100 km^2 , this being the case of Walker Lake [65].

Table 5.5 shows the expected installed capacity (in MW) for each scenario, where the water surface area associated with each scenario has been divided by the area covered by the total number of solar panels. The number of panels and capacity increases rapidly as moving to the 40% scenario, realistically 10% is easier to implement in a short period.

Table 5.5*. Scenarios involving the Brateș Lake area and FPV systems. Installed capacity required for each solar project indicated in MW*

FPV systems	**Lake Brateș - scenarios**			
	10% (2 km)^2	20% (4 km)^2	30% (6 km)^2	40% (8 km)^2
Q-Power-G5 280	289	577	866	1155
GCLM6/60H-325	401	802	1204	1605
Trina Solar	385	769	1154	1538
JRH 540 W	418	836	1254	1672

A similar approach (as presented in [70], will be used to quantify the volume of evaporated water associated with the presence of an FPV project for the Brateș Lake area. First, the natural evaporation of the lake is estimated as [65]:

$$V\left(\frac{m^3}{zi}\right) = E\ \left(\frac{m}{zi}\right) * A_l * (m^2) \qquad (5.6)$$

while the amount of water saved by the presence of FPV panels is indicated as:

$$\Delta V\left(\frac{m^3}{zi}\right) = k * E\ \left(\frac{m}{zi}\right) * A * (m^2) \qquad (5.7)$$

where, E - evaporation amount (from ERA5); A_l - area of Brateș Lake (20 km^2); k - reduction factor associated with FPV type and platform (k=0.6); A - area covered by FPV panels.

An overview of the key parameters related to the Brateș Lake area is provided in Figure 5.8, where monthly boxplots of ERA5 data cover a 22-year time span (2001-2022). Seasonal differences between summer and winter are visible, indicating different patterns depending on the feature under consideration. For example, for the *U100* conditions (Figure 5.8a), higher values are expected during January, where an extreme wind speed value of 19.28 m/s can occur, compared to only 13.28 m/s expected in December. Mean values range from 4.28 m/s (July) and peak at 5.80 m/s in March.

Solar radiation is very low during September and April with average values below 41.02 W/m^2, gradually increasing to 124.30 W/m^2 in July. No outliers are visible during the April and September interval compared to the winter season. A maximum peak of 932.90 W/m^2 is expected in June, gradually decreasing in case of 95th percentile, value of 148.53 W/m^2 for December.

In the case of temperature (Figure 5.8c), values range from -21.14^o C to 40^o C, with average values of 0^o C in January, 33.59^o C in May and 12.17^o C in October, respectively. The evaporation rate (per day) of Lake Brateș, is illustrated in Figure 5.8d, and is estimated in terms of mm water equivalent, where positive values indicate condensation. In June and July, the evaporation rate is much higher, reaching a maximum value of 0.53 m, compared to 0.14 m in December. Condensation shows lower values, with a higher contribution expected between January and February. The ERA5 project is the main data source for the present work.

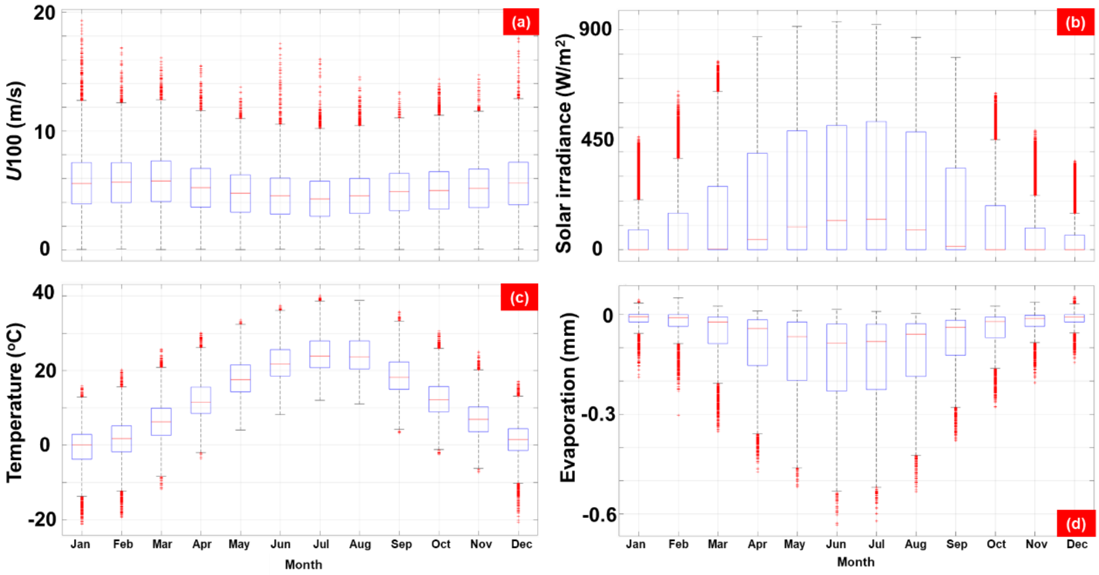

Figure 5.8 Monthly distribution of the main physical parameters of Lake Brateș (point B). Boxplot based on ERA5 data (2001-2022), where: (a) *U100* in m/s; (b) solar radiation in W/m^2; (c) temperature in ºC; (d) evaporation (mm water equivalent - negative values) [65]

Figure 5.9 shows a first analysis of the ERA5 data, in which the monthly wind measurements from Point A (*U10)* are compared with those from the meteorological station operating at this location. As can be seen, ERA5 overestimates the mean wind speed, while an inverse pattern is expected for the maximum values. ERA5 shows mean values in the range of 2.73-3.36 m/s and maximum values ranging from 8.93-12.31 m/s.

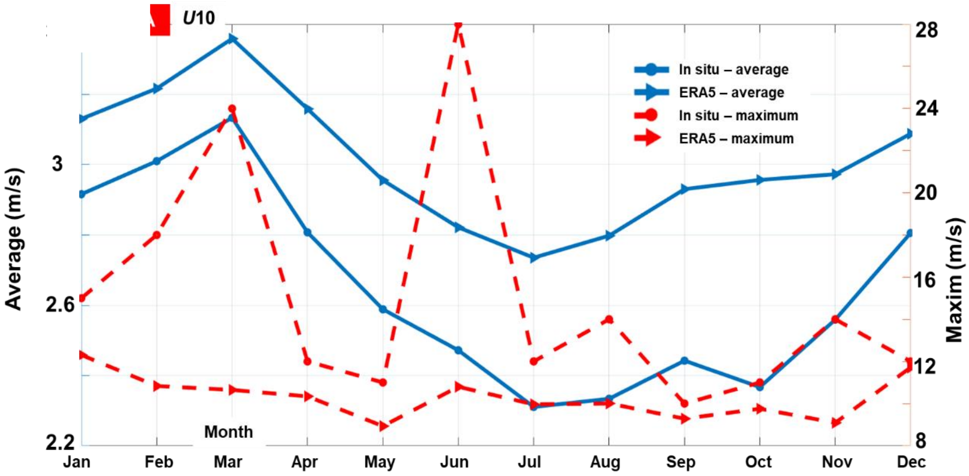

Figure 5.9. *U10* - direct comparison between *in situ* data and ERA5 for the 2001-2020 time interval, for Point A, where: left axis - mean values; right axis - maximum values [65]

Meteorological data indicated in the Figure 5.9, averages of 2.31-3.13 m/s, while the maximum can reach up to 28 m/s. The *in situ* maximum values are defined by a random variation and extreme events may occur during the summer season. This aspect is not visible in ERA5, where the maxima are defined by a smooth monthly fluctuation. This is a characteristic of a reanalysis dataset, where the values are averaged over a particular grid.

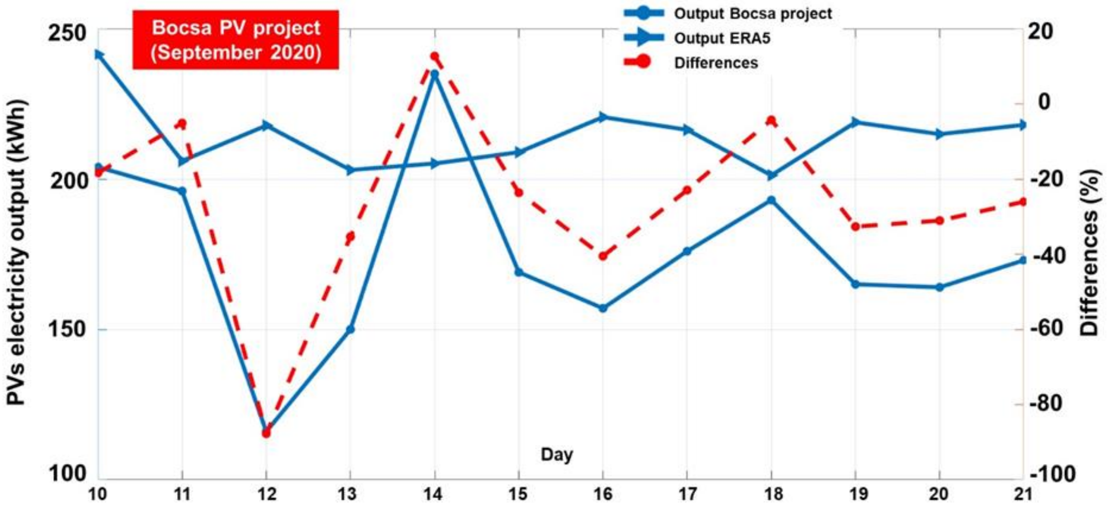

Figure 5.10. Direct comparison between reported electricity production and theoretical production, based on total solar radiation according to ERA5 data for Point C, Bocșa PV project. The results have been processed for the interval 10-21September, 2020, where on the left axis is the electricity production and on the right is the percentage difference [64]

In Figure 5.10, measurements were made from September 10, 2020 to September 21, 2020, the recorded data and ERA5 data for Point 3, Bocșa, PV project a sharp percentage difference is observed on September 11, 14 and 18.

Depending on the month under consideration, the differences between the two datasets are in the range (21.5-31) %, with higher values expected in winter. A different evolution is observed for temperature data where a good agreement between the mentioned datasets is observed.

A more detailed analysis of the *U100* parameter is shown in Figure 5.11, this time considering the wind roses associated with each season. According to this information, the northern and southern sectors represent the dominant wind direction, with the northern sector being defined by more energetic wind resources, frequently exceeding 8 m/s. Each season is defined by particular characteristics, which, for example in the case of summer hours will mean a concentration of wind from the north, which will amount to almost 10% of the entire dataset. Moving into the winter period, a significant presence of wind action from the southwestern sector can be observed, which will have an impact on the performance of a given wind project. Spring and fall values are below 5%, with some energetic peaks expected for the northern sector, where wind speeds above 10 m/s can occur. The International Electrotechnical Commission- IEC 61400, sets out in detail the requirements for the development and operation of a given wind project [71]. Among various parameters, these include the IEC wind classes (from 1 to 4), which are defined by the specific annual average wind speed, namely: C1 (strong wind) - 10 m/s; C2 (medium wind) - 8.5 m/s; C3 (weak wind) - 7.5 m/s; C4 (very low wind) - 6 m/s.

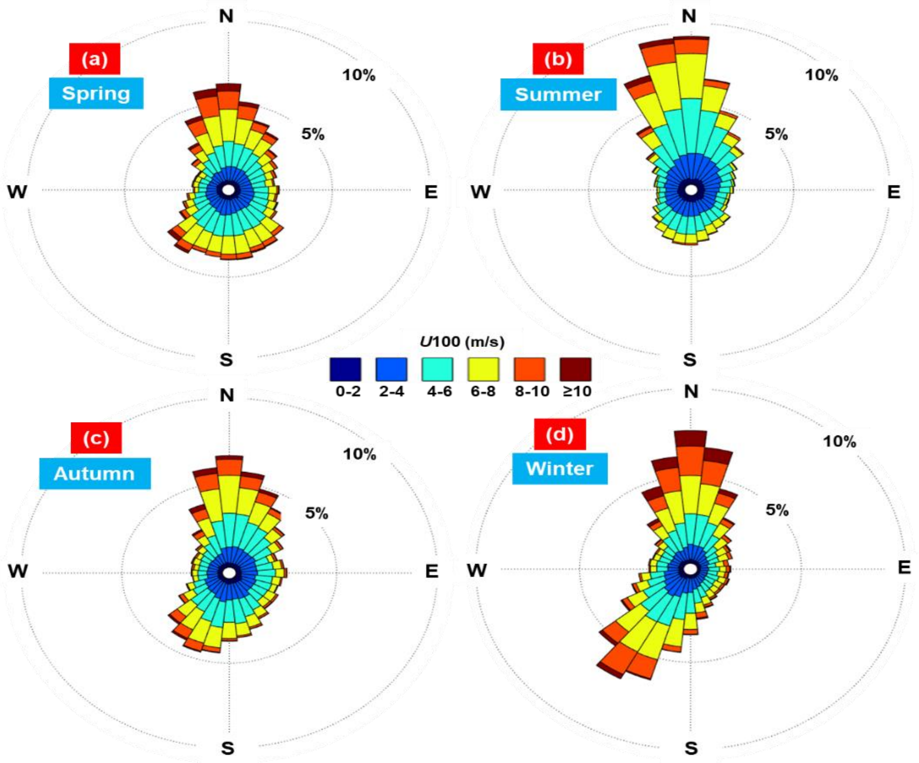

Figure 5.11. Wind runoff for Brateș Lake (point B) considering the ERA5 dataset (2001-2022). The seasonal distributions of parameter *U100* are related to (a) March-April-May; (b) June-July-August; (c) September-October-November; (d) December-January-February [65]

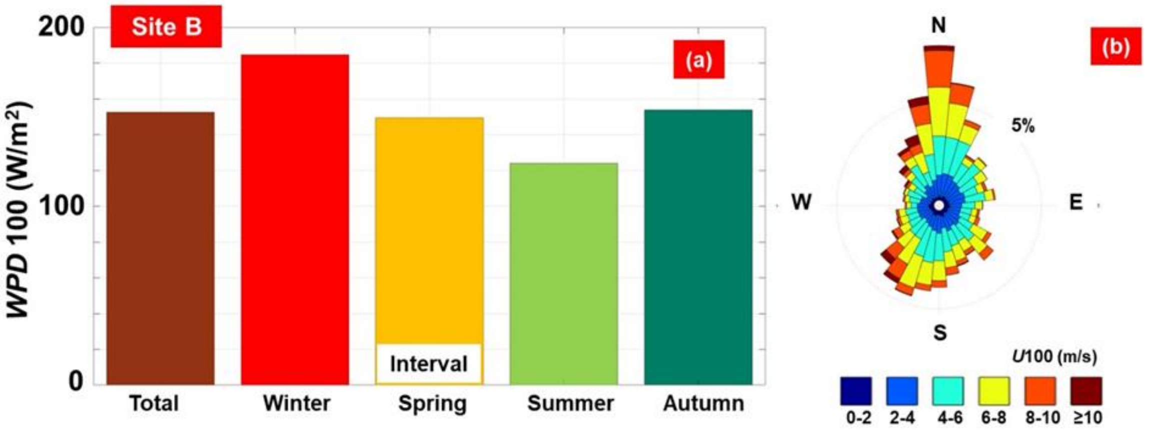

Figure 5.12. Wind energy profile corresponding to point B (Brateș Lake) associated with ERA5 data. The time interval is 2001-2020, where: (a) seasonal distribution of the mean wind power density at 100 m height (WDP); (b) wind rust.

Figure 5.12, plots the seasonal mean wind power density at 100 m height (WPD) and wind rust, I observed an increased WPD in winter and an increase in wind rust from 6 m/s to 10 m/s for the winter period. The monthly distribution of wind classes, with the mention that only the mean wind speed was considered in their selection, without including additional details such as turbulence intensity or gust events for a 50-year period. Class 1 values will represent a suitable scenario for wind project development. For Brateș Lake, these events are more frequent in January, with maximum values of 6% (of monthly values). The values increase gradually as moving from C1 to C4, with a maximum of 9% for class C2 (in March and December), 11% for class C3 or 22% for class C4, in February and March. These results have been calculated on the basis of data associated with the thresholds indicated in the IEC guideline (mentioned above), which means that the missing values (up to 100%) are related to *U100* values below 6 m/s. It can be estimated that in winter a given wind turbine can achieve better performance compared to other time periods. The solar energy potential can be indicated by using solar radiation (W/m^2), and it is expected that a benchmark defined by average values per year of 140 W/m^2 would be of interest for the development of a PV project [72]. Figure 5.13 shows the annual distribution of solar radiation (average values), where the associated months have been divided between each season. In the spring period (Figure 5.13 a), better performance of a PV system can be obtained in March, with a maximum of 275 W/m^2 (in 2003), but in some cases for example in April (in 2020), it is possible to become more significant, with a peak of 245 W/m^2. Turning to the summer season (Figure 5.13 b), one can observe peaks of 294 W/m^2, but also significant interannual fluctuations that are in the range 19.3%-20.4%. During the fall (Figure 5.13c), the values gradually decrease as we move towards November, with a minimum value of 48.4 W/m^2 expected. The values obtained are relatively constant, with some energy peaks of 193 W/m^2 and 132 W/m^2 being observed in September (2012) and October (2022), respectively. As observed, during winter (Figure 5.13d) the values associated with December and January do not exceed 70 W/m^2, with higher values expected in February which are in the range 74.6 -116 W/m^2.

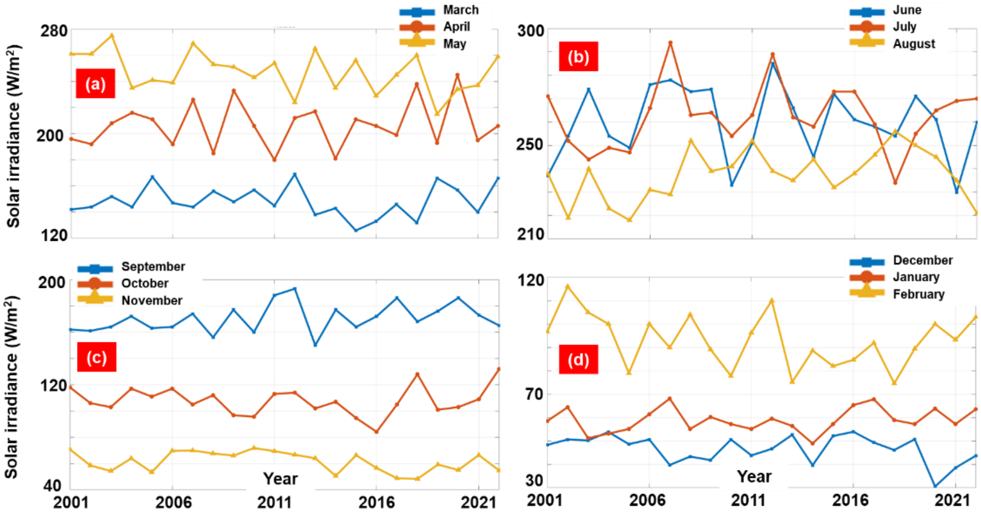

Figure 5.13. Lake Brateș, point B - solar radiation (in W/m^2), corresponding to the ERA5 dataset, calculated for the time interval 2001-2022. Mean values associated with (a) spring; (b) summer; (c) fall; (d) winter [65]

A more detailed analysis of solar radiation is highlighted in Figure 5.14, considering all hourly/monthly combinations. A maximum peak of 725 W/m^2 is observed in the June-August interval, while, as expected, during the night, solar energy will not generate electricity. The November-February time interval is the least energetic, with values not exceeding peaks of 368 W/m^2. Summer hours show the best solar resources, which can be categorized into three ranges: a) 06-07 AM and 04-05 PM - solar radiation < 340 W/m^2; b) 07-08 AM and 03-04 PM solar radiation < 490 W/m^2; c) 08:00-15:00 - solar radiation between 490 and 725 W/m^2. In addition to the resource assessment, the research proposes to identify the expected performance of solar and wind systems that can operate near Lake Brateș.

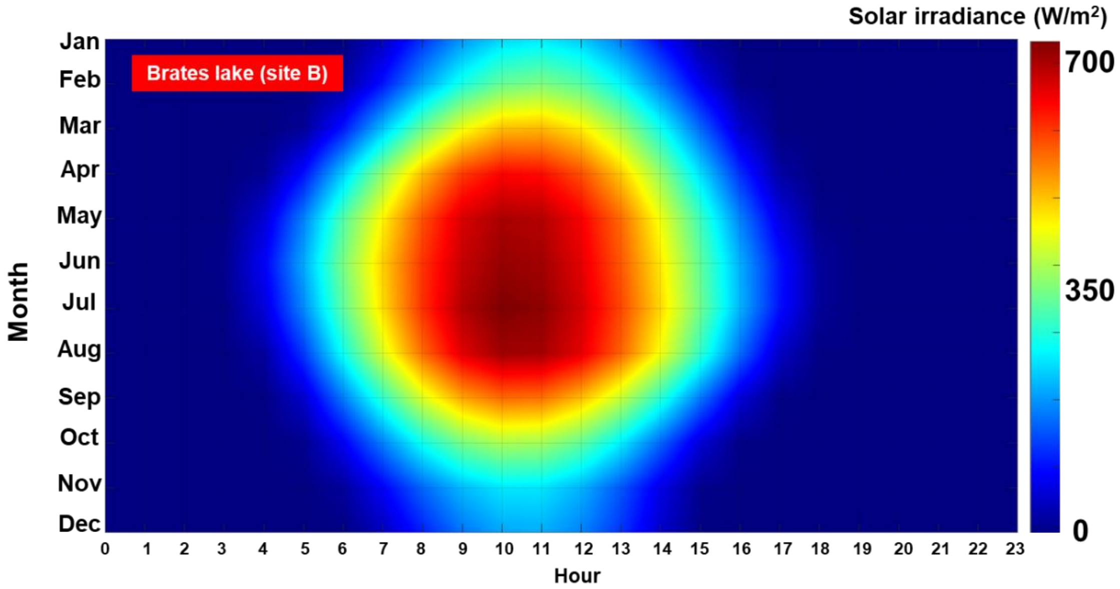

Figure 5.14. Brateș Lake - Point B, solar radiation distribution by months and hours, according to the ERA5 dataset (range 2001-2022) - mean values [73]

Different turbine shaft heights have been estimated in Table 5.6. Although turbines T2 and T4 have the same rated capacity and relatively close operational shaft heights, the AEP production is significantly influenced by the fact that T4 has the lowest rated wind speed (11 m/s) of all the generators considered. Another disadvantage of the T2 turbine is related to the higher value of the coupling limit (4 m/s), which, for example, in the case of the T3 turbine is 2 m/s.

Table 5.6. *The capacity factor (%) of wind turbines expected for the Brateș Lake area. Results based on ERA5 data (2001-2022) considering different tower heights*

Turbine	**Tower heights (m)**											
	67	75	78	80	85	90	95	98	100	105	108	138
T1		11,91							12,68			
T2				11,71			12,2			12,49		
T3			17,82		18,08			18,53			18,83	19,61
T4	19,64		20,24			20,81			21,23			

From Table 5.6 it can be seen that the T4 turbine is the only one that exceeds 21%, reaching a maximum of 21.23%. On the opposite side we can find the T2 turbine which for a shaft height of 80 m can expect a minimum capacity factor of 11.71%. Turbine T3 presents values between 17.82 and 19.61%, compared to turbine T1, where a maximum of 12.68% can be attained. Although the T3 turbine is defined to have the biggest shaft height (138 m), such a solution is not justified, considering that a maximum AEP of 3.44 GWh can be attained. This value is relatively close to that expected from a T4 turbine, which can operate at a much lower shaft height (e.g. 67 m). The AEP production of these systems operates in the range: T1 – 2.61 GWh and 2.78 GWh; T2 – 2.05 GWh and 2.19 GWh; T3 – 3.12 GWh and 3.44 GWh; T4 – 3.44 GWh and 3.72 GWh.

The present results are in line with the average capacity factor reported for other European *onshore* areas [74], which indicate values in the range of 20 % and 30 %. The *onshore* wind industry is evolving very rapidly, including the emergence of large capacity generators.

In order to anticipate the deployments of a 6.2 MW wind turbine in the vicinity of Galați, the performance of the Vestas V162-6.2 MW Vestas V162 turbine, which has already been deployed in some areas in Romania, was considered for the evaluation.

The official information provided by the manufacturer Vestas lacks the nominal wind speed value associated with this generator, and for simplicity two values (11 m/s and 12 m/s) have been assumed [75]. This is in line with the trend in the industry to reduce the nominal wind speed to achieve better performance.

Figure 5.15 shows the performance of the Vestas V162 system, taking into account all possible scenarios (shaft heights and nominal wind speeds).

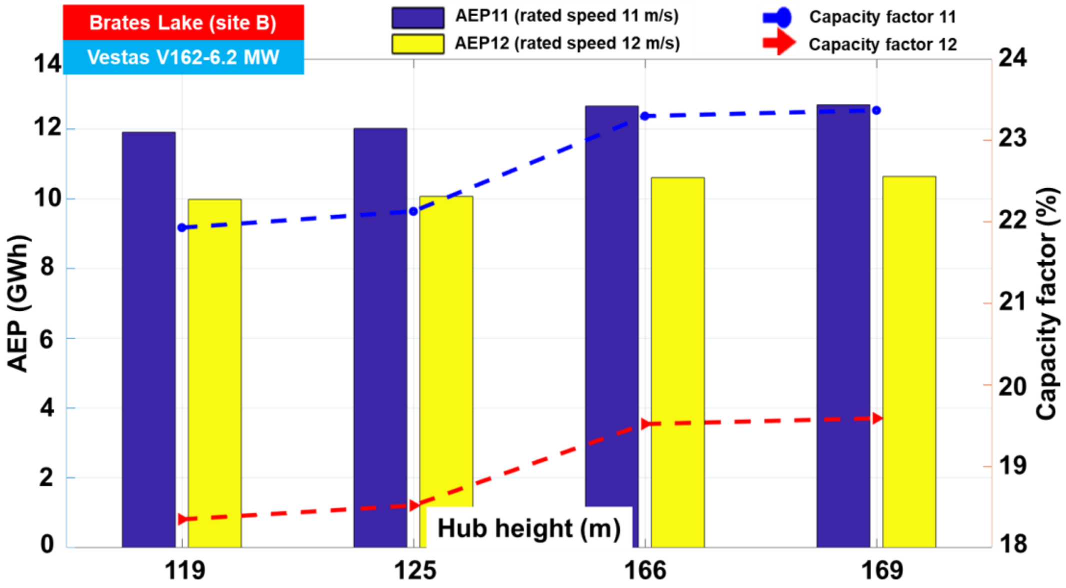

Figure 5.15. Performance of the Vestas V162-6.2 MW Vestas V162-6.2 MW system for the Brateș location, according to ERA5 data (for the time interval 2001-2022). AEP and capacity factor are estimated for different shaft heights and nominal wind speeds 11 m/s and 12 m/s of this turbine

As expected, better performances are associated with a nominal speed of 11 m/s, with AEP values ranging from 11.91 GWh to 12.69 GWh depending on the considered shaft height (from 119 m to 169 m). For the same scenario, the capacity factor starts from 21.93% and reaches a maximum of 23.3% for shaft heights exceeding 166 m. For a wind turbine operating at a rated speed of 12 m/s, the performance decreases by 16.3% for AEP and capacity factor [75]. Figure 5.22 shows the AEP output of the four solar panels shown in Table 5.6, for which the area of water covered by the FPV systems was gradually increased from 10% to 40%.

The production of PEA gradually increases with the area covered, starting from a minimum of 475 GWh for the P1 solar panel (10% area) and reaching a maximum of 2372 GWh for the P4 system (40% area) which is also defined by the highest production capacity of a single unit (540 W). Such a project could provide, on a yearly scale, the following average electricity production if covering the area with: a) 10% - 475 GWh up to 593 GWh (from P1 to P4); b) 20% - 950 GWh up to 1186 GWh; c) 30% - 1425 GWh up to 1779 GWh; d) 40% - 1900 GWh up to 2372 GWh. A scenario of 40% (8 km^2) is difficult to achieve, although similar work has proposed scenarios involving water areas exceeding 20 km^2, from which 7434 GWh of solar energy can be obtained [75].

Figure 5.16 shows the solar radiation incident on a surface for point B, calculated for the time interval 2001-2020, according to the ERA5 dataset, the results indicate for the annual average increased values of more than 165 W/m^2 in 2007 and 2011, and for the monthly average increased values in June and July of more than 250 W/m^2.

Another objective of this thesis is related to the impact of a FPV project on the evaporation of water from Brateș Lake. Figure 5.17 shows such an analysis, where the natural evaporation in this area (without FPV) was estimated based on ERA5 data and Equation 5.6. On an annual scale (Figure 5.17a) there are significant fluctuations, with minimum values of 1.02 x 10^7 m^3 and peaks of 1.36 x 10^7 m^3 expected in warmer years (such as 2017). In terms of the monthly projection (Figure 5.17b), a peak evaporation of 4.37 x 10^7 m^3 is likely to be reached in June and July, compared to only 0.43 x 10^7 m^3 expected for the winter period.

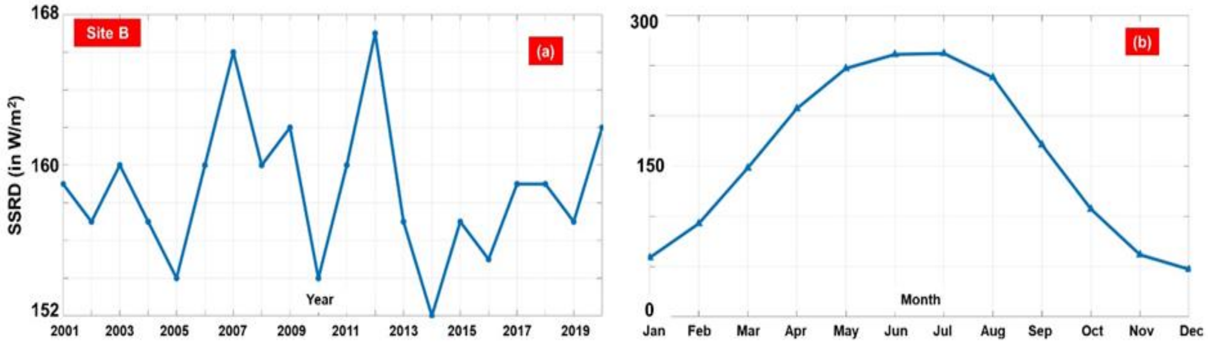

Figure 5.16. Total solar irradiance (in W/m^2) for point B, calculated for the time interval 2001-2020, according to the ERA5 dataset. Results shown in terms of: (a) annual mean; (b) monthly mean.

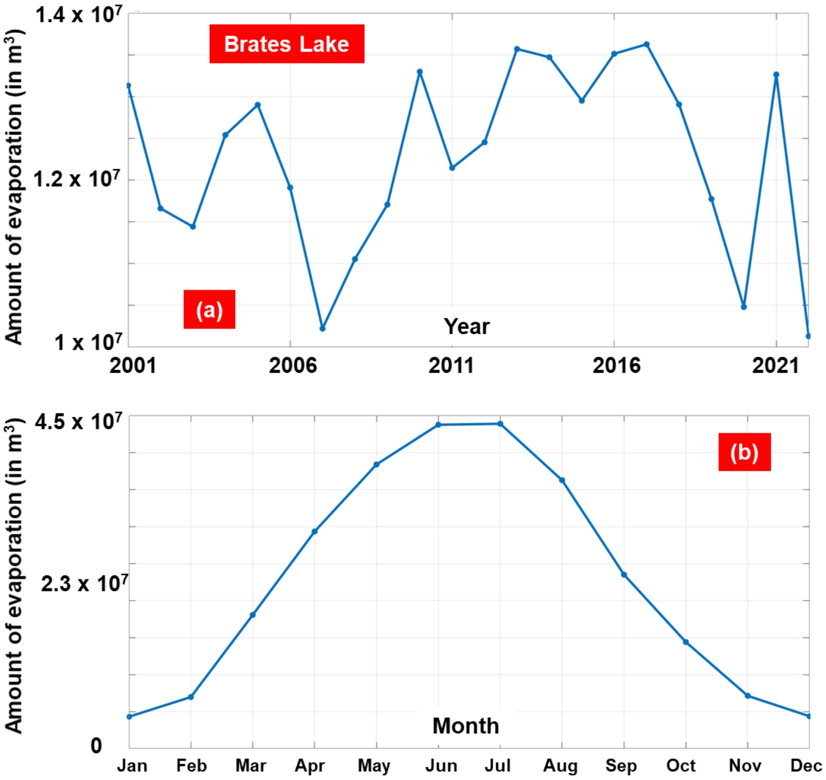

Figure. 5.17. Estimated water evaporation (in m^3) for the whole area of Brateș Lake based on ERA5 data (2001-2022)

Figure 5.18 shows the volume of water expected to be saved by the presence of an FPV project that can operate on Brateș Lake, given the annual distribution. According to these results, the values range from a minimum of 0.5 x 10^6 m^3 for the 10% scenarios and can reach a maximum of 3.27 x 10^6 m^3 for the 40% scenario. A similar analysis was performed in Figure 5.19, this time considering the monthly distribution. A scenario involving a 10% FPV farm can reduce water evaporation with values in the range 0.25 and 2.62 x 10^6 m^3, gradually increasing to a maximum of 5.24 x 10^6 m^3 (for 20%), 7.87 and 10.49 x 10^6 m^3 for the 30 and 40% Scenarios. Comparing this number to the expected volume of water saved by an FPV farm operating on Lake Brateș, I noticed that, on average, a 10% scenario can provide enough water for 3.42 km^2 of agricultural crops, values that increase to 13.71 km^2 for a 40% scenario.

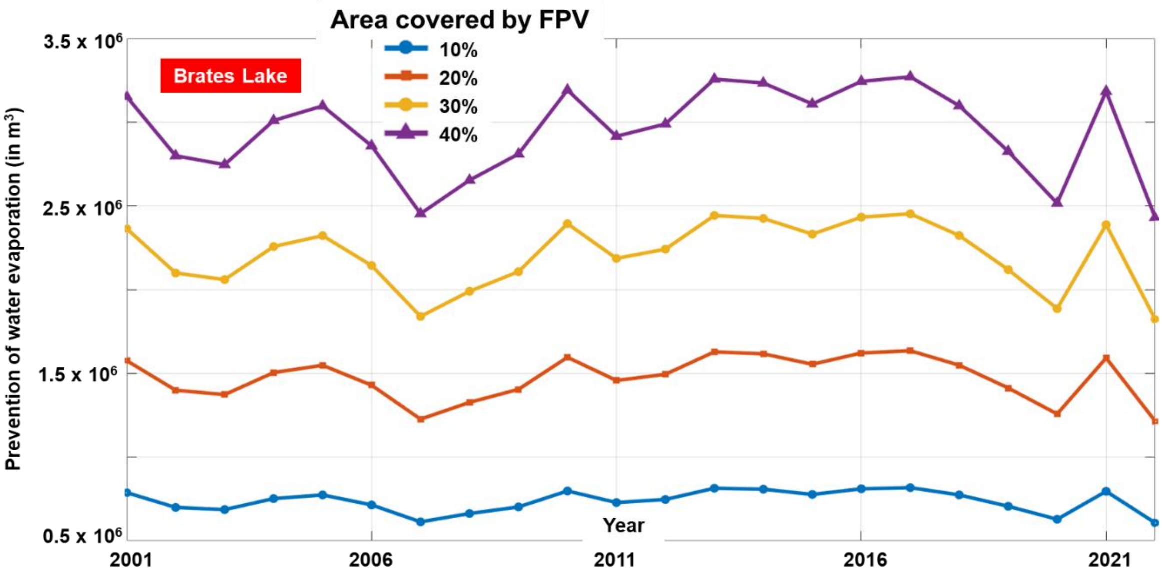

Figure 5.18. Volume of water evaporated by the implementation of the FPV project, considering different scenarios involving Brateș Lake (10%, 20%, 30% and 40%)

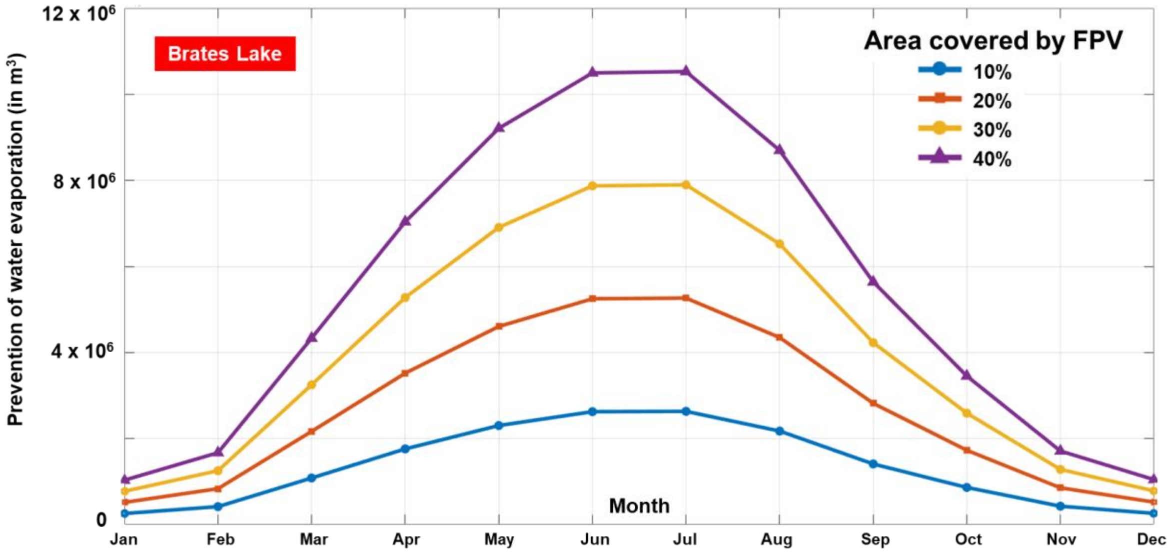

Figure 5.19. Volume of water evaporated per month by implementing the FPV project, considering different scenarios involving Brateș Lake (10%, 20%, 30% and 40%).

5.3 Conclusions

This thesis has provided an overview of the benefits that can be obtained from the implementation of several renewable projects that can be developed in the south-eastern part of Romania. The main objective was to estimate the performance of PV panels for a factory already operating in the neighborhood of Galați, but also in the Caraș Severin region. The results indicate that such a project, placed on the roof of these factories, cannot cover the industrial electricity demand in full, especially in winter, when solar radiation is much lower. The reported results indicate the best-case scenario (CLRSKY), and for values (ALLSKY), which include cloud cover, the expected result may decrease significantly. Concerning the case studies involving wind turbines, it was observed that the southern part of the Romanian coastal area reveals a more attractive wind climate. State of the art wind turbines were considered, but for Sf. Gheorghe and Vama Veche they reveal a much higher value than the energy demand, which indicated that it will probably be more realistic to consider for deployment wind systems with a much lower rated capacity. Going to the Năvodari reference point, it can be observed that for this point a wind farm configuration may be more suitable for deployment, taking into account that this point seems to reveal the lowest wind energy potential of this coastal area. Galați County has a great potential to become a regional *hot-spot in* terms of renewable energy resouces, being expected in the near future the development of a wind project exceeding the capacity of the Fântânele-Cogealac wind project, located in the vicinity of this area and which is among the largest operational onshore wind farms in Europe. On the basis of ERA5 data and *in situ* measurements, the dynamics of wind and solar resources in the vicinity of Lake Brateș, including the evolution of other key parameters (water temperature and evaporation), were identified. This lake, although in an advanced state of degradation, nevertheless remains one of the important water bodies in Romania and the region. For this area, the ERA5 data reproduce quite well the monthly fluctuations of the mean wind speed (*U10)*, while significant differences appear when discussing maximum values. From the performance of the renewable systems, I clearly highlight the AEP output of the Vestas V162-6.2 MW system that is planned to be installed in this region. An objective of the REPowerEU plan is to deploy more floating PV solutions in the marine environment or on lakes to increase electricity production and reduce water evaporation. In this context, the surface area of Lake Brateș (20 km^2) was calculated as % solar panel coverage, the percentage considered ranged from 10% to 40% coverage. In addition to electricity production, it was found that if only 10% of this area was covered, it would save and provide enough fresh water for almost 3.5 km^2 of agricultural land.

Chapter VI
Assessment of Offshore Wind Energy Resources in Romania

6.1 Wind Energy Assessments on the Northern Romanian Coast, Based on Reanalysis and *in Situ* Data for a 20-Year Period

Due to the fact that the wind speed tends to increase as we moving from the shore to the open sea, we set the aim of this paper to analyze a sector of the Romanian coastline located near the Danube Delta. A series of data over 20 years of *in situ* observations (2001-2020) and reanalysis data (ERA5 and MERRA-2) of local wind conditions were analyzed and evaluated from a meteorological and a renewable point of view. This assessment includes two onshore reference points (Galați and Tulcea), one near-shore reference point (Sulina) and two *offshore* reference points defined 64 km and 126 km from the coast.

By 2020, the wind energy sector has an installed capacity of 3,029 MW, covering almost 12% of Romania's total electricity consumption. However, this contribution is expected to rise to almost 35% by the end of 2030 [33]. Certainly, from this region, I can mention the Fântânele-Cogealac wind farm, with an investment of more than 1.1 billion euro and a capacity of 600 MW (120 turbines), which is one of the most important projects in Europe. With an energy production of 255,970 MW/h in 2010, the operating company has reached an important milestone, obtaining with this project a total share of 35.50% of all green certificates in Romania [76]. However, in the long term, *offshore* areas seem to be more promising with regard to wind energy potential. Moreover, in the *Green Deal* agreement promoted by the European Union, *offshore* wind energy is considered as a major pillar and is estimated to reach an installed capacity of 60 GW and 300 GW by 2030 and 2050 respectively [57]. In the whole Black Sea area, the north-western part presents more interest for the *offshore* wind sector as it is defined by more energetic wind resources.

During winter, this area is defined by an average wind power of 823.4 W/m^2 which can easily increase to 857.2 W/m^2 in the near future (2021-2050) [77]. These results are also confirmed in previous studies in which the western part of this sea has been emphasized as an important source of wind and wave energy.

There is a clear distinction between *onshore* and *offshore*, with the wind distribution indicating much higher values, which can reach up to 8.76 m/s in winter. It has also been indicated that the wind speed starts to stabilize or slightly decrease as one reaches the eastern limit of Romania, an economic zone, located 180-260 km from the coastline [57].

From comparison of ERA5 data with *in situ* measurements, it was found that the reanalysis data underestimate onshore wind conditions by at least 11%, this *bias* (systematic error) increases as one goes inshore [78].

Another objective is also to evaluate their influence on the performance of a generic wind turbine. Since some measurements will be used, as a secondary objective, the accuracy of the reanalysis datasets will be discussed at a general level considering different time periods.

Figure 6.1 shows the general structure of the present thesis, while Figure 6.2 shows the target area, which covers the north-eastern part of Romania, more precisely the region of Galați-Tulcea and also the *offshore* area in front of the Danube Delta. The characteristics of the wind profile in this environment will be evaluated by taking into account several reference points located onshore (Galați, Tulcea and Sulina) and also by adding two points in the *offshore* area (O1 and O2).

At this point, it should be emphasized that, from the research done so far, this is the first scientific work in Romania in which the accuracy of different wind speed reanalysis data are processed for this environment and direct comparisons to *in situ* measurements (time series) are discussed.

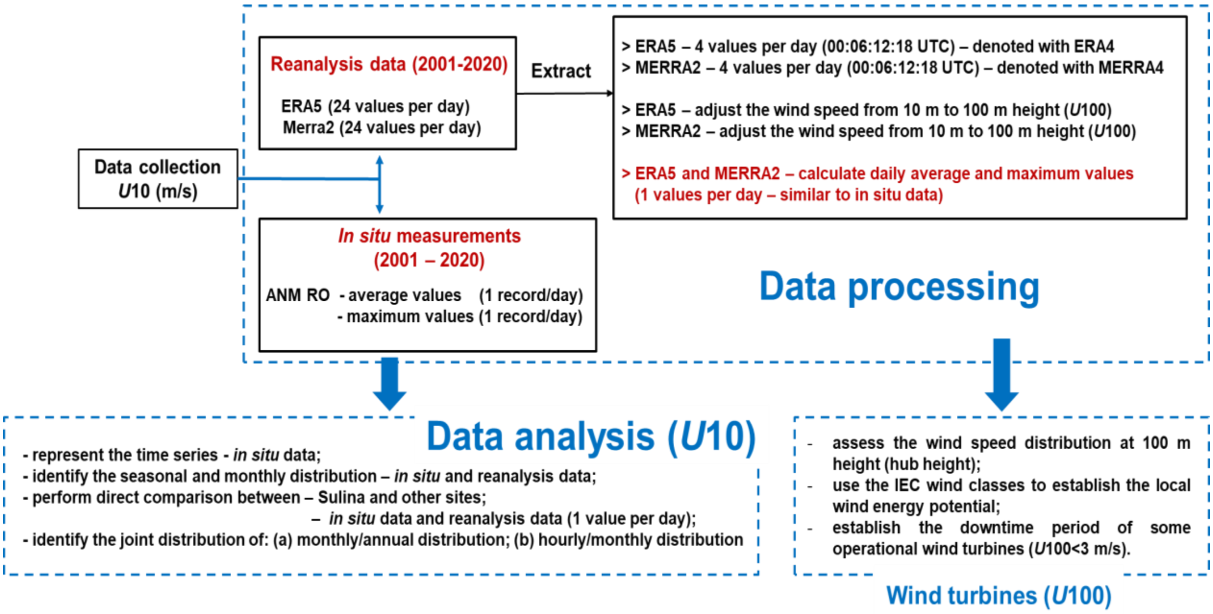

Figure 6.1. Organization chart of the current research, representing the main activities related to data processing, data analysis and wind turbine evaluation, respectively [79].

In Figure 6.2b, more details on these points are shown, that are from an altitude of 72 m (Galați) to a water depth of 171 m (point O2). In comparison to point Sulina (located close to the shore), point O2 is located at a distance of 126 km, being 140 km further from the shore than point Galați.

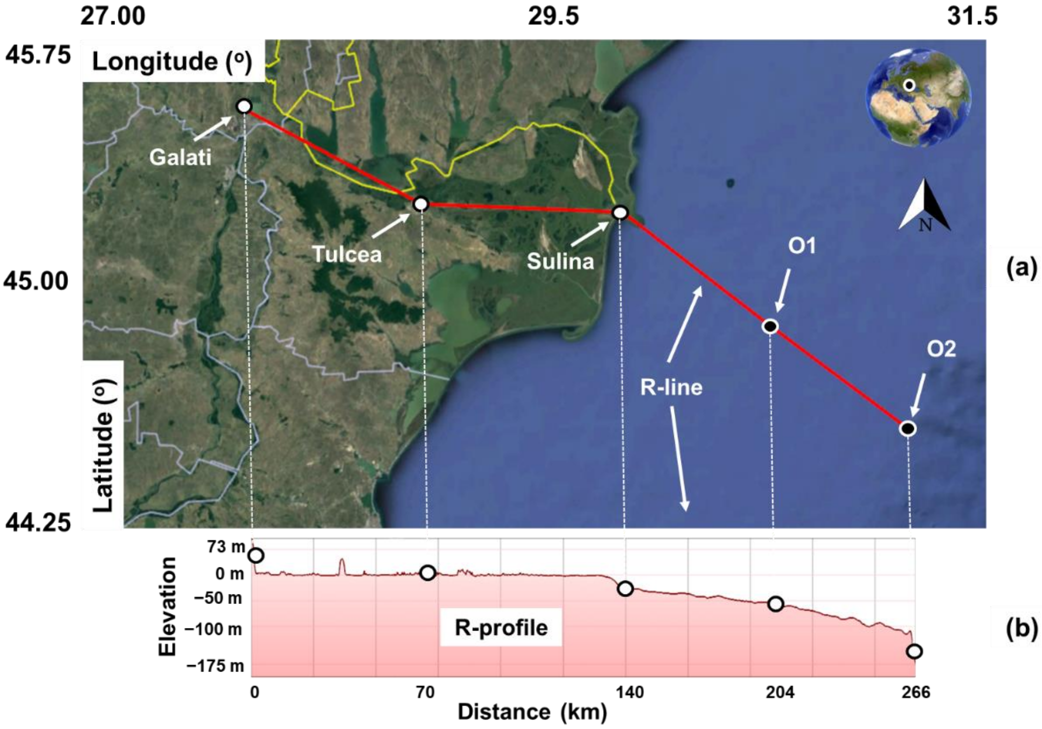

Figure 6.2. Romania's northern coastal area, where (a) is the location of the reference points; (b) the R-profile, including elevation details and distances between points. Information is processed from Google Earth 2022 [79].

Several datasets for different areas will be considered. For points located *onshore* (Galați, Tulcea and Sulina), the primary data source is related to *in situ* measurements corresponding to the wind speed recorded at a height of 10 m (hereafter denoted as *U10*).

These measurements are provided by the National Meteorological Administration of Romania [213], covering a 20-year time span (January 2001-December 2020) of mean and maximum values, with a sampling of 1 value per day.

Table 6.1 shows the reference points chosen for the study, the parameter *U10* mean and maximum of one day, for *in situ* measurements, and for ERA5 and MERRA-2 data 24 values per day, one value per hour and 4 values per day, at different time intervals.

Table 6.1. *Details of the data and points considered for this analysis of ERA5 data with in situ measurements* [79]

Wind data	Benchmarks	Time interval	Parameters	Spatial Resolution (Lat/Long)
Measurements	Galați, Tulcea, Sulina	January 2001-December 2020	U10- average and maximum (1 entry per day) (1 entry per day)	*In situ*
ERA5	All points	January 2001-December 2020	*U10-24* values per day (1 value per hour); *U10-4* values per day (at 00:06:12:18 UTC)	0,25° × 0,25°
MERRA-2	All points	January 2001-December 2020	*U10-24* values per day (1 value per hour); *U10-4* values per day (at 00:06:12:18 UTC)	0,5° × 0,625°

As this work involves *in situ* observations, it represents a good opportunity to assess the accuracy of the dataset for different scenarios (4 values and 24 values daily). Regardless of the scenario considered for comparison, the reanalysis data were processed to obtain daily values of mean and maximum wind speeds (one value per day - similar to *in situ*). A direct analysis with *in situ* measurements will be carried out considering two datasets, covering 4 values per day, denoted with 4 values (denoted with MERRA4) or 24 values (MERRA24). Table 6.2 gives more details on the processed data.

6.2 Results Obtained from the Study of Wind Energy in the Northern Coastal Area of Romania Using MERRA-2 and ERA5 Reanalysis Data

A first view of the local wind resources is represented in Figure 6.3 and Table 6.2, where only *in situ* measurements have been considered. From the time series analysis, we can clearly observe that the Sulina point (located close to the shore) represents more wind energy resources, and more consistent, than the reference points Galați and Tulcea. In terms of mean values, Sulina, with 6.02 m/s, exceeded by far only an average wind speed value of 2.64 m/s. For the points Galați and Tulcea, the time series can be observed to be quite similar.

In order to show more clearly the distribution of the *U10* parameter, a one-month (30-day) rolling filter was applied (for Figure 6.3 only), which is the reason why the statistical values in Table 6.2 may indicate a different pattern. This is also the case for the maximum values, where occasionally some high wind values may occur near the Galați point (28.00 m/s).

From the time series analysis (Figure 6.3b), the Sulina point rises with higher values, consistently reporting values of 8 m/s (mode indicator), the Tulcea point, which for the second part of the time considered interval (2010-2020) shows much higher values than Galați. Based on this information, it can be clearly seen that the wind speed gradually increases from land to shore, reporting a significant jump at the sea-shore interface of the northern sector of Romania.

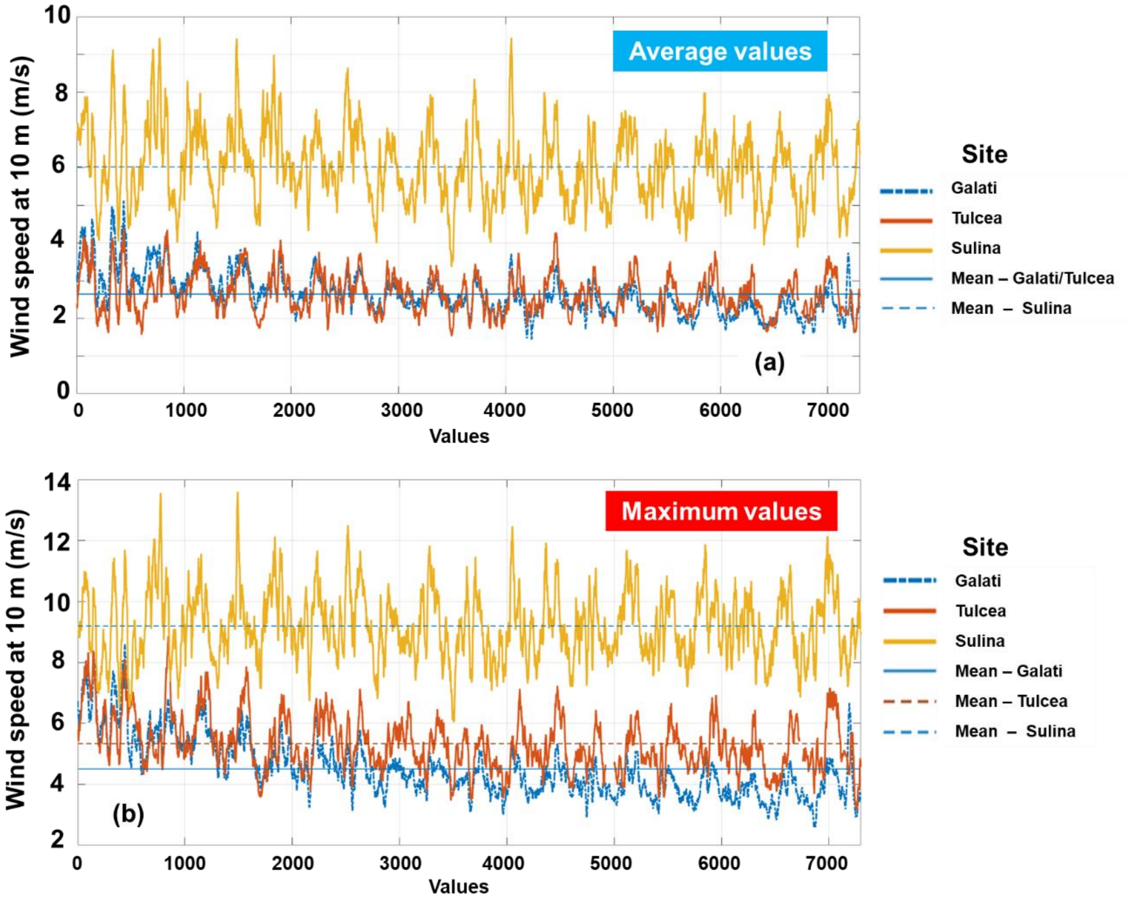

Figure 6.3. *In situ* measurements processed over a 20-year period, from January 2001 to December 2020. Wind speed (*U10)* associated with reference points Galați, Tulcea and Sulina, where: a) mean values; b) maximum values [79].

Table 6.2. *Statistical analysis of parameter U10 recorded by in situ measurements for the points Galați, Tulcea and Sulina. Results are available for the 20-year time interval, from January 2001 to December 2020*

Reference point	**Values**			
	Media (m/s)	**Maxim (m/s)**	**Wind speed (m/s)**	
			Media	**Max**
Galați	2.64	28.00	2.00	4.00
Tulcea	2.65	16.00	1.80	4.00
Sulina	6.02	27.00	5.00	8.00

Figure 6.4, presents a more detailed analysis of the *in situ* observations, focusing this time on the main seasons (MAM: March-April-May; IIA: June-July-August; SON: September-October-November; DIF: December-January-February). In winter (DIF), the average values reach a maximum value of 6.78 m/s near Sulina and a minimum of 2.28 m/s also near Sulina in summer (IIA). In summer time, the average conditions at the Galați point slightly exceed the wind resources at Tulcea, reaching a *U10* value of 2.91 m/s in winter. As for the maximum values, Galați and Sulina are defined by conditions that can exceed 25 m/s, which is the limit operability for most commercial wind turbines. However, a more detailed investigation will be necessary in order to identify the occurrence of adverse wind events that may influence the structural integrity of a wind system.

Using the Sulina point as a reference, the relative balance difference, BRE (in %), for the *in situ* analysis, was calculated as [80,81]:

$$BRE = \left(\frac{X_{base} - X_{compared}}{X_{base}}\right) \tag{6.1}$$

where, X_{base} - *in situ* measurements associated with the Sulina point; $X_{compared}$ *in situ* measurements associated with the Galați/Tulcea points.

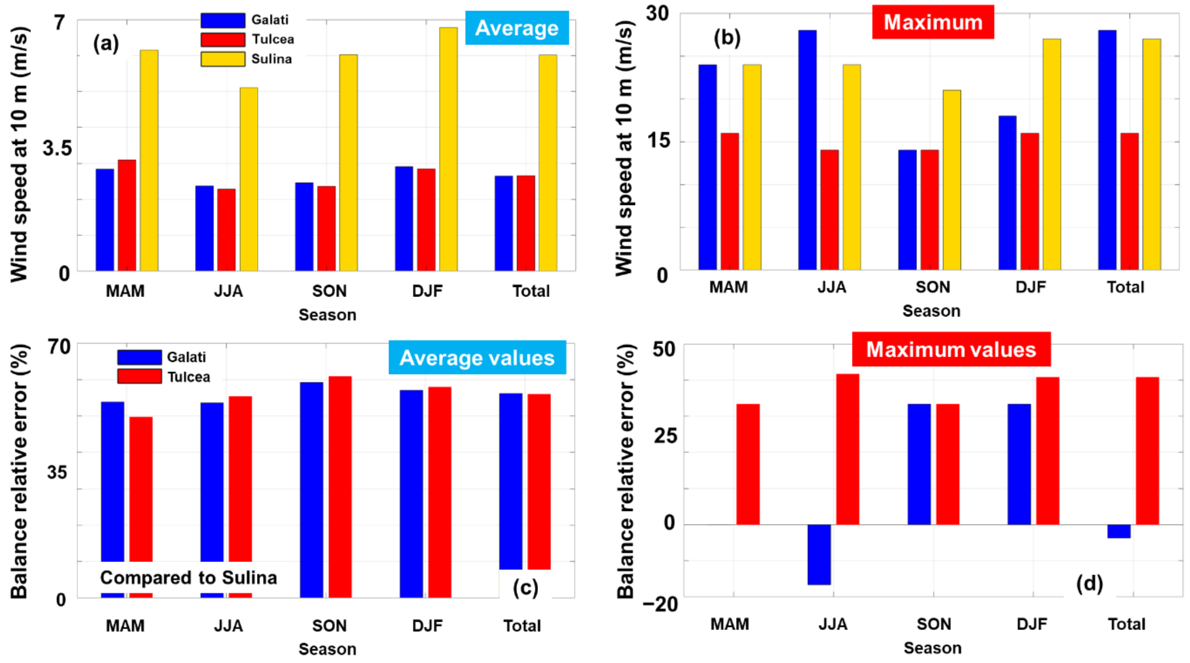

Figure 6.4. *U10*, statistical results over all seasons. The values are associated over a 20-year interval from January 2001 to December 2020, where (a) mean values, (b) maximum values; (c, d) differences reported at the Sulina point, calculated on mean and maximum values [82].

This comparison is more relevant for the mean values (Figure 6.4c), where it can be observed that the wind speed in Sulina shows more consistent differences. For example, during the fall season (SON), the maximum difference of 60.9% is observed from the comparison to Tulcea, while a minimum of 49.8%, is observed, during spring for the same reference point.

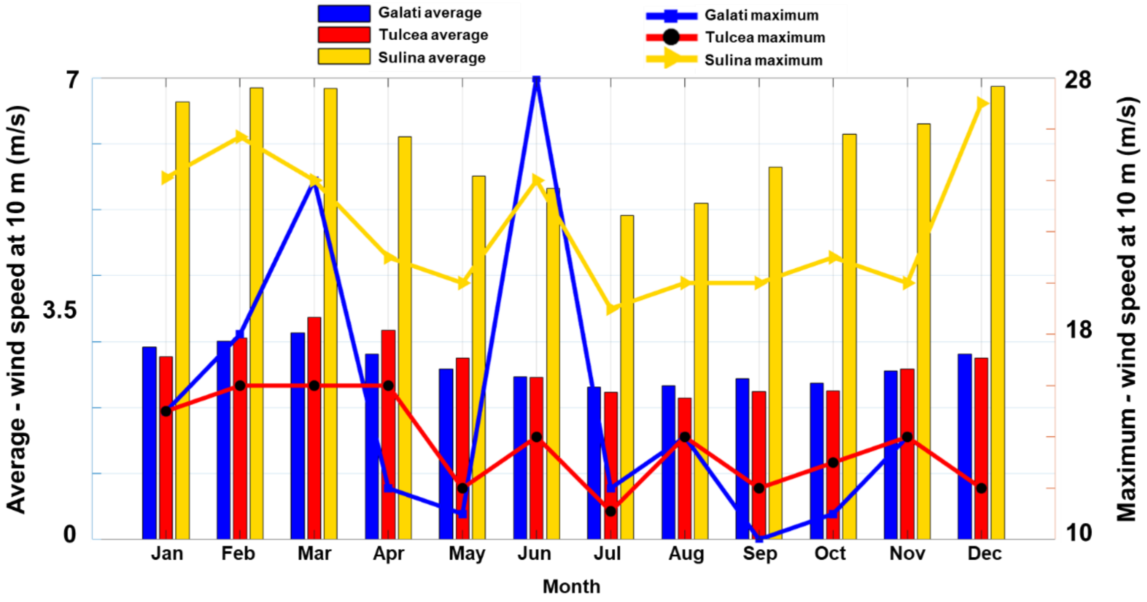

Figure 6.5. *U10*, monthly values corresponding to *in situ* measurements for Galați, Tulcea and Sulina. The statistical results are processed for a 20-year time interval, January 2001 to December 2020, indicated in terms of mean and maximum values [82]

The monthly distribution of wind conditions is shown in Figure 6.5, including mean (left legend) and maximum (right legend) values. The mean values show the seasonal pattern of conditions, with a minimum in summer and maximum in winter. For the maximum values (line representation), there is a random distribution, with peaks occurring throughout the year, which, for example, in the case of the Galați point, can go up to 28 m/s (in June). This seems somewhat counterintuitive, considering that this value is reported over a summer month, exceeding the maximum value associated with the Sulina point (27 m/s in December).

There are four main classes, sorted according to average wind speed (10 m/s; 8.5 m/s; 7.5 m/s and 6 m/s), a suitable area for a wind renewable energy project will be surveyed to cover the higher wind classes. In addition, the selection of a particular wind turbine may be carried out according to a particular IEC wind class.

The initial wind speed *U10* was adjusted for a height of 100 m, using the following formula [35,83]:

$$U100 = U10\left(\frac{\ln(z_{100}) - \ln(z_{10})}{\ln(z_{10}) - \ln(z_0)}\right) \tag{6.2}$$

where *U100* - wind speed at 100 m (in m/s); *U10* - wind speed at 10 m (in m/s); z_{100} and z_{10} - reference heights (100 m and 10 m); and z_0 - sea surface roughness.

From the information provided in Figure 6.6, class IEC1 has been observed only once, only in recent years (2015-2020), with the mention that, in the last three consecutive years the values exceeded 10 m/s (February 2018, December 2019 and 2020). During the winter, summer and fall seasons, the presence of IEC2 and IEC3 values is visible, while during summer most of the values fall into the IEC4 category or below. As a rule, the IEC4 class is not considered suitable for the development of a wind project, and it is possible to encounter these types of conditions even in winter. From this point of view, July represents the least energetic month with values in the range 4.66-7.50 m/s. Overall, in recent years, the IEC2 class is starting to become more frequent, as evidenced by the March and November distributions. The frequency distribution of the wind classes is shown in Figure 6.6, by including all available wind data series reported for the time interval January 2001-December 2020, including mean and maximum values. For the reference points in Galați and Tulcea, the mean values are concentrated in the range 3-10 m/s, while for Sulina there is a constant distribution in the range 6-16 m/s and a peak range for 16-17 m/s.

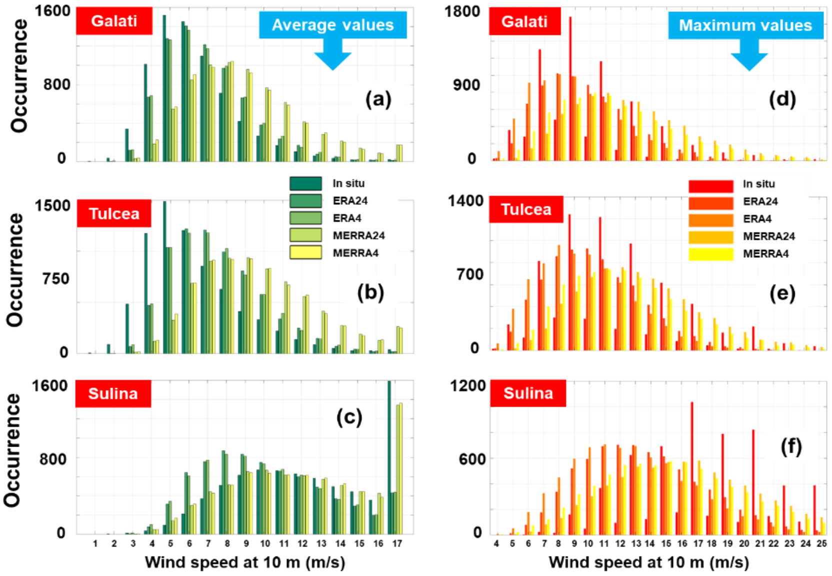

Figure 6.6. Frequency distribution of the parameter *U10 as* indicated by wind datasets at the points Galați, Tulcea and Sulina, using ERA5 and MERRA-2 datasets. The results are processed for the 20-year time interval (2001-2020), where: (a-c) mean values; (d-f) maximum values.

From the observations of the measurements for Galați and Tulcea, the mean values, are much higher for wind conditions (6 m/s), after this threshold was consistently below the distribution indicated for the reanalysis data. As one moves to higher values, the MERRA datasets overestimate the wind conditions, also exceeding the ERA5 values. For the Sulina point (Figure 6.6c), ERA5 shows much higher values for the 0-10 m/s range and appears to underestimate the wind resources for the higher wind classes. From the databases considered (24 daily values and 4 values), per day it appears that in most of the cases in the 24-value category it gives somewhat higher results, but the observed differences were quite small. For the maximum values in Figure 6.6d-f data are from *in situ* measurements, being distributed below 10 m/s, for the onshore points (Galați and Tulcea) and for the Sulina case, above 16 m/s.

A direct comparison between the two datasets (24 values and 4 values per day) is shown in Table 6.4, only for ERA5 wind data, where for the first time, I have introduced *offshore* points O1 and O2, respectively. As shown in Figure 6.7 the differences between the mean values are rather small (close to zero), more important variations are accounted for by the maximum values (e.g. point O2) and the parameter mod, which is the most frequent number associated with a dataset (m/s).

Table 6.4. *Statistical analysis of the U10 parameter based on ERA5 processed data for the 20 years time interval: January 2001-December 2020. The results cover two datasets, namely: (*) all values - 24 values per day; (**) 4 values per day related to 00:06:12:18 UTC*

Reference point	**Data set**	**Parameters**			
		Media (m/s)	**Maxim (m/s)**	**Standard deviation (m/s)**	**Most common value (m/s)**
Galați	All values(*)	3.01	12.30	1.46	2.32
	4 values (**)	3.03	11.70	1.47	2.21
Tulcea	*	3.29	13.70	1.58	3.00
	**	3.30	13.70	1.58	2.19
Sulina	*	4.62	17.10	2.17	2.46
	**	4.62	16.80	2.18	4.99
O1	*	6.17	22.7	2.94	5.95
	**	6.17	22.7	2.94	10.3
O2	*	6.13	25.30	2.93	3.86
	**	6.13	20.30	2.93	10.10

The hourly distribution of wind conditions (mean and maximum values) is shown in Figure 6.7, considering only the reanalysis data. In the case of mean values, MERRA-2 data consistently show values higher than ERA5 over the whole day, and irrespective of the area considered. For the points Galați and Tulcea, it could be considered a wind turbine that performs much better during the day (07:00-16:00 UTC), reaching a maximum peak around 12:00 UTC. As for Sulina, according to ERA5, more significant resources appear during 05:00 and 15:00 UTC.

On the other hand, the MERRA-2 data indicate *U10* values higher than 5.9 m/s between 05:00 and 10:00 UTC, while the values decrease below 5.6 m/s during the second part of the day (14:00-18:00 UTC). From the plot providing maximum values (Figure 6.7b), there is a constant distribution throughout the day, with the exception that for the Sulina reference point, the MERRA-2 data are significantly higher during the first part of the day and decrease gradually, from 23 m/s to a minimum of 18.2 m/s around 13:00 UTC. In this case, the lower values are indicated by the ERA5 dataset for Galați and Tulcea. As a next step, a more detailed assessment of the wind conditions at a height of 100 m (height of the turbine axis) will be performed using only the ERA5 dataset, which seems to show a better result with *in situ* measurements for two (out of three) *in situ* stations. Moreover, ERA5 data are frequently used to assess wind energy [33], showing a good level of global scale observations [84].

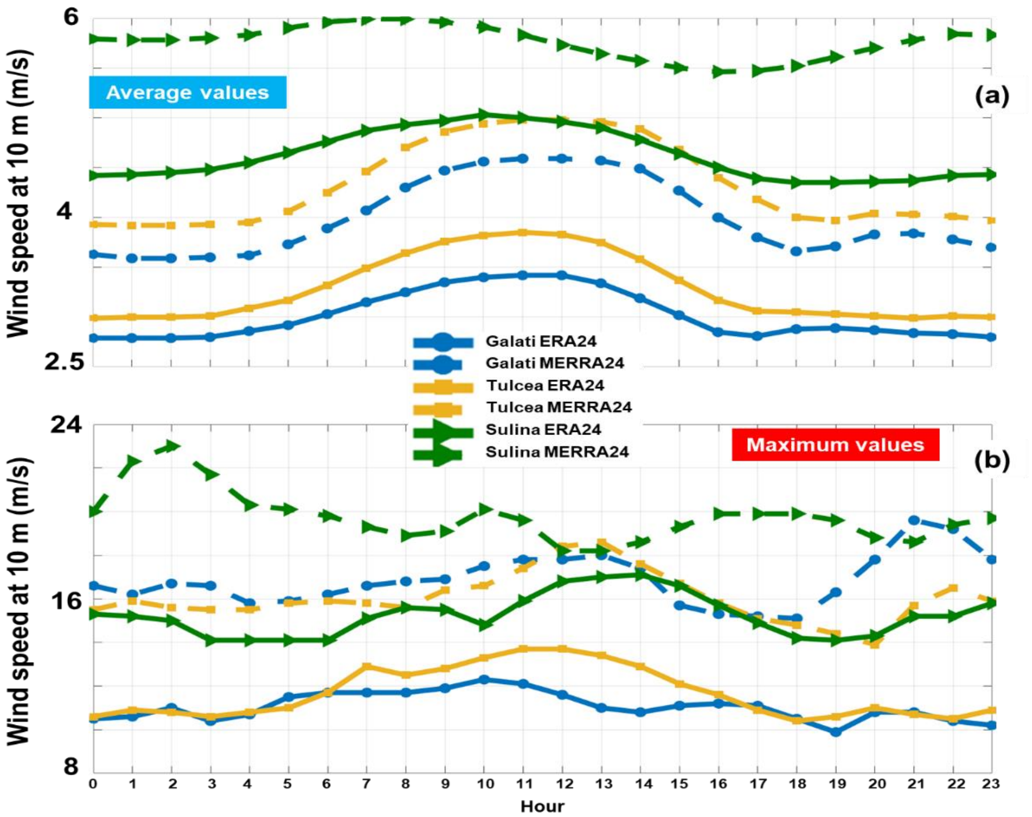

Figure 6.7. Hourly wind speed distribution, as indicated by reanalysis data (ERA5 and MERRA-2), for reference points Galați, Tulcea and Sulina, where: (a) mean values; (b) maximum values [79]

Figure 6.8 shows the distribution of the parameter *U100* with an average value by months and hours, considering only the reference point, Sulina. The seasonal variations are more important than the diurnal distribution, expecting higher wind resources during November-March, an interval with a maximum peak for the time interval 07:00-13:00 UTC.

During this period, wind conditions frequently reach 7 m/s, with periods in the range (6 m/s-6.5 m/s) also reported. During summer, maximum wind speed values of 5 m/s are observed during the day, while, at night, the values decrease to 4 m/s. In this case, the transition between the two energy zones is observed around 03:00 UTC and 17:00 UTC, respectively.

Besides Tulcea, in the case of Galați, there are two points with low wind speed occurring at 19:00 UTC in May and August (24%).

The maximum differences usually occur in winter, but in the case of Tulcea, for example, these types of values are observed during all months, except for the central part of the distribution, where the hour of the day has a greater influence. The differences between O1 and O2 are very similar, showing a better agreement in May (20%) compared to the rest of the months.

A maximum would be the value of 33.12% which is present in summer after 16:00 UTC, while a minimum would be the value of 8%, which is frequently observed in winter (January-February-December). Based on these values, it is expected that a maintenance task will be planned during summer, especially at night.

For *onshore* benchmarks, downtime periods of 63% can be expected during summer (e.g. Galați), compared to only a maximum of 23% for *offshore* (e.g. O1).

During winter, which is considered to be a more energetic period, the values can go down to: Galați - 20.36%; Tulcea -15.39%; O1 - 3.95%; and O2 - 3.8%. From the onshore points, also Tulcea shows a lower shutdown period during August-December, especially for the interval 06:00 - 14:00 UTC.

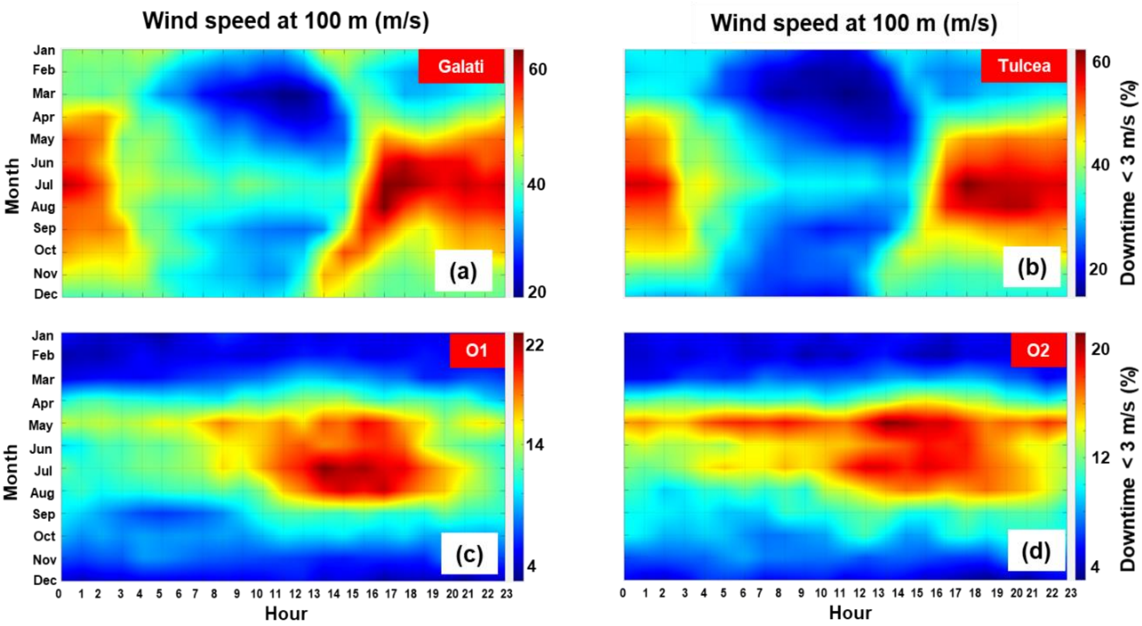

Figure 6.8. Differences between the *U100* parameter (mean values) corresponding to the reference points Sulina, (a) Galați, (b) Tulcea, (c) O1; (d) O2. ERA5 reanalysis data cover the whole-time interval (2001-2020) [79]

6.3 Synthesis and Analysis of the Study of Wind Energy in the Northern Coastal Area of Romania, using 20 Years of Reanalysis Data

The aim of the European Green Deal is to achieve climate neutrality by reducing greenhouse gas emissions by at least 55% (compared to 1990) by 2030 and to promote the use of renewable solutions.

Clearly, it can be seen that in winter wind energy production increases (e.g. 1000 MW in 2015), while in summer it is reduced by almost 50%. At the end of 2021, electricity from wind exceeded coal production and was relatively close to the values from nuclear.

Based on the results obtained and compared to previous works, the following novelties can be highlighted. For the first time, several *in situ* time series are used to quantify the variation of wind conditions as moving from the shore to the open sea (Galați-Tulcea-Sulina). These results confirm previous studies focused on the spatial analysis of wind conditions, where only the reanalysis datasets (ERA-Interim, NCEP or ERA5) were processed. The differences between the hourly values (24 values) and 4 values (at 00:06:12:18 UTC) of the reanalysis dataset were performed. For the current target area and for the time interval considered (2001-2020), there are no significant differences, indicating that much lower data can be used to utilize wave energy. To the author's knowledge, such an assessment has not yet been carried out. Modern data analysis for MERRA-2 research and analysis an assessment of the values has been used for the first time in the northwestern part of the Black Sea to assess the wind energy potential. From comparison to *in situ* data, they seem to give a better yield for points along the coastline compared to ERA5. However, this needs to be further developed.

6.4 Conclusions

The south-eastern part of Romania is defined by significant wind resources and it result is targeted by wind energy developers, with the majority of projects being located between the county of Galați and the Black Sea coast. According to previous research work by the author, based on reanalysis data, it was found that local wind energy increases significantly as one moves from *onshore* to *offshore* regions, with a significant jump near the coastal profile. In this context, for the present work, data over a 20-year period (2001-2020) were studied and evaluated considering *in situ* measurements from three onshore points (Galați, Tulcea and Sulina) and reanalysis data (ERA5 and MERRA-2), which also include some marine areas located near the Danube Delta.

According to the *in situ* observations (*U10*), the differences between the two *onshore* points (Galați and Tulcea) are quite small in terms of mean values (2.65 m/s), compared to Sulina, where a maximum of 6.02 m/s is observed. At this point, I can say that the Sulina point is more attractive for a wind project, with future work expected to include some *offshore* measurements (e.g. from the Gloria platform) to confirm this trend for marine regions. From comparison to the reanalysis data, ERA5 gives better agreement for the *onshore* points (Galați and Tulcea) in terms of mean values, while for the Sulina point (coastal area) MERRA- 2 values are more accurate. The first time MERRA-2 wind data were used for the Romanian coastal area, and consequently, further analysis will be needed to confirm this model. In order to reduce the computational demand, for long-term and climatological studies only four times of the day, (00:06:12:18 UTC), were used instead of hourly data. The selection of these hourly time intervals seems to be appropriate for these types of studies, with very small differences observed between the two categories of data. This can be observed for both databases (ERA5 and MERRA-5) in terms of mean values, while for maximum values, the four-valued category always underestimates these types of events. From the distribution of IEC classes (*in situ* U100-data values), it was evident that in winter and spring periods, the dominant wind classes are C2 and C3, with C1 values (four events) briefly observed in January, February and December. Moreover, on an interannual basis, the wind profile changes, with more energizing wind conditions observed over the last 10 years (2010-2020). During the summer and fall, most wind conditions fall into the C4 category, which is considered unattractive for a wind project. For this range, better performance could be expected in April and October, when class C3 (*U100* > 7.5 m/s) frequently occurs.

Depending on the period of inactivity (*U100* < 3 m/s), the points of Galați and Tulcea, are defined by a lower period of inactivity during the day (05:00-15:00 UTC), indicating that maintenance tasks should be performed during the night, preferably in summer and autumn. The downtime can reach up to 60%, compared to only 33% for the Sulina point. For the chosen *offshore* points (O1 and O2), the downtime values are directly influenced by the monthly distribution, but even so do not exceed a maximum of 23%. Finally, I can conclude that the Romanian wind sector is in continuous expansion, where new projects are constantly appearing near the Black Sea coast (*onshore)*, and if this trend will continue, some *offshore* wind farms are expected to appear in the near future.

Chapter VII
Analysis of Energy Potential in the Black Sea Coastal Areas

7.1 Climate Characteristics and Wind Data in the Black Sea Area

The Black Sea, one of the most intriguing and complex marine ecosystems in the world, serves as a fascinating research topic for biologists, oceanographers and climatologists [246]. The Black Sea covers an area of approximately 436,000 square kilometers, making it one of the largest inland seas in the world. Its average depth is about 1,200 meters and the deepest depth reached, known as the Crimean Trench, goes down to 2,212 meters. The climate of the Black Sea is significantly influenced by its geographical position, with average annual temperatures ranging between 11°C and 17°C, warming in summer and cooling in winter.

A distinctive feature of the Black Sea wind is its seasonality. In summer, westerly and north-westerly winds prevail, bringing cold, dry air from central Europe. The main conclusion is that the Black Sea is susceptible to significant variations in wind, waves and water temperature due to the influence of meteorological phenomena.

From a general perspective, it is clear that *offshore* areas (100 km offshore) are defined by much higher wind speed values than onshore areas, reaching an average of 8.75 m/s for points located in the western sector. In winter, these values can reach up to 8.75 m/s, although the northern parts of Ukraine and Russia can slightly exceed 8 m/s. In terms of wind turbine selection, for *offshore* areas defined by consistent wind resources, generators will be considered to be defined by a nominal wind speed of 11 m/s. Finally, it can be mentioned that a theoretical *offshore* wind turbine of 20 MW can achieve a capacity factor ranging from 20.9 to 48.3%, while a maximum annual electricity production of 84.6 GWh can be obtained from locations located near the Romanian and Ukrainian sectors, respectively.

7.2 Assessment of Near-Shore Wind Energy Resources from Onshore to Offshore as Reflected by the ERA5 Dataset for the Black Sea

Each wind project is defined by particular characteristics, depending on the installation area (*onshore* and *offshore*). The best example is the Fântânele-Cogealac project, defined by an operating capacity of 600 MW and is located about 17 km offshore [85]. Looking at existing studies focused on wind conditions in the Black Sea, I observed that these resources increase significantly as we go from *onshore* to *offshore*, and a sharp transition is expected near the shore. For example, in that thesis [83], from the spatial distribution of wind conditions, it was shown that wind resources in offshore areas consistently exceed those onshore (by at least 2 times). Another interesting aspect is represented by the fact that, in this region, the best wind resources are noticed in the central part, in the Sea of Azov, where maximum wind speeds of more than 8.24 m/s can occur in winter (*U10* values). In the paper [86], regional wind resources (*U10* values) were evaluated, taking into account measurements according to reanalysis data. During winter, average wind speed values of 8 m/s can occur in the north-western areas (e.g. Crimean Peninsula) while minimum average values of 3.5 m/s, are associated with the south-eastern sector. Although wind conditions increase significantly from the shore offshore, a stabilization of conditions is expected. This seems to be the case for the Romanian coastal sector [78], where mean wind conditions (*U10)* can start from 4.37 m/s (shoreline), reach a maximum of 5.89 m/s (100 km offshore), and decrease to 5.75 m/s at a distance of 220 km offshore. These values are specific to the southern part of this region being based on ERA5 reanalysis data. Most of the wind studies have focused on the whole Black Sea basin and cover only marine areas, where they have been analyzed on various topics, such as extreme event analysis [87], climate change [77] or as input data for regional wave models [88].

Figure 7.1 illustrates the target area of the Black Sea, including the reference points for the analysis, which are considered. In total, there are nine reference lines, defined along different coastal areas, such as Romania, Russia, Georgia or Turkey with the mention that among all the reference points located close to the shoreline (noted with No. 2), a distance of 100 km was considered to define the points (No. 1), while a similar distance was associated with the *offshore* points (No.3). More details on the considered points are provided in Table 7.1.

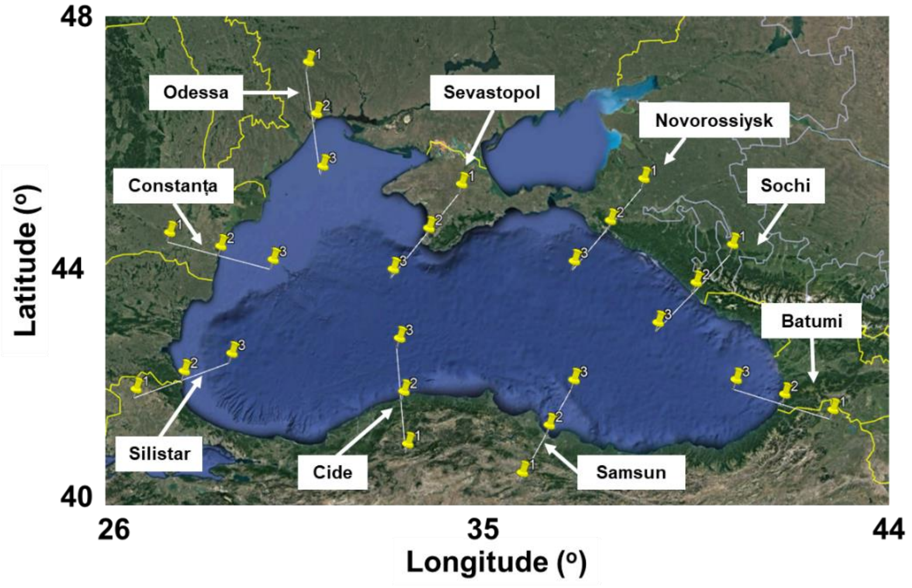

Figure 7.1. Black Sea target area includes reference points, where: 1- *onshore*, 2 *-nearshore,* 3- *offshore*. Map processed from Google Earth, 2022 [89]

Table 7.1 *Characteristics of reference points along the Black Sea shoreline* [89]

Reference line	**Reference point**	**Lat (º)**	**Long (º)**	**Height/depth (m)**
L1	Constanța (RO)	44.15°	28.66°	-9
L2	Odessa (UA)	46.47°	30.76°	1
L3	Sevastopol (UA)	44.60°	33.55°	47
L4	Novorosiisk (RU)	44.70°	37.81°	63
L5	Soci (UK)	43.59°	39.75°	78
L6	Batumi (GA)	41.60°	41.66°	47
L7	Samsun (TR)	41.31°	36.29°	0
L8	Cide (TR)	41.87°	33.04°	216
L9	Silistar (BG)	42.01°	28.01°	17

Table 7.1 shows the characteristics of reference points and profile lines, including information related to sea level (height=0 m) and distance to nearshore sites (distance from shoreline=0 km).

7.3 Analysis and Classification of Coastal Wind Classes

The evolution of regional wind resources is realized using the ERA5 dataset [63], which includes wind fields directly reported at the 100 m level (denoted by *U100*), this height is commonly considered for the development of *onshore* and *offshore* wind generators. A total of 20 years of data, covering the interval from January 2002 to December 2021, are processed, the initial dataset being defined by a spatial resolution of 0.25^0 and four values per day (00-06-12-18 UTC).

Figure 7.2 shows the profile lines, including information related to sea level (height=0 m) and distance to nearshore locations (distance from shoreline=0 km). Each line is defined by particular characteristics that vary from a maximum altitude of 2,694 m to water depths of 2,605 m, the most attractive for the implementation of wind farms being located on the western sector (L1- Constanța and L2- Odesa). The marine points located near the L1 and L2 lines can enable the implementation of a monopile design, because they are located in a plateau area where the water depth is close to 50 m (or below).

This dataset is commonly used to assess wind energy worldwide and is also considered for some coastal sectors in the Black Sea [90]. Various analyses are performed, including seasonal distribution, which are sorted as follows: Spring- March, April, May; Summer- June, July, August; Fall- September, October, November; Winter- December, January, February. One way to quantify the quality of wind resources is to use wind classes. These start from class C1 (low energy level) to C7 (ideal conditions), as can be seen from Table 7.2, in thesis.

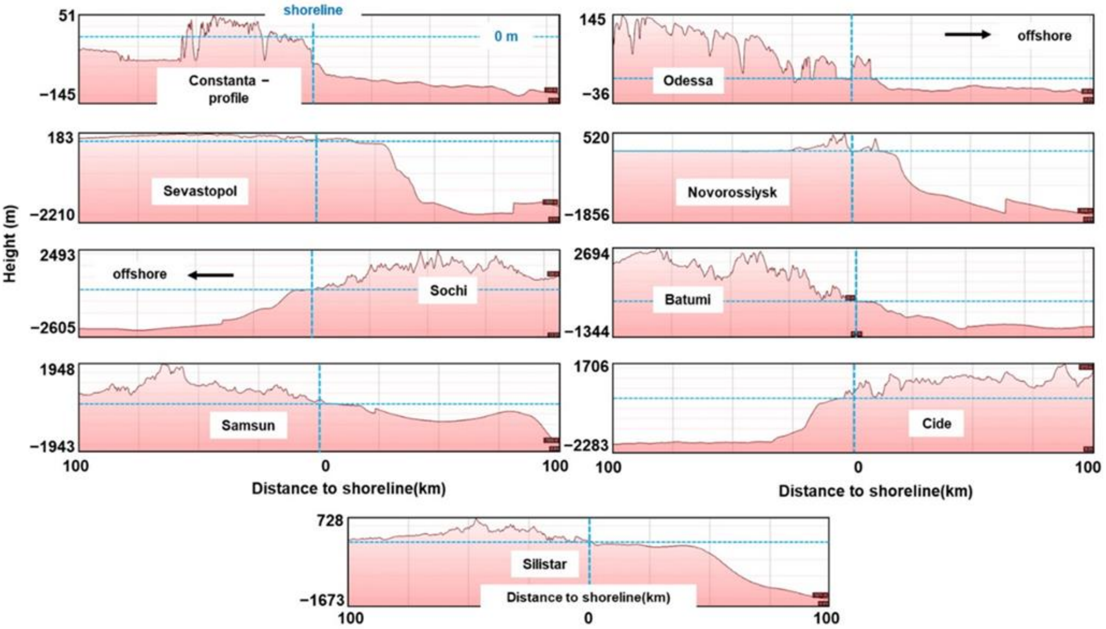

Figure 7.2. Profile lines plotted for all reference points. All values are relative to sea level (h=0) as provided in Google Earth 2022 [82].

The EWSO indicator is related to the wind speed distribution between the coupling and decoupling values of a turbine (4 m/s and 25 m/s, in this case) and if more than 80% is observed, each indicator is assigned a normalized value of 1.

This type of analysis has been developed to assess only the wind potential of a specific offshore point, while in the present work several onshore reference points have been considered, which can be considered as a novelty.

In the next step (denoted by b), each indicator is given a weighting value according to their importance, the most important being considered W_{ann} and EWSO, while on the opposite side,I found water depth (0.07) and monthly variability (0.05) respectively. The RLO indicator is related to the occurrence of wind energy density greater than 200 W/m^2 and, for example, if a distribution of 90% above this threshold is observed, a normalized distribution value is accounted for. For the parameters C_v and Mv, if the values reported by a reference point exceed 1.75, a normalized value is taken into account, which is zero. In the case of water depth and distance to the coast, if it does not exceed 25 m and 0,5 m respectively, a maximum score will be given, while on the opposite side, if the depth exceeds 500 m, a normalized value, which is zero, is taken into account.

In an ideal scenario, a given point can be classified as superb (class C7) if for all criteria, a normalized value of one is obtained. Finally, for each reference point, a number in the range 0-1 is obtained, which can be included in seven classes (from C1 to C7), depending on their attractiveness for a wind project. More details on this approach and the definition of the parameters involved are provided in [91].

The wind speed carrying the maximum energy parameter (denoted by V_{maxE}) can be used to find the suitable location for a given wind turbine at a given reference point, taking into account the available wind resources [92].

Another objective of the present work was to evaluate the performance of wind turbines that can operate both offshore and onshore.

In Table 7.3, where, several parameters are considered, namely: W_{aann} (m/s) - annual average wind speed, referred to *U100*; EWSO (%) - frequency of occurrence of effective wind speed; RLO (%) - occurrence of high level; C_v - coefficient of variation; M_v - monthly variability; EWS (m/s) - extreme wind speeds; WD (m) - water depth; DC (°) - distance to the coast. In the first part (denoted by a), a normalized value between 0 and 1 (with a value of 0.25 as a range) are assigned to each indicator.

Table 7.3 *Classification of wind energy resources involving several parameters. Results processed from (a) to (c) according to Costoya* [91]

(a) normalized criterion

Normalized values	EWSO (%)	RLO (%)	C_v	M_v	EWS (m/s)	WD (m)	DC (º)
0	<20	<20	>1.75	>1.75	>28	>500	>4
0,25	20-40	20-40	1.25-1.75	1.25-1.75	25-28	100-500	3-4
0,5	40-60	40-60	0.75-1.25	0.75-1.25	20-25	50-100	2-3
0,75	60-80	60-80	0.25-0.75	0.25-0.75	15-20	25-50	0.5-2
1	80-100	80-100	<0.25	<0.25	<15	0-25	<0.5

(b) the importance of each parameter

	W_{ann}	EWSO	RLO	C_v	M_v	EWS	WD	DC
Weight	0.22	0.22	0.1	0.1	0.05	0.14	0.07	0.1

(c) classification of resources

Class	1	2	3	4	5	6	7
Category	x≤0.4	0.4≤x≤0.5	0.5≤x≤0.6	0.6≤x≤0.7	0.7≤x ≤0.8	0.8≤x≤0.9	x>0.9
Indicators	Slab	Marginal	Reasonable	Good	Excellent	Remarkable	Great

In this case, a generator defined by a nominal wind speed that is close to the value of this indicator is more than recommended.

This indicator can be calculated like [93]:

$$V_{maxE} = c\left(1+\frac{2}{k}\right)^{1/k} \qquad (7.2)$$

where c and k are the scale and shape parameters of a Weibull distribution function.
The Weibull distribution can be defined as [94]:

$$f(u) = \left(\frac{k}{c}\right)\left(\frac{u}{c}\right)^{k-1} exp\left[-\left(\frac{u}{c}\right)^{k}\right] \qquad (7.2)$$

where c, k are Weibull parameters; u- wind speed (U100 in this case).

Two wind turbines are given in Table 7.4, the GE Energy 2.5xl wind turbine, which is frequently used in *onshore* projects, such as the one at Fântânele-Cogealac, Romania Since it is expected that in the near future, such systems will become operational, having a nominal capacity that can easily exceed 20 MW [95,96].

Table 7.4. *Characteristics of wind turbines investigated in this paper* [82]

Turbine model	**Power (MW)**	**Starting speed (m/s)**	**Nominal wind speed (m/s)**	**Stopping speed (m/s)**	**Tower height (m)**	**References**
GE Energy 2.5xl	2,5	3,5	13,5	25	75-100	[97]
20 MW model	20	3	10,7	25	160.2	[98]

The annual electricity production of a turbine can be defined as [38]:

$$AEP = T \times \int_{cut-in}^{cut-out} f(u)P(u)du \qquad (7.3)$$

where AEP - is expressed in GWh, T - the number of operating hours in a year (8760 in this case), f(u) - the Weibull function from equation (2), P(u) - the power curve of a given wind turbine, defined by the decoupling values.

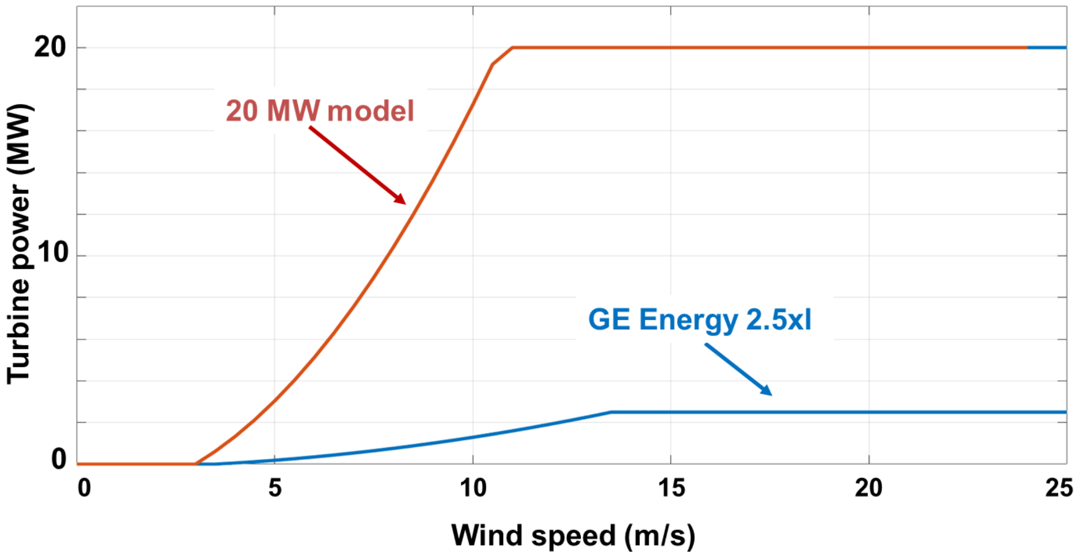

Figure 7.3. Wind turbines - power curve [89].

The power curve of a wind turbine is a key feature for understanding how it produces electricity as a function of wind speed. And the power curve graph shows the relationship between wind speed and the electrical power generated by the wind turbine. This is an important tool to evaluate the performance of a wind turbine and to optimize energy production.

More details of the power curves of the two wind turbines used in this work can be found in Figure 7.3.

$$Cf = \frac{P_{generated}}{P_{nominal}} \tag{7.4}$$

where $P_{generated}$ - the power generated by a wind turbine; $P_{nominal}$ - the rated power of a turbine.

In Figure 7.3, the distribution of the parameter *U100* (mean values) is shown the distribution with the full norm. The results are sorted by different intervals, ranging from a minimum of 2.45 m/s to a maximum of 7.35 m/s.

From this representation, it can be clearly seen that *offshore* reference points are defined by much higher values, frequently exceeding 7 m/s in the case of the western region. Considerably lower values are associated with the *onshore* reference points in the south and south-east, where, for this time period, the average wind speed values are below 3 m/s. The onshore points move from the Constanta, Odessa and Sevastopol lines, where they are defined by similar wind conditions, to the *offshore* points (100 km offshore) associated with the Sevastopol, Novorossiysk and Cide lines, which exhibit wind resources in the range of 6-7 m/s.

The seasonal evolution of wind speed could be observed, with more impressive values from the west for the *offshore* reference points, and the north can reach average wind speed values up to 8.75 m/s. During spring, these average wind speed values oscillate in the range of 2.44-7.36 m/s, with the mention that, this time, the *offshore* point at Silistar is not listed as having among the most important values. As for the summer, I can expect maximum 6.02 m/s only from the site associated with Odessa, while a minimum of 2.07 m/s is observed on the eastern and southern land areas. In winter, an *offshore* wind turbine will perform the best near the sites in the northern and western sectors, compared to the south-eastern point (Georgia), which is at the same energy level as the onshore points of Constanta and Silistar (100 km onshore). For class C5, the site in the western sector (along the coast and offshore) shows values in the range of 5-5.5%, including a marine point in Cide (southern sector). The differences between *onshore* and *offshore* reference points tend to become more significant as we go to higher classes, for example in the case of class C7 when it goes from 0.021 to 26.1%. For the C7 class, only the Odessa point shows more consistent wind resources, closely followed by other benchmarks showing a distribution in the 20-25% range. The evolution of the indicator V_{maxE} is shown in Figure 7.4, taking into account all available wind data (*U100*- for total time). During spring, these values evolve from 3.96 to 11.4 m/s, followed by a fall with values in the range 3.47-11.3 m/s, while during summer a maximum of 9.44 m/s is expected near *offshore* points.

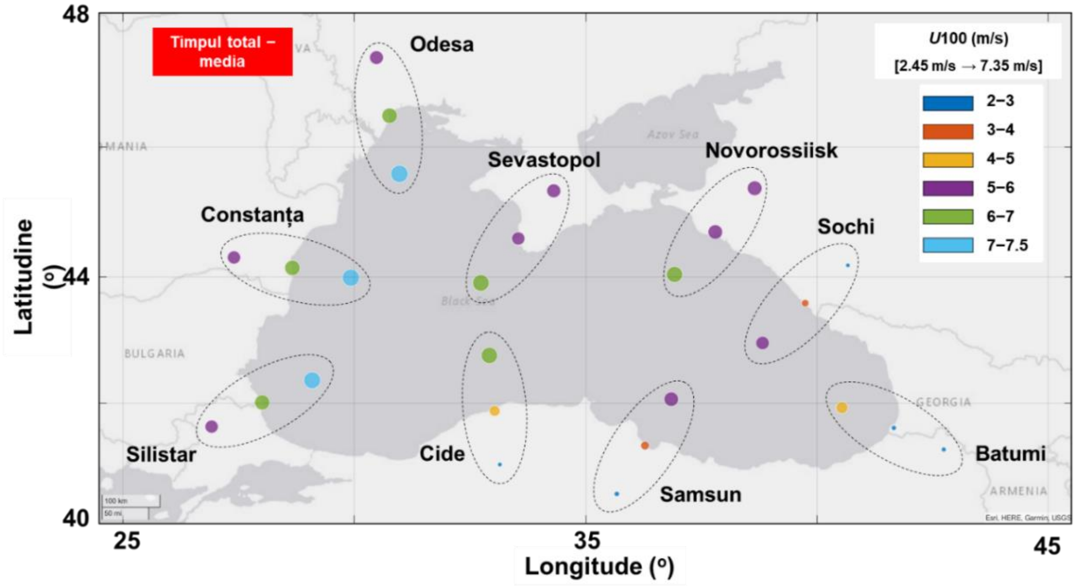

Figure 7.4. Average U100 values of ERA5 wind data corresponding to the 20-year time interval from January 2002 to December 2021. Numbers in square brackets indicate the minimum and maximum associated with this map [87].

During spring, these values evolve from 3.96 to 11.4 m/s, followed by autumn, with values in the range 3.47–11.3 m/s, while during summer a maximum is expected of 9.44 m/s, near offshore points.

7.4 Comparative Study of Indicators Specific to Coastal Turbines

These maps clearly show that the wind speed increases the farther it is measured from the shore. However, the data show that only the central part of the deep-sea sector has higher average wind speeds (close to 7 m/s), compared to the south-eastern part of the Romanian EEZ, where wind speeds decrease. In terms of seasonal distribution, the marine areas have wind speeds in the range of 8-9 m/s in winter, compared to a maximum of 7 m/s in the north-eastern part of the EEZ in summer. The average wind speed value is a relevant indicator in this context, as it indicates which type of wind turbine is suitable for the coastal environment analyzed. Capacity factor is an indicator that helps us to calculate the efficiency of a given generator. Closer to the shore, the capacity factor of a single turbine is in the range of 24-28%, which can go up to 35%, close to the 50 m contour line.

Finally, analysis areas that could not be fully included in the Romanian EEZ were excluded. For the AEP estimation, the calculations assumed losses of 15% due to factors such as freezing, downtime, fleet effects, transformer losses etc.

In this area, none of the reference points are included in class C7 (superb) and only the Odessa marine point is associated with section C6 (outstanding). Three of the benchmarks are related to class C5 (excellent) and this is the case of Constanta and Silistar. Taking into account all seasons, regardless of the season considered, none of the points is rated as a class C7 site, with values recorded in ranges such as: spring - 0.33 m/s - 0.78 m/s; summer- 0.33 m/s - 0.74 m/s; fall - 0.33 m/s - 0.84 m/s; winter - 0.37 m/s - 0.87 m/s. During the spring, a significant part of the points is included in classes C4 and C5 (good and excellent), while, in the summer, the balance is shifted to classes C4 and C3 (fair). For the fall season, sea points in Constanta and Odessa are included in class C6. The general presentation of the V_{maxE} indicator (in m/s), is represented in Figure 7.5 for the U(100) parameter, where there are areas with a wind speed of 11m/s -11.5 m/s. Considering all seasons, regardless of the season considered, none of the points is assessed as a C7 class site, with values recorded in the ranges such as: spring-0.33–0.78 m/s; summer-0.33–0.74 m/s; autumn-0.33–0.84; winter-

0.37–0.87 m/s. During the spring, a significant part of the points is included in the C4 and C5 classes (good and excellent), while in the summer the balance is moved to the C4 and C3 class (reasonable). For the autumn season, the marine points in Constanța and Odesa are included in class C6, all are represented in Figure 7.6 involving the eight parameters (W_{ann}, EWSO, RLO, CV, M_v, EWS,WD, DC) for the classification of wind energy.

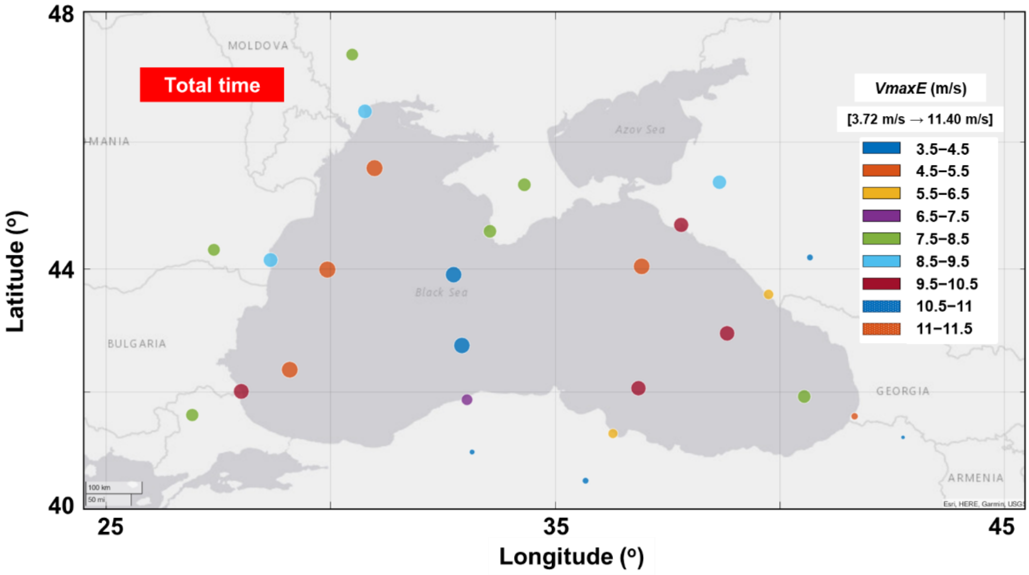

Figure 7.5. The indicator V_{maxE} (in m/s), the nominal wind speed, associated to each reference point; the result calculated for a 20-year period (2002-2021) and related to the parameter *U100*; the numbers in square brackets indicate the minimum and maximum values related to this map [89].

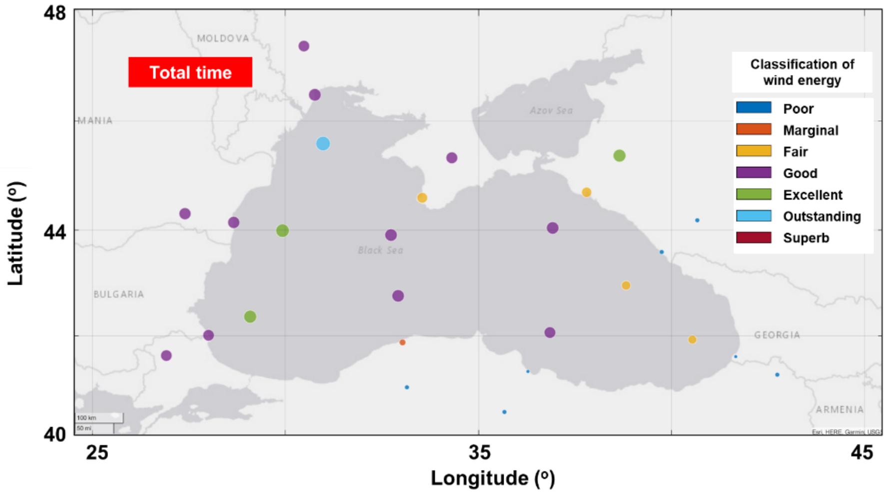

Figure 7.6 Wind energy classification involving the set of eight parameters (W_{ann}, EWSO, EWSO, RLO, CV, Mv, EWS, WD, DC) corresponding to the total time distribution (2002-2021). These results consider the *U100* parameter and are based on the methodology proposed in Costoya et al. [91]

The annual electrical energy production (AEP) of an individual GE Energy 2.5 xl system is considered for all benchmarks (*onshore* and *offshore*). It can be seen that production starts from 0.159 GWh up to 6.84 GWh, with better performance expected in the western sector. From all marine points located in the west (Odessa, Constanta and Silistar), production is expected in the range of 6-6.84 GWh, which gradually decreases to 4.5 GWh for onshore and further to 2.3 GWh for *onshore*. The annual electrical energy production (AEP) of an individual GE Energy 2.5 xl system is considered in Figure 7.7, considering all reference points (onshore and offshore). Figure 7.8 shows the spatial distribution of the reported capacity factor for this wind turbine. Better performances are expected in *offshore* areas, where a maximum value of the capacity factor of 31.2% is expected near Constanta and Odessa, while a maximum of 30% can be reached by the marine points in the central part of the Black Sea. Figure 7.8 a more detailed classification of the points, taking into account different indicators of interest for a wind project. In this area, none of the reference points are included in class C7 (superb) and only the Odessa marine point is associated with section C6 (outstanding). Three of the reference points are related to class C5 (excellent), this is the case of Constanta and Silistar to which we add the onshore point in Novorossiysk. For the remaining points, most of them are included in class 4, except for the western ones which are associated with class 1 (poor).

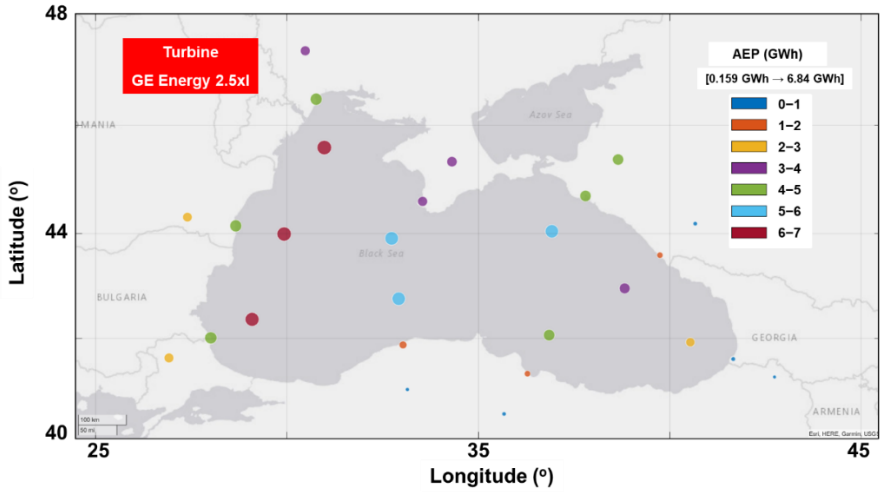

Figure 7.7. Annual electricity production (in GWh) of the GE Energy 2.5 xl wind turbine.

The annual electrical energy production (AEP) of an individual GE Energy 2.5 xl system is considered in Figure 7.6, taking into account all reference points (onshore and offshore).

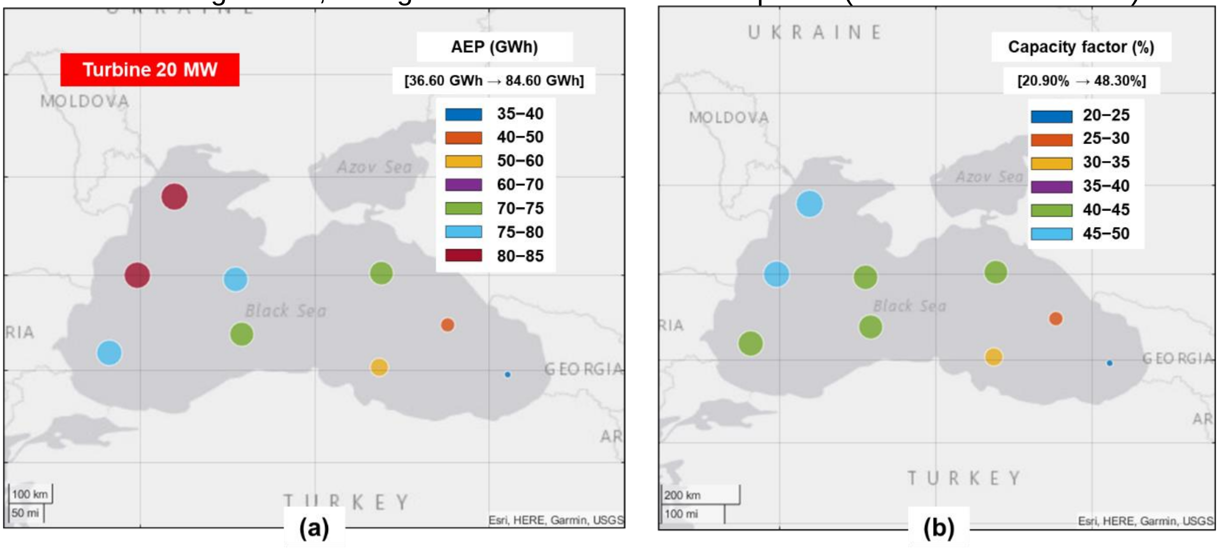

Figure 7.8 Performance of a theoretical wind turbine defined by a rated capacity of 20 MW, where: (a) annual electricity production; (b) capacity factor. These results are processed for a shaft height of 160.2 m, as detailed in Ashuri et al. [99]. The numbers in the legend indicate the minimum and maximum values, corresponding to each map.

Nearshore, the capacity factor, is relatively close to 25% (western sector) or 20% (northern sector) and does not exceed 5% for the eastern and southern points. For *onshore* points located at the western sector, a capacity factor in the range of 10-15% is expected. In terms of capacity factor (Figure 7.8b), this turbine is defined by higher values compared to the previous turbine (GE model), the main reasons being related to the values of the coupling characteristics and the nominal wind speed. Values in the 45-48.3% range are expected for the Constanta and Odessa points, while the second place is the 40-45% range, which defines the central part of the Black Sea. The south-eastern reference points represent a certain category that does not exceed 35% and can reach a minimum of 20.9% in the case of Batumi.

7.5 Conclusions

From the analysis of ERA5 (*U100)* wind data, the *offshore* wind resources in the Black Sea are significantly higher than those on the dry zone, the first time a study has investigated this issue. The western and northern points show larger wind resources that can run at average wind speeds of up to 8.75 m/s in winter.

The purpose of this thesis is not to make a direct comparison between the two wind turbines (2.5 MW and 20 MW) as they are intended for different projects. The purpose is to make a direct comparison between onshore and offshore areas in the Black Sea Region. A 2.5 MW turbine may be a suitable solution, as similar generators can be found in *onshore* projects (e.g. Fântânele-Cogealac, Romania) or *offshore* (as older technology). As for marine areas, the near future may see the emerge of a new generation of wind turbines that can easily exceed 20 MW in terms of rated power, making them a suitable candidate for the Black Sea environment or for a *repowering* project. Thus, a maximum of 10.2 t/MWh can be expected from the GE Energy 2.5 xl, while a maximum of 22.8 t/MWh is associated with the 20 MW turbine considered in this paper.

The research provides an overview of the wind energy resources in the Black Sea coastal environment (*onshore* and *offshore)*, ERA5 presents data on wind potential covering a 20-year time span from January 2002 to December 2021. In addition to a general analysis of wind resources at turbine hub height (100 m), specific wind energy related analyses have also been carried out. These include wind class distribution, a multi-criteria point ranking, the evolution of the V_{maxE} indicator and the performance of a 20 MW wind turbine. On the basis of these results, I can conclude that regional *offshore* wind resources are significantly stronger than onshore wind resources, regardless of the coastal sector considered. Furthermore, it has also been observed that wind resources gradually increase from onshore to offshore, with the mention that points along the shoreline may present suitable conditions for the development of a wind project. Looking now at the initial research questions formulated in the introduction, the following answers can be offered.

- According to the evolution of the indicator V_{maxE} , the rated speed of a wind turbine should be in the range of 3.5-11.5 m/s on a general scale, with higher values related to an *offshore* wind generator. In winter, a generator operates in the vicinity of 12.8 m/s, this nominal speed can be considered effective for most marine areas (100 km offshore);
- By applying a multi-criteria idea, it was found that the marine point located near Odessa area (Ukraine) has wind conditions rated as outstanding (class C6), while in the fall and winter other points are included in this category, e.g. Constanta, Romania;
- a wind turbine rated at 20 MW (*offshore*) will have a higher electricity production capacity compared to a 2.5 MW generator (*onshore* version), indicating better performance in terms of capacity factor.

The present work has some constraints, among them, one may mention the use of the ERA5 wind dataset, which are not real data, but reanalysis data. At present there is no wind project running with a 20 MW generator, but in the longer term, this is the policy promoted by the European Union, it may be applicable in projects such as Mobil-Grid-CoP [100].

Chapter VIII
Conclusions

8.1 General Conclusions

In the near future, the share of energy sources in the energy sector is expected to increase, at least at the European level, which is also the philosophy promoted by the European Union through various strategies, such as the European Green Pact. Various targets are proposed, such as for example the expansion of offshore wind farms in Europe to a capacity of about 60 GW by 2030, and to a maximum of 300 GW, which is estimated for the end of 2050. The wind sector in Europe is dynamic and these targets are expected to become reality. At the end of 2021, conventional (onshore) wind farms had an installed capacity of about 207 GW, while for offshore this reached 16 GW. Even under these conditions, offshore projects are becoming increasingly interesting, with turbines currently installed with an average capacity of around 8.5 MW, compared to 4 MW for conventional projects, and it is estimated that systems of approx. 20 MW could possibly be developed using floating platforms located in deep water areas.

Solar energy is another important energy source and is being considered in various projects to produce electricity or hot water. At the European level, this sector grew by around 50% between 2006 and 2016, and then fell by 32% in 2017. New FPV farms can be located in different areas with water, such as coastal areas, different hydro systems. Such a project has the potential to reduce algal blooms and water evaporation, performs better than land-based systems, while shaded areas are almost non-existent.

Several research directions have been addressed in this PhD thesis, which are closely related to the promotion of renewable energy sources in Europe, with a particular focus on the Black Sea coastal areas and Romania.

One of the addressed case studies is related to the evolution of the Black Sea wind resources. Previous studies have shown to be a promising area for the development of *offshore* wind farms, so a detailed analysis was carried out considering ERA5 data, covering the time interval 2002-2021 (20 years). From the analysis of these results, it has been highlighted that those *offshore* areas, located at a distance of about 100 km from the coast, have more wind resources compared to the coastal zone. Average values reaching a maximum of about 8.75 m/s in the western part of the Black Sea basin can be mentioned. Concerning the performance of some turbines, based on theoretical analysis of a turbine with a capacity of about 20 MW, a capacity factor in the range of 20.9 - 48.3% was obtained, which is associated with a maximum electricity production of about 84.6 GWh, especially for the regions near Romania and Ukraine.

Considering that the Black Sea is characterized by an increase in wind speed near coastal areas, the following case study focused on the assessment of these conditions near the Romanian coastal areas, more specifically near the Danube Delta. The analysis was carried out considering *in situ* wind measurements and reanalysis data (ERA5 and MERRA-2), covering the 2001-2020 period, the results obtained covering meteorological studies, but also renewable energy studies. The assessment included two points on land (Galați and Tulcea), one close to the shoreline (Sulina), and two *offshore* points about 64 km and 126 km from the shore. Comparison to *in situ* measurements shows that the ERA5 data are more accurate for the onshore points, while, for Sulina, the MERRA-2 values are more accurate. It was observed that only by using four values from the reanalysis data (00:06:12:18 UTC), the mean wind speed values are very close to those indicated when considering the daily values (24 values). Regarding the performance of a wind turbine at *U100*, for onshore areas, a period of inactivity during the night (up to 63%) was recorded, compared to only 23%, which can occur for *offshore* areas throughout the whole day.

Moving from coastal to inland areas, another important case study focused on the assessment of solar and wind resources near Brateș Lake, which is located in the northern part of Galați. In time, this lake has been one of the most important lakes in Romania, with a water surface area of about 100 km^2; over time this area has been significantly reduced, reaching now a minimum of about 20 km^2 and a water depth of maximum 3 m. This lake is estimated to be in an advanced state of degradation, the main causes being related to agricultural activities in the area and the activity of some industrial agents in the area. In this context, another objective of this thesis was to see how a renewable energy project (solar or wind) could contribute to the economic revitalization of this area. The used data cover the interval 2001-2022, involving ERA5 reanalysis data as well as *in situ* measurements. Analyzing the wind conditions specific to a height of 100 m, a maximum of 19.28 m/s in the winter period was highlighted, while for solar radiation more significant values occur in summer, up to 932 W/m^2. For this area, several specific onshore wind turbines were considered, their capacities starting from 2 MW and reaching 6.2 MW. The obtained results indicate a capacity factor that can reach a maximum of 21%, with more promising values being recorded by the Gamesa G90 system. The next step was to consider floating solar panels, placed on the Brateș lake, with the covered area gradually increasing from 10% to 40%. The amount of evaporated water that can be saved by the panels was considered, estimating an annual volume of water to cover the water needs for an agricultural area of at least 3,42 km^2.

In conclusion, it can be said that there is a substantial interest for the development of the renewable energy sector at European level, Romania being located in an area suitable for the implementation of large capacity projects, based on solar/wind energy, considering, in a harmonious way, both energy sources.

8.2 Personal Contributions

Based on the present study, the author's contributions are:

- identification of the energy potential of some natural resources in Romania considering maps and statistical data available in specialized literature and data bases;
- analyzing the wind resources in the Black Sea coastal zone, highlighting the variations that occur between the onshore and offshore areas;
- identification of the specific wind energy potential of the Black Sea, taking into account specific parameters (e.g. EWSO, value classes) as well as the performance of some classical and large (20 MW) wind turbines that could be deployed in the near future in this region;
- assessment of the energy potential of the Brateș Lake (Galați, Romania) in terms of solar and wind energy. The analysis was based on *in situ* measurements and reanalysis data, the obtained results being related to the meteorological analysis of these resources, as well as to the performance of solar panels and wind turbines;
- conducting studies on how a floating solar farm on Lake Brateș can help reduce evaporation. This is an original element, as it is one of the first case studies of its kind to consider a lake in Romania;
- detailed analysis of wind resources in the northern part of the Romanian coastal area (Galați, Tulcea, Sulina areas), considering different data sources. A novel element is the comparison between datasets with 24 values per day and that including only 4 values (00:06:12:18 UTC). The results obtained do not indicate statistically significant differences between the two datasets, especially in the case of studies covering long time periods;
- presentation of the concept of repowering and case studies on how such an approach may applied to the Fântânele-Cogealac project, Romania;
- analysis of wind resources near several marine energy areas in Europe, considering RCP 4.5 and 8.5 data for time range 2006-2100;
- Performance assessment of an offshore turbine located in different coastal areas of Europe, considering RCP data (2006-2100);
- Assessment of the solar and wind energy potential in the Republic of Moldova, considering specific data from 1983-2005;
- performance analysis of solar panels located in different coastal areas of Romania (Sfântul Gheorghe, Năvodari, Vama Veche).

8.3 Perspectives for Future Studies

The studies presented in this thesis may represent a starting point for the development of other research directions, such as:

- deepending and implementing the concept of repowering, but also to develop case studies for existing wind farms in coastal areas, which, in the next 20 years, should stop their activity;
- climatological analysis of solar and wind resources to become up-to-date databases (e.g. CMIP6);
- assessing in detail the energy potential of the Republic of Moldova and scenarios involving the development of solar/wind projects;
- spatial configuration of wind farms that could operate within enclosed basins, considering different coastal constraints (e.g. protected areas, shipping lines);
- analyzing the performance of solar-wind hybrid farms that could be developed in different coastal areas of Europe;
- coastal impact assessment specific to marine energy farms, located near coastal zones;
- analysis of the different types of turbines specific to maritime areas, such as vertical axis turbines;
- identifying the optimal periods for carrying out specific *offshore* project activities (e.g. installation, inspection, maintenance), taking into account the analysis of specific parameters of the marine environment, such as wave height and period, wind speed;
- Performance analysis of wave energy extraction systems located near the coastline (e.g. oscillating water column systems);
- identifying the performance of floating solar farms that could operate in natural lakes or reservoirs in Romania. Different aspects may be considered, such as identifying the reduction of evaporated water volume.

List of works

The research carried out during the PhD studies was included in the following scientific publications:

Papers published in Web of Science (ISI) indexed journals. SCOPUS indexed.

1. Rusu E., Georgescu P. L., Onea F., **Yildirir V.,** Dragan S., 2023**.** The potential of lakes for Extracting Renewable Energy- A Case study of Brateș Lake in the South-East of Europe. Inventions. **(FI=3.4/2022), Q1** Engineering Multidisciplinary in ECSI edition.
   https://doi.org/10.3390/inventions8060143 , WOS:001130724900001.
2. **Yildirir V.**, Rusu E., Onea F., 2022**.** Wind Variation near the Black Sea Coastal Areas Reflected by the ERA5 Dataset. INVENTIONS 7(3), 57, https://doi.org/10.3390/inventions7030057, WOS:000858623600001, (**FI: 3.4/2022), Q1** ENGINEERING, MULTIDISCIPLINARY in ESCI edition 2022. WOS:000858623600001.
   https://doi.org/10.3390/inventions7030057, https://www.mdpi.com/2411-5134/7/3/57
3. **Yildirir V.,** Rusu E, Onea F, 2022. Wind Energy Assessments in the Northern Romanian Coastal Environment Based on 20 Years of Data Coming from Different Sources. Sustainability 14 (7), 4249, WOS:000781321400001, (**FI: 3.9/2022**), **Q2** ENVIRONMENTAL SCIENCES in SCIE edition.
   https://doi.org/10.3390/su14074249 , WOS:000781321400001.

Papers published in BDI journals

4. Onea F., Rusu L., **Yildirir V. (Caranfil**), 2018**.** Renewables and the Romanian energy system. *Mechanical Testing and Diagnosis*, *8*(2), 5-10.
   https://doi.org/10.35219/mtd.2018.2.01 https://doi.org/10.35219/mtd.2018.2.01
5. **Yildirir V., (Caranfil**), Onea F., Rusu E., 2018, An evaluation of the solar and wind energy in the southeast of Romania, Mechanical testing and Diagnosis, Galați, ISSN 2247-9635, 2018 (VIII), Volume 2, pp. 15-20
   DOI:10.35219/mtd.2018.2.03

1. **Yildirir V. (Caranfil**), Onea F., Rusu E., 2022. Partial energy consumption supplied by renewable energy sources for a production halls. Annals of “Dunarea de jos” University of Galați – fascicle, Galati. https://www.gup.ugal.ro/ugaljournals/index.php/math
2. **Yildirir** V., Rusu E., Onea F., 2021**.** Wind condition analysis and partial repowering concept for Fântânele - Cogealac *onshore* project. SCOPUS Indexed. 21st International Multidisciplinary Scientific GeoConference SGEM, 16 - 22 August, V-21, 2021.DOI:10.5593/sgem2021/4.1/s17.24
   https://www.proquest.com/docview/2677065807?pq-origsite=gscholar&fromopenview=true&sourcetype=Conference%20Papers%20&%20Proceedings

Papers presented at international conferences

3. **Yildirir** V., Rusu E., Onea F., 2021. Current analyses of the wind condition and repowering perspective for Fantanele –Cogealac Onshore Project. 21st International Multidisciplinary Scientific GeoConference SGEM, August 16-22, V-21, 2021. DOI:10.5593/sgem2021/4.1/s17.24. **Indexed SCOPUS**
   https://www.proquest.com/docview/2677065807?pq-origsite=gscholar&fromopenview=true&sourcetype=Conference%20Papers%20&%20Proceedings
4. **Caranfil** (Yildirir) V., Rusu E., Onea F., 2018. An analysis of the renewable energy resources in the Republic of Moldova- 18th International Multidisciplinary Scientific GeoConference SGEM, July 02-08, 2018, V18 pp 119-126 International Multidisciplinary Scientific GeoConference SGEM. DOI:10.5593/sgem2018/4.1/S17.016. **indexed SCOPUS**
   https://www.proquest.com/docview/2182646714?pq-origsite=gscholar&fromopenview=true&sourcetype=Conference%20Papers%20&%2

0Proceedings

Papers presented at national conferences

5. Scientific Conference of Doctoral Schools SCDS-UDJG, Perspectives and challenges in doctoral research 6th Edition, "Dunarea de Jos" University of Galați, 7-8 of June 2017. Sectiunea postere**. Caranfil V.** *, Rusu E., Onea F., Partial energy consumption supplied by renewable energy sources for production halls. Universitatea ,,Dunărea de Jos" din Galați, Facultatea de inginerie, RO-800008, Galați, Romania
6. Scientific Conference of Doctoral Schools SCDS-UDJG. UGAL - Scientific and Cultural Dialogues, October 18-28, 2021. Perspectives and challenges in doctoral research 9th Edition, „Dunarea de Jos" University of Galați, 10-11 of June 2021. Sectiunea postere. **Yildirir V.***, Rusu E., Onea F. Current analyses of the wind condition and repowering perspective for Fântânele -Cogealac *Onshore* Project.
7. Scientific Conference of Doctoral Schools SCDS-UDJG. The 10th edition of CSSD-UDJG 2022, organized from 09-10 June 2022. Poster Section. **Yildirir V.***, Rusu E., Florin O., Assessment of the Wind and Solar Energy Potential in the Area of the Brateș Lake, Romania. University „Dunărea de Jos" of Galați, Faculty of Engineering, RO-800008, Galați, Romania

Awards

1. First Prize. Section 1. Advanced Research in Mechanical and Industrial Engineering within the Scientific Conference of Doctoral Schools CSSD-UDJG 2022, **Yildirir** V. *, Florin Onea F, Rusu E, Evaluation of the *onshore* and *offshore* wind energy resources associated to the Black Sea basin.
2. Diploma of excellence 14.12.2022, For excellent results in research activity within IOSUD-UDJG in 2022. Doctoral School of Mechanical and Industrial Engineering. **Yildirir** V. *, Onea F., Rusu E., Wind Energy Assessments in the Northern Romanian Coastal Environment Based on 20 Years of Data Coming from Different Sources.

Bibliography

[1] Ciucci M. Energia din surse regenerabile 2023, https://www.europarl.europa.eu/erpl-app-public/factsheets/pdf/ro/FTU_2.4.9.pdf, accesat 15.03.2024.
[2] ***Buletin informativ ANRE — Trimestrul II 2014 I. utoritatea Națională de Reglementare în domeniul energiei; 2014.
[3] Ţenchea A.I., Contribuţii privind cercetarea arderii în strat fluidizat a biomasei. Universitatea “Politehnica” din Timişoara, 2008.
[4] Gleixner, S.; Demissie, T.; Diro, G.T., Did ERA5 Improve Temperature and Precipitation Reanalysis over East Africa?, MDPI Atmosphere 2020;11:996. https://doi.org/10.3390/atmos11090996.
[5] ***Raport Privind Progresul Înregistrat în Îndeplinirea Obiectivelor Naţionale de Eficienţă Energetic. Bucuresti: Agentia Nationala pentru Reglementare in domeniul Energiei (ANRE)., 2016.
[6] ***Europe’s onshore and offshore wind energy potential. Copenhagen,: EEA technical report; 2009.
[7] ***Global wind map n.d. ESMAP V DTU, World Bank group, Global Wind Atlas, 2024, https://globalwindatlas.info/en, accesat 12.07.2022.
[8] Souvik S., Ganguly S., Opportunities, barriers and issues with renewable energy development—A discussion. Renew Sustain Energy Rev 2017;Volumul 69, paginile 1170-1181. https://doi.org/10.1016/j.rser.2016.09.137.
[9] Pană I., Energia Eoliană 1989, https://op.europa.eu/webpub/eca/special-reports/windsolar-power-generation-8-2019/ro/index.html, accesat 15.03.2024.
[10] ***Energy and environment report 2008. Copenhagen: European Environmental Agency, 2008, https://www.eea.europa.eu/publications/eea_report_2008_6, accesat 24.07.2023.
[11] Ciutacu A., Bellu C, Tiron M. Conferinţa ZF/Liberty Galaţi Green Valley – noul pol de investiţii pentru viitor. https://www.zf.ro/companii/ajay-aggarwal-liberty-steel-europe-romania-are-un-potential-enorm-de-21762707, 2023
[12] ***Meteoblue. MeteoblueCom. https://www.meteoblue.com/ro/user/order/historyplus, 2006.
[13] Ion I, Câmpian C.V, Cuzmoş A, Dumbravă C. Determinarea vitezei vântului pe baza valorilor măsurătorilor experimentale obţinute de la stâlpi anemometrici n.d.,A XIIConferință Națională multidisciplinară-cu participare internațională „Profesorul Dorin Pavel-fondatorul hidroenergeticii românești" Sebeș, 2012. https://stiintasiinginerie.ro/wpcontent/uploads/2013/12/60-determinarea-vitezeiv% c3%82ntului-pe-baza.pdf, accesat 23.06.2024.
[14] ***Hólmfríður H., Sandström M. Lifetime Analysis of a Wind Turbine Component. Department of Energy and Environment, Chalmers University of Technology, Gothenburg, 2016.
[15] ***Carlson O., Lecture notes in Sustainable Power Production and Transportation. . Chalmers University of Technology, 2015.
[16] A Al-Shahrani A., A.Nada, Jazan University, S. . Shape optimization of Low Speed Wind Turbine Blades using Flexible Multibody Approach. Elsevier;134:577–87, 2017.
[17] Martínez E., Latorre-Biel JI, Jiménez E, Sanz F, Blanco J. Life cycle assessment of a wind farm repowering process. Renewable and Sustainable Energy, 2018;93:260–71. https://doi.org/10.1016/j.rser.2018.05.044.
[18] Google MAPS. Https://WwwGoogleCom/Maps n.d.
[19] Bezbradica M., Kerkvliet H., Borbolla IM, Lehtim¨aki P. Wind farm repowering a strategic management perspective. Department of Earth Sciences, Swed 2016:11.

[20] Hussain I., Haider A., Ullah Z., Russo M., Casolino GM, Azeem B. Comparative Analysis of Eight Numerical Methods Using Weibull Distribution to Estimate Wind Power Density for Coastal Areas in Pakistan. Energies 2023;16:1515. https://doi.org/10.3390/en16031515

[21] Abadie L., Goicoechea N., Old Wind Farm Life Extension vs. Full Repowering: A Review of Economic Issues and a Stochastic Application for Spain,. Energies, 2021:4. https://doi.org/10.3390/en14123678.

[22] Onea F., Rusu E. ,Efficiency assessments for some state of the art wind turbines in the coastal environments of the Black and the Caspian seas. Energy Explor Exploit 2016;34:217–34. https://doi.org/10.1177/0144598716629872

[23] ***IRENA (International Renewable Energy Agency). Renewable energy technologies: cost analysis series. Wind power, 2012.

[24] Kosky P., Balmer R., William K., George W., Exploring Engineering. vol. Third edition, 2013.

[25] ECMWF reanalysis. ERA5 data n.d. https://doi.org/DOI: 10.24381/cds.adbb2d47.

[26] ***J. Store. Consiliul aprobă concluzii privind un val de renovări în UE, Consiliul European; 2021.

[27] ***Raport anual privind activitatea ANRE 2022. Bucureşti: Autoritatea Națională de Reglementare în Domeniul Energiei, https://anre.ro/despre/rapoarte/, accesat 15.02.2023

[28] Florea NM., Bădîrcea RM, Meghisan-Toma G-M, Puiu S, Manta AG, Berceanu D. Linking Public Finances’ Performance to Renewable-Energy Consumption in Emerging Economies of the European Union. Sustainability 2021;13:6344. https://doi.org/10.3390/su13116344.

[29] ***Guillot J.D., Emisiile de gaze cu efect de seră pe țări și pe sectoare. Parlamentul European 2023:3.

[30] ***Buletin informativ ANRE - Trimestrul II 2014 I. Autoritatea Națională de Reglementare în Domeniul Energie, 2014.

[31] ***Timnea R.Ș., Strategia de Dezvoltare Durabilă 2021-2027 a Municipiului Galați, 2020.

[32] Barton J.P., and D. G. Infield. Energy storage and its use with intermittent renewable energy. IEEE Transactions on Sustainable Energy 2004;19:441. https://doi.org/10.1109/TEC.2003.822305.

[33] ***Romania Wind Energy Market | 2022 - 27 | Industry Share, Size, Growth - Mordor Intelligence 2022. https://www.mordorintelligence.com/industry-reports/romania-wind-energy-market, accesat 28.01.2022.

[34] Dudău R. MB. Romania’s Offshore Wind Energy Resources: Natural potential, regulatory framework, and development prospects,. Bucharest, 2020.

[35] Onea F., Rusu E., Sustainability of the Reanalysis Databases in Predicting the Wind and Wave Power along the European Coasts. Sustainability 2018;10:193. https://doi.org/10.3390/su10010193.

[36] MERRA-2 n.d. https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/, accesat 25.06.2024.

[37] Devis A., Van Lipzig NPM, Demuzere M. Should future wind speed changes be taken into account in wind farm development? Environmental Research Letters 2018;13:064012. https://doi.org/10.1088/1748-9326/aabff7.

[38] Rusu E., Onea F., A parallel evaluation of the wind and wave energy resources along the Latin American and European coastal environments. Renewable Energy 2019. https://doi.org/10.1016/j.renene.2019.05.117.

[39] Al-Nassar WK, Neelamani S., Al-Salem KA, Al-Dashti HA. Feasibility of offshore wind energy as an alternative source for the state of Kuwait. Energy 2019;169:783–96. https://doi.org/10.1016/j.energy.2018.11.140.

[40] ***Evaluarea gradului de pregătire privind valorificarea energiei regenerabile: Republica Moldova, Agenţia Internaţională pentru Energie Regenerabilă, Abu Dhabi, 2019

[41] ***Raport privind monitorizarea securității aprovizionării cu energie electrică și gaze naturale a Republicii Moldova pentru perioada 2020-2021. Ministerului Infrastructurii și Dezvoltării Regionale nr. 200, 2022

[42] Rachier V., Evaluarea potenţialului energetic eolian al Republicii Moldova. Universitatea Tehnică a Moldovei, Facultatea de energetică şi inginerie electrică, 2016.

[43] S Solar radiation. MY NASA DATA, 2018. https://mynasadata.larc.nasa.gov/glossary/solar-radiation-2/.

[44] ***Moldova Country Strategy 2023-2028, 2021.

[45] ***Serviciul Hidrometeorologic de Stat, 2005. https://www.meteo.md/index.php/transparenta/planuri-rapoarte-de-activitate/.

[46] ***Evaluarea gradului de pregătire privind valorificarea energiei regenerabile. Republica Moldova. IRENA, 2019.

[47] C Caranfil V, Rusu E, Onea F. An Evaluation of the Solar and Wind Energy in the South-East of Romania. Mechanical Testing and Diagnosis 2018;8:15–20. https://doi.org/10.35219/mtd.2018.2.03.

[48] Ali S., Lee S-M., Jang C-M., Techno-Economic Assessment of Wind Energy Potential at Three Locations in South Korea Using Long-Term Measured Wind Data. Energies 2017;10:1442. https://doi.org/10.3390/en10091442.

[49] V Vestas V90-3.0 - 3,00 MW - Wind turbine 2018. https://en.wind-turbinemodels.com/turbines/603-vestas-v90-3.0 , accesat 29.07.2018.

[50] Areva M5000-116 - 5,00 MW - Wind turbine 2018. https://en.wind-turbine-models.com/turbines/23-areva-m5000-116 , accesat 29.07.2018.

[51] Senvion 6.2M126 Offshore - 6,15 MW - Wind turbine 2018. https://en.wind-turbine-models.com/turbines/885-senvion-6.2m126-offshore, accesat 29.07.2018

[52] Agarwal A., Venugopal V., Harrison GP., The assessment of extreme wave analysis methods applied to potential marine energy sites using numerical model data. Renew Sustainability Energy Review 2013;27:244–57. https://doi.org/10.1016/j.rser.2013.06.049.

[53] Onea F., Raileanu A., Rusu E., Analysis of extreme wind and wave conditions in the Black Sea , as reflected by the Altimeter Measurements. Mechanical Testing and Diagnosis,1:5–12, ISSN 2247 – 9635, 2016 (VI), Volume 1, pp. 5-12.

[54] Wang J., Mamkhezri J., Khezri M, Karimi MS, Khan YA. Insights from European nations on the spatial impacts of renewable energy sources on CO2 emissions. Energy Rep 2022;8:5620–30. https://doi.org/10.1016/j.egyr.2022.04.005.

[55] Hersbach H., Bell B., Berrisford P., Hirahara S., Horányi A., Muñoz-Sabater J., et al. The ERA5 global reanalysis. Quarterly Journal of the Royal Meteorological SocietyVolume 146, Issue 730 p., 2020;146:1999–2049. https://doi.org/10.1002/qj.3803.

[56] ***A European Green Deal | European Commission 2022. https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en , accesat 22.05.2022.

[57] ***Wind energy in Europe: 2022 Statistics and the outlook for 2023-2027. WindEurope 2023. https://windeurope.org/data-and-analysis/product/wind-energy-in-europe-2022-statistics-and-the-outlook-for-2023-2027, accesat 20.03.2023.

[58] Constantin D-E., Bocăneala C., Voiculescu M, Roşu A, Merlaud A, Roozendael MV, et al. Evolution of SO2 and NOx Emissions from Several Large Combustion Plants in Europe during 2005–2015. International Journal of Environmental Research and Public Health 2020;17:3630. https://doi.org/10.3390/ijerph17103630.

[59] Durakovic G., del Granado PC., Tomasgard A., Powering Europe with North Sea offshore wind: The impact of hydrogen investments on grid infrastructure and power prices. Energy 2023;263:125654. https://doi.org/10.1016/j.energy.2022.125654.

[60] Madsen DN., Hansen JP., Outlook of solar energy in Europe based on economic growth characteristics. Renewable Sustainbility Energy Reviews 2019;114:109306. https://doi.org/10.1016/j.rser.2019.109306.

[61] Dragomir G., Șerban A., Năstase G., Brezeanu AI., Wind energy in Romania: A review from 2009 to 2016. Renew Sustain Energy Rev 2016;64:129–43. https://doi.org/10.1016/j.rser.2016.05.080.

[62] Onea F., Rusu L., A Study on the Wind Energy Potential in the Romanian Coastal Environment. J Mar Sci Eng 2019;7:142. https://doi.org/10.3390/jmse7050142.

[63] Guillory A., ERA5. ECMWF 2017. https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5, accesat 31.03.2019.

[64] Spunei E., Piroi I., Piroi F., Efficiency of a small power photovoltaic installation connected to the low voltage network. J Phys Conf Ser 2022;2212:012020. https://doi.org/10.1088/1742-6596/2212/1/012020.

[65] Rusu E., Georgescu P.L., Onea F., Yildirir V., Dragan S.,. The potential of lakes for Extracting Renewable Energy- A Case study of Brates Lake in the South-East of Europe. Inventions 2023; Multidisciplinary in ECSI edition. https://doi.org/10.3390/inventions8060143.

[66] Nascimento MM, Shadman M, Silva C, de Freitas Assad LP, Estefen SF, Landau L. Offshore wind and solar complementarity in Brazil: A theoretical and technical potential assessment. Energy Conversion and Management 2022;270:116194. https://doi.org/10.1016/j.enconman.2022.116194.

[67] Khalifeh S. SR, Mostafaeipour A, Almutairi K, Hosseini Dehshiri SJ, Hosseini Dehshiri SS, Techato K. Predicting effect of floating photovoltaic power plant on water loss through surface evaporation for wastewater pond using artificial intelligence: A case study. Sustainable Energy Technologies and Assessments 2022;50:101849. https://doi.org/10.1016/j.seta.2021.101849.

[68] Urraca R, Gracia-Amillo AM, Koubli E, Huld T, Trentmann J, Riihelä A, et al. Extensive validation of CM SAF surface radiation products over Europe. Remote Sens Environ 2017;199:171–86. https://doi.org/10.1016/j.rse.2017.07.013.

[69] López M., Rodríguez N., Iglesias G., Combined Floating Offshore Wind and Solar PV. J Mar Sci Eng 2020;8:576. https://doi.org/10.3390/jmse8080576.

[70] Fereshtehpour M, Javidi Sabbaghian R, Farrokhi A, Jovein EB, Ebrahimi Sarindizaj E. Evaluation of factors governing the use of floating solar system: A study on Iran's important water infrastructures. Renewable Energy 2021;171:1171–87. https://doi.org/10.1016/j.renene.2020.12.005.

[71] ***International Electrotechnical Commission. International Standard IEC 61400-1 Wind turbines –Part 1:Design requirements. 2005.

[72] Onea F., Rusu E., An Evaluation of Marine Renewable Energy Resources Complementarity in the Portuguese Nearshore. Journal of Marine Science and Engineering, 2022;10:1901. https://doi.org/10.3390/jmse10121901.

[73] Popa P., Murariu G., Timofti M., Georgescu LP., Multivariate statistical analyses of Danube River water quality at Galați, Romania. Environmental Eng Manag J 2018;17:1249–66. https://doi.org/10.30638/eemj.2018.124.

[74] Michalco BT. Kim Tranberg and David. Statistics 2023. https://turbines.dk/statistics, accesat 3.04.2023.

[75] Boretti A., Castelletto S., Trends in performance factors of wind energy facilities. SN Appl Sci 2020;2:1718. https://doi.org/10.1007/s42452-020-03526-z.

[76] ***Romania: CEZ Cogealac-Fântânele wind farm case study. Eurofound, 2022. https://www.eurofound.europa.eu/hu/observatories/emcc/case-studies/the-greening-of-industries-in-the-eu/romania-cez-cogealac-fntnele-wind-farm-case-study, accesat 28.01.2022.

[77] Rusu E., A 30-year projection of the future wind energy resources in the coastal environment of the Black Sea. Renewable Energy 2019;139:228–34. https://doi.org/10.1016/j.renene.2019.02.082.

[78] Onea F., Rusu E., Rusu L., Assessment of the Offshore Wind Energy Potential in the Romanian Exclusive Economic Zone. J Mar Sci Eng 2021;9:531. https://doi.org/10.3390/jmse9050531.

[79] Yildirir V., Rusu E., Onea F., Wind Energy Assessments in the Northern Romanian Coastal Environment Based on 20 Years of Data Coming from Different Sources. Sustainability 2022;14:4249. https://doi.org/10.3390/su14074249.

[80] Bezrukovs V., Zacepins A., Bezrukovs V., Komasilovs V., Comparison of different methods for evaluation of wind turbine power production based on wind measurements. Renewable Energy Environ Sustain 2016;1:22. https://doi.org/10.1051/rees/2016025

[81] Silhavy R., Silhavy P., Prokopova Z., Computational Statistics and Mathematical Modeling Methods in Intelligent Systems. vol. Volume 1047. Switzerland: Springer; 2019.

[82] Yildirir V., Rusu E., Onea F., Wind Variation near the Black Sea Coastal Areas Reflected by the ERA5 Dataset n.d. Inventions, https://www.mdpi.com/2411-5134/7/3/57, accesat 4.06.2024.

[83] Rusu L., Ganea D., Mereuta E., A joint evaluation of wave and wind energy resources in the Black Sea based on 20-year hindcast information. Energy Exploration & Exploitation 2018;36:335–51. https://doi.org/10.1177/0144598717736389.

[84] Olauson J., ERA5: The new champion of wind power modelling? Elsevier Renewable Energy 2018;Volume 126:PP 322-331. https://doi.org/10.1016/j.renene.2018.03.056.

[85] Dawn S., Tiwari PK., Goswami AK., Singh AK., Panda R., Wind power: Existing status, achievements and government's initiative towards renewable power dominating India. Energy Strategy Rev 2019;23:178–99. https://doi.org/10.1016/j.esr.2019.01.002.

[86] Kubryakov A., Stanichny S., Shokurov M., Garmashov A., Wind velocity and wind curl variability over the Black Sea from QuikScat and ASCAT satellite measurements. Remote Sens Environ 2019;224:236–58. https://doi.org/10.1016/j.rse.2019.01.034.

[87] Divinsky BV., Kosyan RD., Spatiotemporal variability of the Black Sea wave climate in the last 37 years. Cont Shelf Res 2017;136:1–19. https://doi.org/10.1016/j.csr.2017.01.008.

[88] Amarouche K., Akpınar A., Soran MB., Myslenkov S., Majidi AG., Kankal M., et al. Spatial calibration of an unstructured SWAN model forced with CFSR and ERA5 winds for the Black and Azov Seas. Appl Ocean Res 2021;117:102962. https://doi.org/10.1016/j.apor.2021.102962.

[89] Yildirir V., Rusu E., Onea F., Wind Variation near the Black Sea Coastal Areas Reflected by the ERA5 Dataset n.d. Inventions, https://www.mdpi.com/2411-5134/7/3/57, accesat 4.06.2024.

[90] Archer CL., Jacobson MZ., Evaluation of global wind power. Journal of Geophysical Research: Atmospheres 2018;110. https://doi.org/10.1029/2004JD005462.

[91] Costoya X., deCastro M., Carvalho D., Gomez-Gesteira M., On the suitability of offshore wind energy resource in the United States of America for the 21st century. Applied Energy 2020;262:114537. https://doi.org/10.1016/j.apenergy.2020.114537.

[92] ***Fundamentals and Source Characteristics of Renewable Energy Systems, 2022.

[93] Shu ZR, Jesson M. Estimation of Weibull parameters for wind energy analysis across the UK. J Renewable Sustainability Energy 2021;13:023303. https://doi.org/10.1063/5.0038001.

[94] Al-Nassar WK., Neelamani S., Al-Salem KA., Al-Dashti HA., Feasibility of offshore wind energy as an alternative source for the state of Kuwait. Energy 2019;169:783–96. https://doi.org/10.1016/j.energy.2018.11.140.

[95] Qin C (Chris), Loth E, Zalkind DS, Pao LY, Yao S, Griffith DT, et al. Downwind coning concept rotor for a 25 MW offshore wind turbine. Renewable Energy 2020;156:314–27. https://doi.org/10.1016/j.renene.2020.04.039.

[96] Souza CES., Bachynski-Polić EE. Design, structural modeling, control, and performance of 20 MW spar floating wind turbines. Marine Structure 2022;84:103182. https://doi.org/10.1016/j.marstruc.2022.103182.

[97] GE Energy 2.5xl - Manufacturers and turbines - Online access - The Wind Power 2019. https://www.thewindpower.net/turbine_en_59_ge-energy_2.5xl.php, accesat 10.03.2019.

[98] Manufacturers and turbines - Online access - The Wind Power, 2018. https://www.thewindpower.net/turbines_manufacturers_en.php , 20.05.2018.

[99] Ashuri T., Martins JRRA., Zaaijer M.B.., van Kuik GAM, van Bussel GJW. Aeroservoelastic design definition of a 20 MW common research wind turbine model: A 20 MW common research wind turbine model. Wind Energy 2016,19:2071–87. https://doi.org/10.1002/we.1970.

[100] Mobil-Grid-CoP 2022. https://www.iwes.fraunhofer.de/en/research-projects/current-projects/mobil-grid-cop.html, accesat 22.06.2022.