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Offshore Wind Energy Potential: Assessing Capacity Factor and Electricity Generation in Montenegro

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ABSTRACT

Montenegro, as a signatory to international agreements, is committed to reducing CO_2 emissions and achieving full decarbonization by 2050. To meet these environmental goals, the country must permanently shut down the coal-fired thermal power plant in Pljevlja. This study assesses the potential electricity generation capacity of an offshore wind farm in Montenegro using 15 MW wind turbines at a location identified in prior research. Two offshore wind farm technical capacity criteria are applied: one defined by the World Bank (WB), specifying a capacity of 3 MW/km^2, and another by the National Renewable Energy Laboratory (NREL) under the U.S. Department of Energy, specifying 5 MW/km^2. The study also examines two operational scenarios of Montenegro's electricity system. Results show that a fixed-bottom offshore wind farm in an area of 88,438 km^2, with sea depths up to 60 meters, could generate 55,71% of the electricity produced by the Pljevlja plant based on WB criteria, or 92,86% based on NREL criteria. For depths over 60 meters, a floating offshore wind farm in 678,16 km^2 could generate 4,22 times the electricity output of the Pljevlja plant based on WB criteria, or 7,04 times its output based on NREL criteria.

1 Introduction

By adopting the Declaration on the Proclamation of Montenegro as an Ecological State in 1991 and the Constitution in 2006, the Parliament of Montenegro legally defined the country as an ecological state [1,2]. Despite this legal designation, a significant portion of Montenegro's energy is still generated through coal combustion, which accounted for 37,67% of the total electricity production in 2023 [3].

Fossil fuels continue to form a significant foundation of global energy production [4]. Under the framework of the United Nations, the Paris Agreement was adopted in 2015 with the aim of limiting global warming to 1,5–2°C [5]. Achieving this goal primarily requires focusing future efforts on reducing CO_2 emissions resulting from the combustion of fossil fuels [6]. The largest share of total greenhouse gas (GHG) emissions, including CO_2 emissions, in Montenegro comes from the energy sector, specifically from coal combustion at the Pljevlja thermal coal-fired power plant [7,8].

Under the EU Energy Law of 2021, the European Union has set ambitious targets for reducing greenhouse gas (GHG) emissions in the fight against climate change. These targets include reducing emissions by at least 55% by 2030 compared to 1990 levels, and achieving net-zero harmful greenhouse gas emissions by 2050 [9]. Although Montenegro is not yet a member of the European Union, its membership in the Energy Community obligates the country to reduce harmful exhaust gas emissions by 55% by 2030 [10]. Upon joining the EU, Montenegro will be required to achieve carbon neutrality by 2050 [9].

Energy generated through wind turbines has emerged as a leading renewable energy source due to its reliability, safety, and the absence of pollution [11]. Offshore wind farms are an integral part of the blue-green economy, as they harness the marine ecosystem to generate goods essential for humanity, while ensuring sustainable energy production [12,13]. The production of electricity from offshore wind farms plays a key role in the transition to net-zero harmful exhaust emissions [14]. To keep global temperature rise below 1,5°C by 2050, studies suggest that achieving 500 GW of offshore wind capacity by 2030 and 2500 GW by 2050 is essential [15].

In the year when the Parliament of Montenegro declared the country as an ecological state, Denmark built the first offshore wind farm, named Vindeby [1,16]. This wind farm, located at a depth of 2 to 5 meters, consisted of 11 wind turbines, each with a capacity of 450 kW. The wind farm operated successfully until 2016 [16].

In the part of the Adriatic Sea under Montenegro's jurisdiction, no offshore wind farms have been constructed yet. However, onshore, two wind farms are operational: the Krnovo wind farm (72 MW), commissioned in 2016, and the Možura wind farm (46 MW), commissioned in 2019 [17–19].

1.1 Case Study – Montenegro's Power System

The electricity generation system of Montenegro is based on hydropower plants, wind farms, solar sources, and its only thermal coal-fired power plant. By the end of 2023, the Montenegrin energy system comprised 50 power plants with a total installed capacity of 1067,238 MW, of which 21,08% is accounted for by the Pljevlja thermal coal-fired power plant. In 2023, a total of 4046,71 GWh of electricity was generated within Montenegro's energy system, with the thermal coal-fired power plant contributing 37,64% of the country's total electricity production [3]. Commissioned in 1982, the Pljevlja thermal coal-fired power plant is the only stable source of electricity in Montenegro and forms the backbone of the country's energy system [20].

As shown in Figure 1, the main source of CO_2 emissions in Montenegro comes from the energy sector, with the Pljevlja thermal coal-fired power plant having the dominant impact on CO_2 emissions [7].

This study assesses the potential electricity generation capacity of an offshore wind farm in Montenegro using 15 MW wind turbines at a location identified in the authors' prior research [25]. Two offshore wind farm technical installed capacity criteria were applied: one defined by the World Bank (WB), specifying a capacity of 3 MW/km^2, and another by the National Renewable Energy Laboratory (NREL) under the U.S. Department of Energy, specifying 5 MW/km^2. The study also examines two operational scenarios of Montenegro's electricity system. The first scenario analyzes the construction of a fixed offshore wind farm (bottom-fixed and jacket-fixed wind farm) up to 60 m, with the shutdown of the Pljevlja coal-fired thermal power plant. The second scenario analyzes the construction of an offshore wind farm across the entire area deemed suitable for development, encompassing bottom-fixed, jacket-fixed, and floating foundations, with the shutdown of the Pljevlja coal-fired thermal power plant.

This study makes a novel and significant contribution by solely assessing the viability of offshore wind energy development in Montenegro and its potential contribution to the country's energy transition. While previous researchers have primarily focused on onshore wind, solar and hydropower resources, this study explores offshore wind energy as a viable alternative to coal-based electricity generation. By applying multiple capacity assessment methodologies and analyzing different offshore wind farm configurations, this research provides a comprehensive framework for decision-making within Montenegro's renewable energy strategy.

The primary aim of this study is to evaluate the potential of offshore wind energy as a viable alternative to replace coal-based electricity generation in Montenegro. A key objective is to assess the potential electricity production from an offshore wind farm along Montenegro's coastline, with calculations based on the identification of the wind farm's capacity factor.

The results offer a more precise evaluation of wind energy as a renewable source in Montenegro, providing a scientifically grounded basis for future strategic deci-

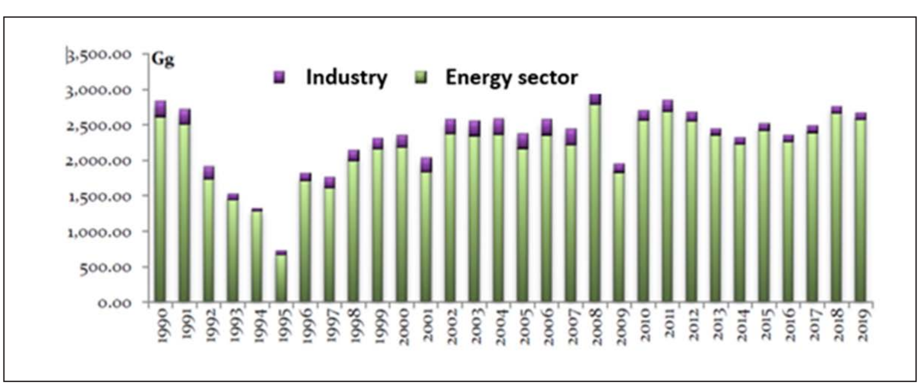


Figure 1 Montenegro CO_2 Emissions by Sector (1990-2019) [8]

sions in the context of the country's energy transition and efforts to attract investors in the energy sector. A particularly significant aspect of this research is the analysis of the offshore wind potential to replace the Pljevlja coal-fired power plant, Montenegro's only stable electricity source. This replacement could play a crucial role in long-term planning for a sustainable energy system, contributing to the country's abandonment of fossil fuels.

This paper is structured into five sections. In Section 2, the research methodology and the data used in the study are outlined. Section 3 compares the electricity generation of the Pljevlja coal-fired power plant with the potential output of offshore wind farms. In Section 4, Montenegro's electricity system is evaluated through two scenarios: the first considers the decommissioning of the Pljevlja coal-fired power plant and the construction of a fixed-bottom and jacket-fixed wind farm, while the second examines the shutdown of the Pljevlja plant with the development of both fixed (bottom-fixed and jacket fixed) and floating wind farms. Finally, Section 5 presents the conclusions and key insights drawn from the study.

2 Materials and Methods

The study aims to determine the degree of wind energy utilization for areas defined in previous research conducted by the authors of this paper [25]. The determination of the capacity factors for fixed offshore wind turbines, jacket-fixed offshore wind turbines, and floating offshore wind turbines has enabled the precise estimation of the amount of electricity these turbines can generate. The entire study relies heavily on the extensive use of the Global Wind Atlas 3.1 (GWA) and QGIS software (QGIS).

The research methodology applied in this study is presented in Figure 2.

The previous research results, along with the power curve from the NREL IEA 15 MW model, were used as input data for the "Energy Yield" analysis, a component of the GWA software [25]. By processing these data for areas identified as suitable for the construction of fixed, jacket-fixed, and floating offshore wind farms, a qualitative map (shapefile layer) of the capacity factor for each individual offshore wind farm was generated. Additionally, a monthly wind speed index for each specific offshore wind farm area was produced.

To define the average capacity factor for each individual wind farm (fixed, jacket-fixed, and floating) using the NREL IEA 15 MW wind turbine model, the shapefile layer generated by the GWA software was imported into QGIS software. Using the analytical tools in QGIS, the average capacity factor for each wind farm was calculated. The capacity factor represents (C_f) the ratio between the total amount of electricity produced during the observed period and the maximum amount of energy that the wind turbine or wind farm could theoretically produce during the same period and can be expressed by the following equation:

$$C_f = \frac{E_{actual}}{E_{max}} \, x \, 100 \tag{1}$$

where E_{actual} represents the actual amount of electricity generated during the observed period, while E_{max} denotes the maximum possible amount of electricity that can be theoretically produced during the observed period [21].

Based on previous research conducted by relevant institutions and their recommendations, this paper examines two specific criteria for the installed capacity of wind turbines. In accordance with the criteria established by the WB, the technical wind potential of an area is defined as the product of the sea area that has average annual wind speeds between 7 and 8 m/s and a value of 3 MW/km² [22]. In contrast, NREL, which is part of the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy, defines the technical potential of offshore areas as the product of the sea area

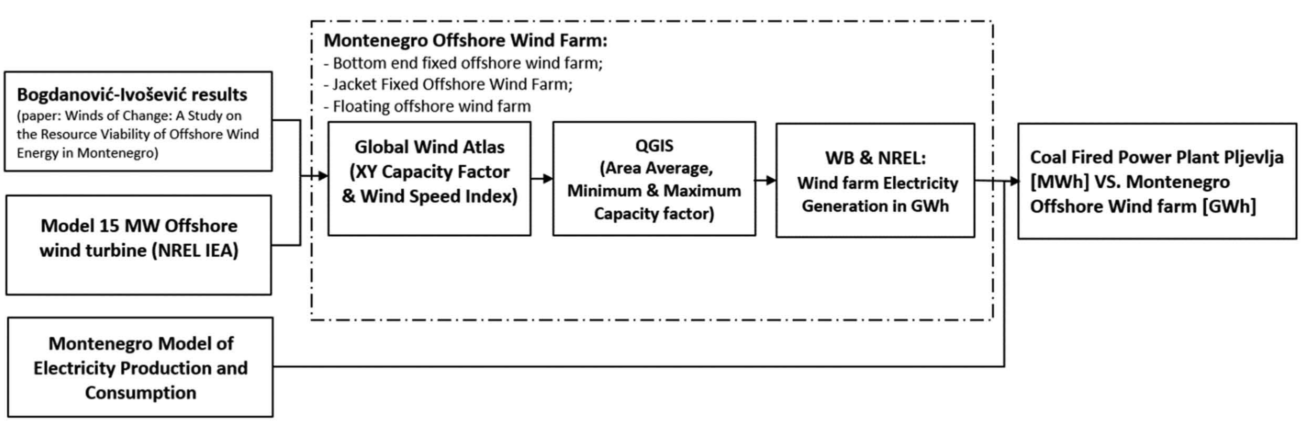


Figure 2 Conceptual Research Methodology

with average annual wind speeds greater than 7 m/s and a value of 5 MW/km² [23]. According to estimates, in Europe, the average density of installed capacity for offshore wind farms in 2022 ranged between 5 MW/km² and 5,4 MW/km² [24].

In accordance with the criteria established by the WB and NREL, the maximum possible amount of electricity that can be theoretically produced during one year (or 8760 hours) can be expressed by the following equation:

$$E_{max} = c\, A\, 8760 \tag{2}$$

where c represents the constant (3 MW per km² when using the WB criteria or 5 MW per km² when using the NREL criteria), A represents the offshore area in km² considered suitable for wind farm construction at sea, and 8760 is the time period of one year (in hours) [22,24].

According to equation (1), by multiplying the E_{max} of the wind farm (based on both WB and NREL criteria) with the calculated average capacity factor of the wind farm, the total yearly amount of electricity (E_{actual}) that can be generated by the wind farm is estimated.

The relationship between wind speed and energy production is based on the fundamental principle that wind power is proportional to the cube of wind speed [27]. The Wind Speed Index (WSI) is a relative indicator used to compare wind speed at a specific location over different time periods (e.g., months or seasons) [27,28]. It represents the ratio between the average wind speed in a given period and a reference wind speed [27,28]. Since WSI provides a relative measure of wind speed, it follows that wind power is also proportional to the cube of WSI. To distribute the total actual energy production across individual months, the energy allocated to each month is determined by scaling the total actual energy production according to the ratio of the cube of the monthly WSI to the sum of the cubes of WSI for all months [27,28]. This leads to the following equation:

$$E_{month} = E_{actual}\, \frac{(WSI_{month})^3}{(\sum WSI_{month})^3} \tag{3}$$

where E_{actual} represents the total annual electricity production, WSI_{month} denotes the wind speed index for the given month, and ∑WSI represents the sum of wind speed indices for all 12 months.

Based on the analyses conducted in this study within the GWA software, the monthly wind speed index was calculated. By knowing the values of the monthly wind speed index and the total yearly generated electricity for each individual wind farm, the monthly distribution of electricity production was further calculated in the subsequent analysis.

In the final step of the research, the estimated electricity production that could be generated by the offshore wind farms was compared with the amount of electricity currently generated by the Pljevlja thermal coal-fired power plant. The ultimate goal of this study is to determine the extent to which the construction of offshore wind farms in Montenegro could replace the electricity currently produced by the Pljevlja thermal coal-fired power plant, which is scheduled to be decommissioned in the future, in order to meet the imposed environmental targets for reducing greenhouse gas emissions, primarily CO_2.

2.1 Bogdanović and Ivošević: Previous Research on Offshore Area for Wind Farm Development

The authors' previous research, published in 2024, identified an area of 766,598 km² in the southern part of the Adriatic Sea, with precise geographic coordinates, which is estimated to be suitable for the construction of a wind farm. The study, based on bathymetric data analysis, determined that 42,253 km² of this area is located at sea depths up to 50 m, which is the depth range where wind farms can be constructed using fixed-bottom structures. Further bathymetric analysis revealed that 46,185 km² of the identified area lies at depths between 50 and 60 m, where wind farms can be constructed using jacket foundations. The largest part of the identified area is located at depths greater than 60 m, where wind farms can only be built using modern technological solutions, such as floating foundations. In their research, the Global Wind Atlas software was used, developed by the Technical University of Denmark, while exploring the depths with available bathymetric data sets. The entire study is based on the intensive use of QGIS software, ensuring that all obtained data is available in real geographic coordinates [25]. The identified research area of their research is shown in Figure 3.

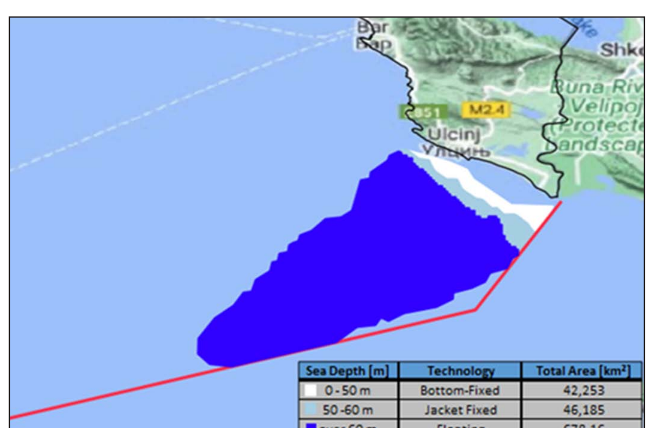


Figure 3 Offshore Montenegro suitable area for offshore wind farm development [25]

Power Curve of the IEA Wind 15-MW Turbine					
Wind Speed [m/s]	Power [kW]	Wind Speed [m/s]	Power [kW]	Wind Speed [m/s]	Power [kW]
2,999999831	70,021377	6,960000175	4265,458105	10,78699989	14994,53141
3,499999916	301,9937	6,969999584	4283,898392	10,78799997	14994,51543
4	595,088475	6,980000341	4301,948494	10,78899937	14994,52466
4,500000084	964,887394	6,989999749	4320,289911	10,78950042	14994,59142
4,750000126	1185,081978	6,999999831	4339,296326	10,8000002	14994,53984
5,000000169	1429,216889	7,499999916	5338,82324	10,89999968	14994,4265
5,249999874	1695,245223	8	6481,116995	10,99999983	14994,26629
5,999999663	2656,263808	8,500000084	7774,570984	11,24999987	14994,02192
6,199999966	2957,216831	9,000000169	9229,227024	11,50000059	14994,10762
6,40000027	3275,743373	9,500000253	10855,04374	11,75000063	14994,17514
6,499999747	3442,669566	10,00000034	12661,25448	11,99999933	14994,17331
6,55000016	3528,654678	10,2499997	13638,148	12,99999949	14994,76256
6,599999899	3614,989064	10,49999975	14660,65727	13,99999966	14994,76121
6,700000051	3791,164267	10,60000057	14994,84635	14,99999983	14994,75771
6,800000202	3971,967845	10,70000005	14994,64979	17,50000025	14994,82665
6,900000354	4155,58904	10,72000022	14994,61195	20,00000067	14994,82754
6,919999845	4192,387051	10,73999971	14994,55374	22,49999975	14996,27008
6,929999928	4210,773549	10,76000055	14994,52082	24,99999882	14997,62687
6,94000001	4228,841377	10,78000004	14994,55424		
6,950000093	4247,186435	10,78400034	14994,52965		

IEA 15-MW Turbine Power Curve Diagram

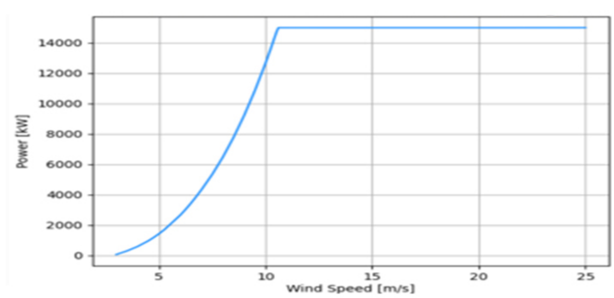


Figure 4 NREL 15 MW wind turbine model [26]

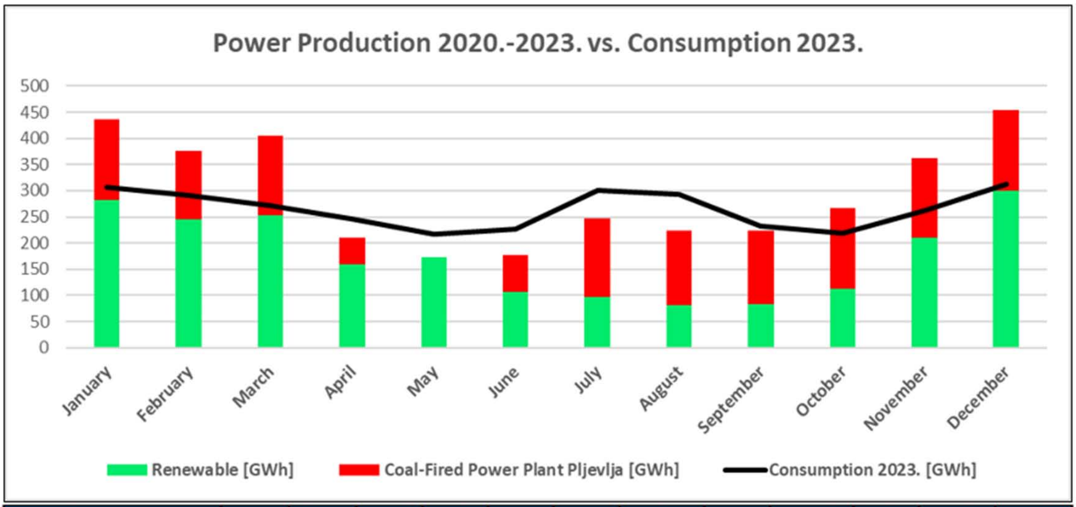
2.2 Offshore Wind Turbine Model – NREL IEA 15 MW

The prevailing trend in offshore wind farm development is the use of high-power wind turbines, which reduces the investment costs per MW. In 2022, several wind turbine manufacturers, including Siemens Gamesa, Vestas, and General Electric, began testing prototypes of 15 MW wind turbines designed for offshore use. These turbines are planned to be commercially available by 2024, with the nacelle installed at a height of 150 meters above sea level [25].

For the purposes of this research, the NREL IEA 15 MW wind turbine model (National Renewable Energy Laboratory, International Energy Agency) was selected. The power curve of the IEA 15 MW wind turbine model is shown in Figure 4.

2.3 Montenegro Model of Electricity Production & Consumption

Due to the fluctuating annual share of the Pljevlja thermal power plant in Montenegro's total electricity production, a model of electricity generation and consumption was developed for the purposes of this study. The share of electricity production from the Pljevlja thermal coal-fired power plant within the Montenegrin power system primarily depends on the hydrological situation, specifically the production from the Piva and Perućica hydropower plants. The share of electricity produced by the Pljevlja thermal coal-fired power plant in the Montenegrin power system was 46% in 2020, 36,51% in 2021, 44,95% in 2022, and 37,67% in 2023. The model is based on data from energy reports for 2020–2023, published by the Ministry responsible for the energy sector. This model is shown in Figure 5, it includes the values of average monthly electricity production for the period from 2020 to 2023, as well as the monthly consumption for 2023 [3,19,29–31].



Production 2020.-2023.	January	February	March	April	May	June	July	August	September	October	November	December
Renewable [GWh]	281,65	244,39	253,53	158,65	172,33	106,19	97,44	81,90	83,81	112,53	210,58	299,25
Coal-Fired Power Plant Pljevlja [GWh]	155,65	131,67	152,37	50,52	0,00	71,18	149,42	140,95	139,22	153,71	151,48	154,85
Total Power Production [GWh]	437,30	376,07	405,90	209,16	172,33	177,37	246,85	222,85	223,03	266,24	362,06	454,11
Consumption 2023. [GWh]	307,44	290,06	271,35	245,46	217,31	226,74	299,96	293,85	231,78	219,41	262,45	313,31

Figure 5 Model of average monthly electricity production (2020–2023) & consumption (2023)

3 Results

The research results are presented separately for three areas identified by authors' previous research, which are part of the total surface area of 766,598 km^2. The first area includes locations suitable for offshore wind farms using fixed support structures (sea depth up to 50 m). The second area pertains to locations suitable for the construction of wind farms with jacket fixed support structures (sea depth from 50 to 60 m). The third area encompasses regions where wind farms can only be built using floating structures (sea depth exceeding 60 m) [25].

3.1 Results of Bottom-Fixed Wind Farm

The identified area with a sea depth of up to 50 meters, claimed to be suitable for the construction of offshore wind farms with fixed-bottom support structures based on average annual wind speeds, covers 42,253 km^2 [25]. By loading the shapefile of the 42,253 km^2 area, generated by authors' previous research, into the GWA Energy Yield function along with the NREL IEA 15 MW turbine model, software analysis produced a shapefile of the capacity factor for the 42,253 km^2 area [25]. Further analyses within the GWA software calculated the monthly wind speed index, which is presented in Figure 6.

For the designated area, at a height of 150 m, the GWA software estimated an average annual wind speed of 7,24 m/s. To calculate the average capacity factor, the shapefile generated by the GWA software was imported into QGIS for analysis. . The results of the data processing using the "Zonal Statistic" function indicated that the area has capacity factor values ranging from 0,3282 to 0,3555, with an average capacity factor of 0,3429. The results of this analysis are illustrated in Figure 7.

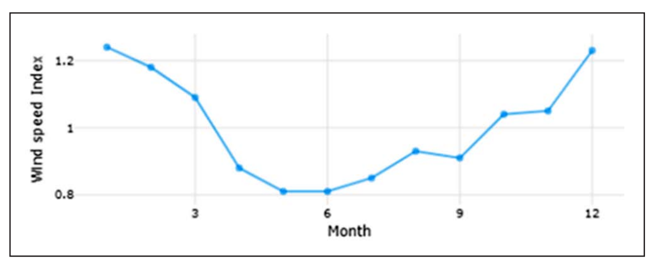


Figure 6 Monthly Wind Speed Index of the Bottom-Fixed Offshore Wind Farm

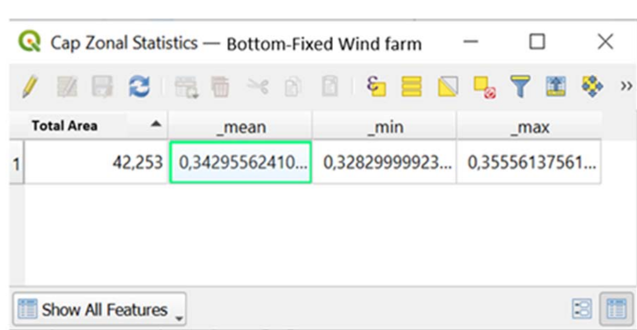
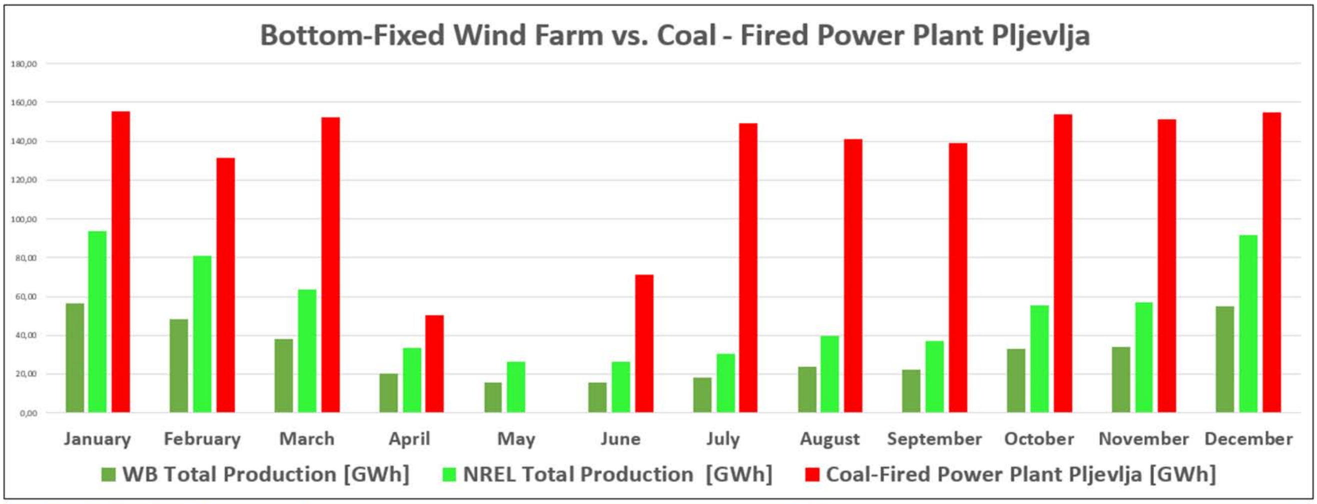


Figure 7 Average Capacity Factor of Bottom-Fixed Wind Farm (Offshore Montenegro)



Avg wind speed at 150 m [m/s]	7,12												
Month	January	February	March	April	May	June	July	August	September	October	November	December	Total
Wind Speed Index	1,24	1,18	1,09	0,88	0,81	0,81	0,85	0,93	0,91	1,04	1,05	1,23	
Avg monthy wind speed [m/s]	8,83	8,40	7,76	6,27	5,77	5,77	6,05	6,62	6,48	7,40	7,48	8,76	
WB Total Production [GWh]	56,26	48,48	38,21	20,11	15,68	15,68	18,12	23,73	22,23	33,19	34,16	54,91	380,76
NREL Total Production [GWh]	93,76	80,80	63,69	33,51	26,13	26,13	30,20	39,56	37,06	55,32	56,93	91,51	634,60
Coal-Fired Power Plant Pljevlja [GWh]	155,65	131,67	152,37	50,52	0,00	71,18	149,42	140,95	139,22	153,71	151,48	154,85	1451,03

Figure 8 Bottom-Fixed Wind Farm vs. Coal-Fired Power Plant Pljevlja

According to the criteria defined by the WB (3 MW/km^2), the technical potential of this area is estimated at 126,759 MW. On the other hand, applying the NREL criterion (5 MW/km^2), the technical potential of the area is defined as 211,265 MW. Based on the known technical potential, capacity factor, and monthly wind speed index, the amount of electricity that can be produced annually on a monthly basis for offshore wind farms with fixed-bottom structures of capacities 126,759 MW and 211,265 MW was calculated. These results are presented in Figure 8.

Based on the data presented in Figure 8, it is estimated that the construction of a bottom-fixed wind farm on the 42,253 km^2 area of the Montenegrin sea could generate 380,76 GWh of electricity according to the WB criteria, and 634,60 GWh according to NREL criteria. Although significant, these amounts of electricity are considerably lower than the output of the Pljevlja coal-fired power plant, indicating that the construction of just this wind farm would not fully replace the electricity production of the Pljevlja power plant. However, according to the NREL criteria, the estimated electricity generation from a wind farm with jacket fixed structures would cover approximately 43,6% of the Pljevlja power plant's output.

3.2 Results of Jacket Fixed Wind Farm

Based on previous authors' research, a 46,185 km^2 offshore area with depths of 50 to 60 meters has been identified as potentially suitable for wind farm construction using jacket-fixed supporting structures [25]. By importing the shapefile layer of 46,185 km^2, into the GWA Energy Yield function, along with the NREL IEA 15 MW wind turbine model, a shapefile layer containing the capacity factor data for this area was obtained. Further analysis within the GWA software was used to calculate the monthly wind speed index, which is shown in Figure 9.

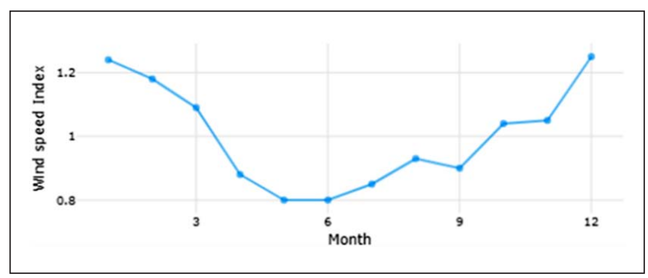


Figure 9 Monthly Wind Speed Index of the Jacket Fixed Wind Farm

For the area claimed to be suitable for the construction of a wind farm using jacket fixed support structures, at a height of 150 m above sea level, the estimated average annual wind speed is 7,36 m/s, according to the GWA software.

To determine the average capacity factor, the shapefile layer generated by the GWA software was imported into QGIS. The results of the data processing using the "Zonal Statistic" function indicated that the area has capacity factor values ranging from 0,3524 to 0,3601, with an average capacity factor of 0,3524. The results of this analysis are shown in Figure 10.

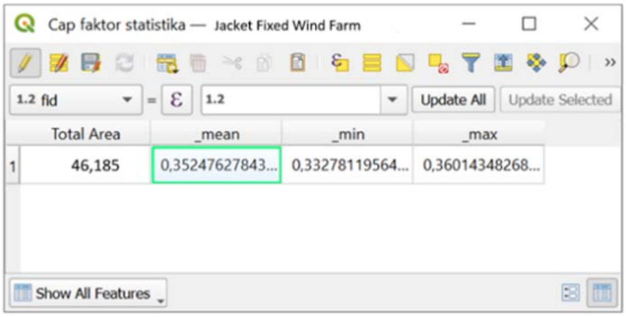


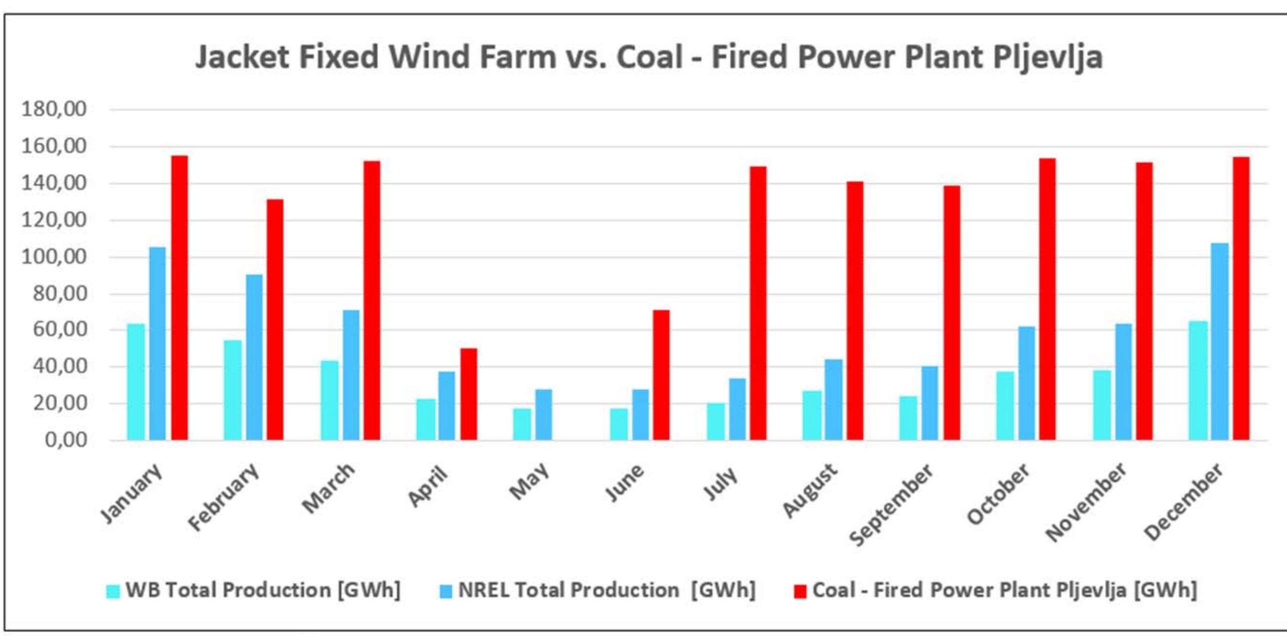
Figure 10 Average Capacity Factor of Jacket Fixed Wind Farm (offshore Montenegro)

According to the criteria established by the WB (3 MW/km^2), the technical potential of this area is estimated at 138,555 MW. On the other hand, if the NREL criteria (5 MW/km^2) are applied, the technical potential of the area amounts to 230,925 MW. Based on the known technical potential of the area, the capacity factor, and the monthly wind speed index, the amount of electricity that can be produced over the course of a year on a monthly basis for a wind farm with jacket fixed structures of 138,555 MW and 230,925 MW has been calculated. These results are shown in Figure 11.

Based on the data shown in Figure 11, it is estimated that the construction of an offshore wind farm with jacket fixed structures on the area of 46,185 km^2 of the sea in Montenegro could generate 427,72 GWh of electricity according to the WB criterion, or 712,87 GWh according to the NREL criterion. Although these electricity amounts are considerable, they remain lower than the current output of the Pljevlja thermal coal-fired power plant, meaning the construction of this wind farm would not completely replace the power generated by the Pljevlja plant. However, according to the NREL criterion, the estimated amount of electricity that could be generated by the construction of the wind farm with jacket fixed structures would provide about 49% of the electricity produced by the Pljevlja thermal coal-fired power plant.

3.3 Results of Floating Wind Farm

For areas that are estimated to have sufficient average annual wind speeds and are located in water depths greater than 60 meters, offshore wind turbines can only be installed using floating support structures. In the authors' previous research, they determined that 678,16 km^2 of the identified offshore areas are considered suitable for wind farm development are located in depths exceeding 60 meters [25]. By loading the shapefile layer of the 678,16 km^2 area, into the GWA Energy Yield function along with the NREL IEA 15 MW turbine model, a shapefile containing capacity factor data for this area was obtained through software analysis. Further analy-



Avg wind speed at 150 m [m/s]	7,36												
Month	January	February	March	April	May	June	July	August	September	October	November	December	Total
Wind Speed Index	1,24	1,18	1,09	0,88	0,80	0,80	0,85	0,93	0,90	1,04	1,05	1,25	
Avg monthy wind speed [m/s]	9,13	8,68	8,02	6,48	5,89	5,89	6,26	6,84	6,62	7,65	7,73	9,20	
WB Total Production [GWh]	63,05	54,34	42,83	22,54	16,93	16,93	20,31	26,60	24,11	37,20	38,28	64,59	427,72
NREL Total Production [GWh]	105,09	90,56	71,38	37,56	28,22	28,22	33,85	44,34	40,18	62,00	63,81	107,65	712,87
Coal - Fired Power Plant Pljevlja [GWh]	155,65	131,67	152,37	50,52	0,00	71,18	149,42	140,95	139,22	153,71	151,48	154,85	1451,03

Figure 11 Jacket Fixed Wind Farm vs. Coal-Fired Power Plant Pljevlja

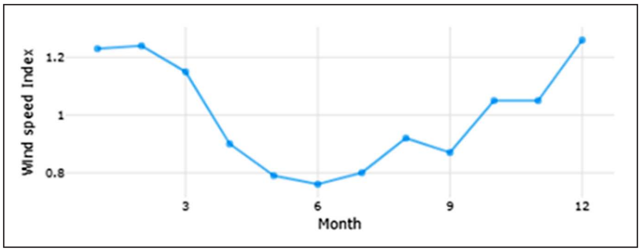


Figure 12 Monthly wind speed index of the floating wind farm

ses within the GWA software calculated the monthly wind speed index, which is shown in Figure 12.

For the specified area, at a height of 150 meters, the GWA software calculated the average annual wind speed to be 7,45 m/s. To determine the average capacity factor, the shapefile layer generated by the GWA software was loaded into the QGIS software. The results of the data processing using the "Zonal Statistic" function showed that the area has a capacity factor ranging from 0,3295 to 0,3670, with an average capacity factor of 0,3440. The results of the analysis are presented in Figure 13.

According to the criterion set by the WB (3 MW/km^2), the technical potential of this area is estimated to be 2034,48 MW. On the other hand, if the NREL criterion (5 MW/km^2) is applied, the technical potential of the area is 3390,8 MW. Based on the known technical potential of

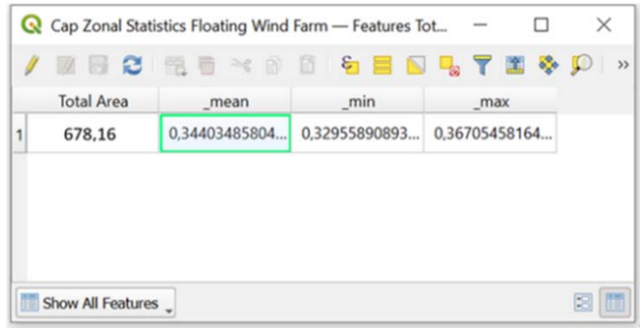
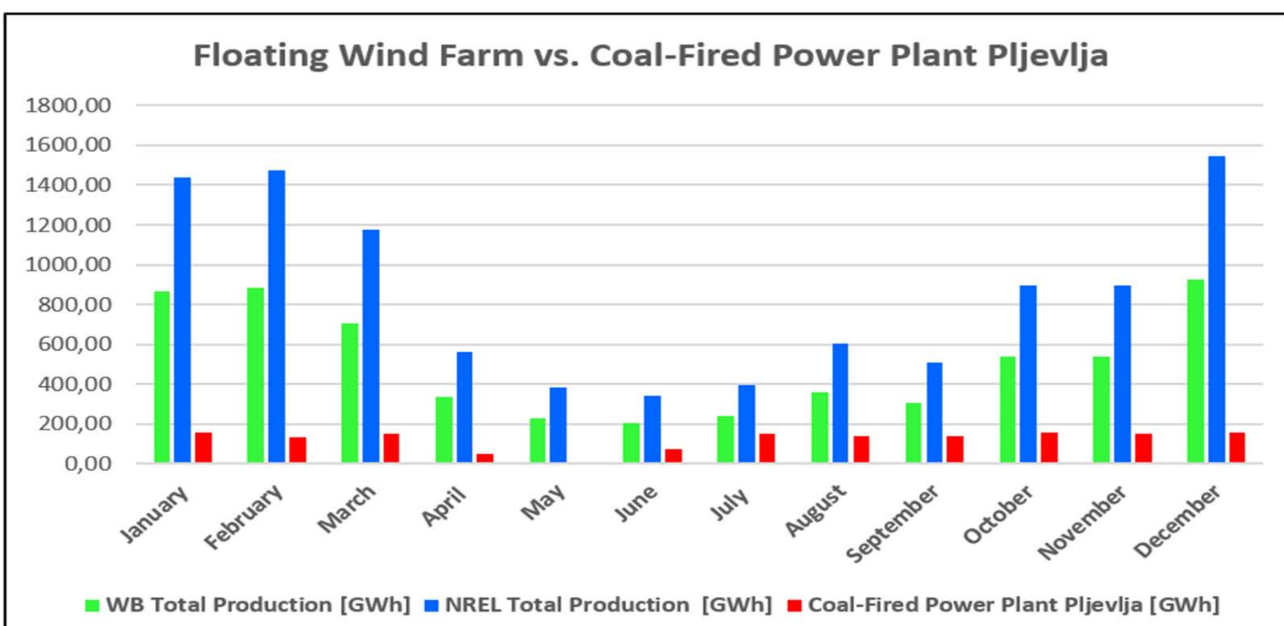


Figure 13 Average Capacity Factor of Floating Wind Farm (offshore Montenegro)

the area, the capacity factor, and the monthly wind speed index, the amount of electricity that can be produced annually on a monthly basis for a floating wind farm with capacities of 2034,48 MW and 3390,8 MW was calculated. These results are shown in Figure 14.

Based on the data shown in Figure 14, it is estimated that the construction of a floating wind farm on an area of 678,16 km^2 of Montenegro's sea could generate 6130,78 GWh of electricity according to the WB criterion, and 10217,97 GWh according to the NREL criterion. These quantities of electricity are significantly higher than the annual production of the Pljevlja thermal coal-fired power Plant, and the construction of this wind



Avg wind speed at 150 m [m/s]	7,45												
Month	January	February	March	April	May	June	July	August	September	October	November	December	Total
Wind Speed Index	1,23	1,24	1,15	0,90	0,79	0,76	0,80	0,92	0,87	1,05	1,05	1,26	
Avg monthy wind speed [m/s]	9,16	9,24	8,57	6,71	5,89	5,66	5,96	6,85	6,48	7,82	7,82	9,39	
WB Total Production [GWh]	863,36	884,59	705,62	338,22	228,75	203,66	237,54	361,28	305,52	537,09	537,09	928,08	6130,78
NREL Total Production [GWh]	1438,93	1474,31	1176,03	563,70	381,25	339,44	395,91	602,13	509,19	895,14	895,14	1546,80	10217,97
Coal-Fired Power Plant Pljevlja [GWh]	155,65	131,67	152,37	50,52	0,00	71,18	149,42	140,95	139,22	153,71	151,48	154,85	1451,03

Figure 14 Floating Wind Farm vs. Coal-Fired Power Plant Pljevlja

farm could completely replace the production of the Pljevlja thermal coal-fired power plant. According to the NREL criterion, the estimated amount of electricity that could be generated by the construction of the floating wind farm would provide 8766,94 GWh more electricity than is currently produced at the Pljevlja thermal coal-fired power plant, while according to the WB criterion, the floating wind farm would provide 4679,75 GWh more electricity than the current production of the Pljevlja thermal coal-fired power plant.

4 Discussion

This study represents the first scientific assessment of the potential for offshore wind energy production in Montenegro, particularly in terms of capacity factor estimation. Given the absence of previous studies evaluating these parameters in the Montenegrin context, the results presented here establish a foundation for future research and policy considerations. While international studies provide insights into offshore wind feasibility, direct comparisons are limited due to geographical, meteorological, and bathymetric differences.

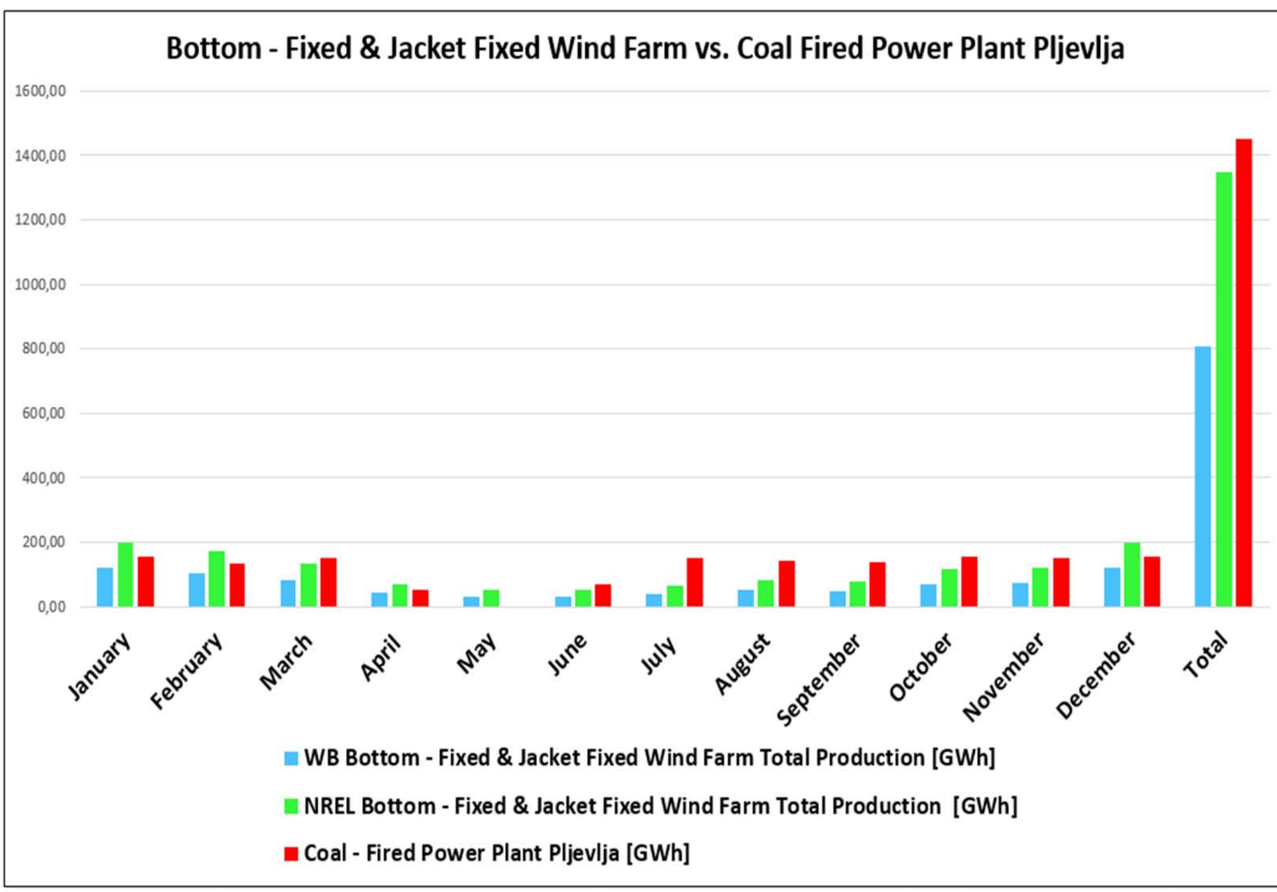
The primary objective of this research was to determine the extent to which the construction of offshore wind farms in Montenegro could offset the electricity production currently provided by the Pljevlja coal-fired power plant. To achieve this goal, the study was structured around two scenarios.

In the first scenario, it is assumed that fixed offshore wind farms will be constructed in waters with depths up to 60 meters (encompassing bottom-fixed and jacket-fixed designs), accompanied by the permanent shutdown of the Pljevlja power plant.

The second scenario considers the development of wind farms across the entire area identified by previous author's research (a combination of bottom-fixed, jacket-fixed, and floating wind farms), also involving the permanent shutdown of the Pljevlja power plant [25].

4.1 Scenario No. 1

Bottom-fixed and jacket-fixed wind farms connected to the grid, while the Pljevlja coal-fired power plant is permanently shut down.



Month	January	February	March	April	May	June	July	August	September	October	November	December	Total
WB Bottom - Fixed & Jacket Fixed Wind Farm Total Production [GWh]	119,31	102,82	81,04	42,64	32,61	32,61	38,43	50,33	46,34	70,39	72,44	119,50	808,48
NREL Bottom - Fixed & Jacket Fixed Wind Farm Total Production [GWh]	198,85	171,36	135,07	71,07	54,36	54,36	64,05	83,89	77,24	117,32	120,74	199,17	1347,47
Coal - Fired Power Plant Pljevlja [GWh]	155,65	131,67	152,37	50,52	0,00	71,18	149,42	140,95	139,22	153,71	151,48	154,85	1451,03

Figure 15 Bottom-Fixed & Jacket Fixed Wind Farms vs. Pljevlja Coal-Fired Power Plant

Based on the results presented in Section 3, the comparison of the annual electricity production of the Pljevlja Coal-Fired Power Plant with the expected electricity generation from the construction of fixed offshore wind farms (bottom-fixed and jacket-fixed) is illustrated in Figure 15.

Based on the results shown in Figure 15, it can be concluded that constructing the aforementioned wind farms in Montenegrin waters could compensate approximately 55,71% of the electricity production of the Pljevlja coal-fired power plant under the WB criteria and 92,86% under the NREL criteria.

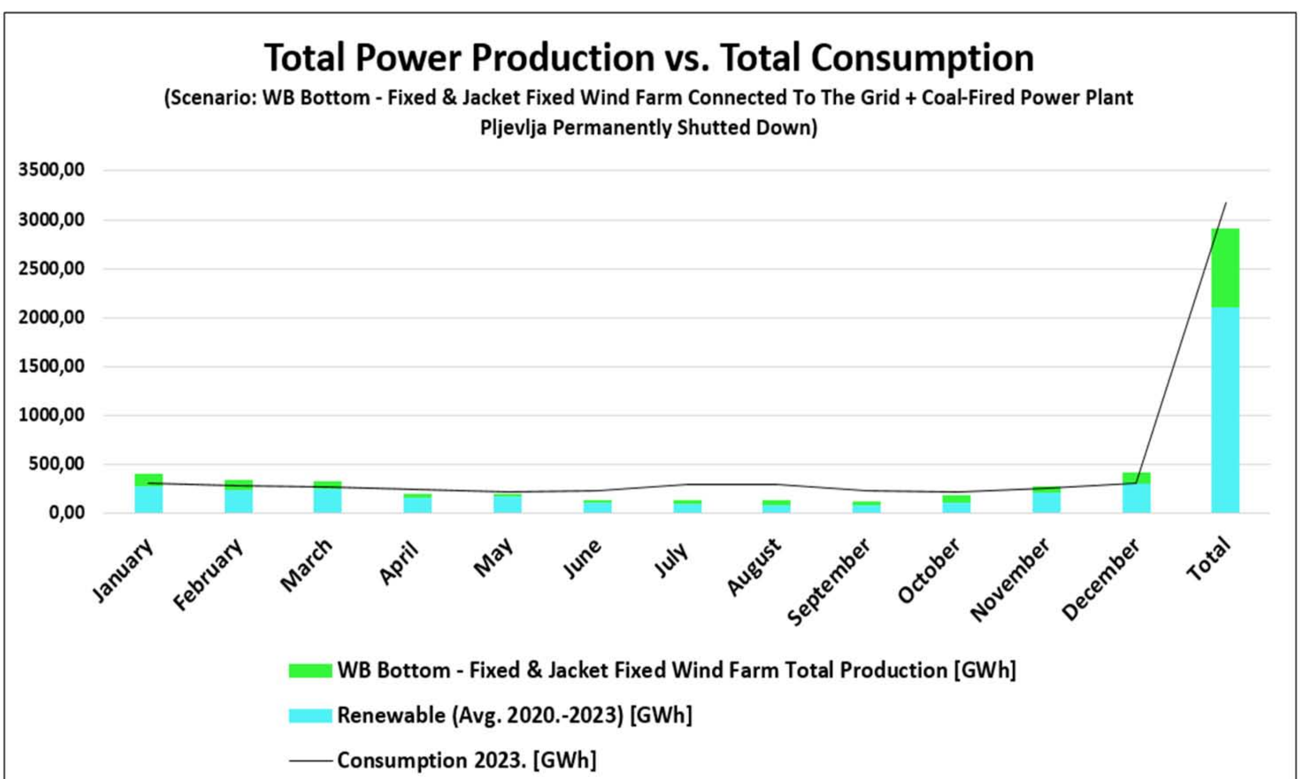
Monthly production analysis reveals that, according to the NREL criteria, the wind farms would generate more electricity than the Pljevlja coal-fired power plant during the months of January, February, April, May, and December.

For Scenario No1, using the model of average monthly electricity production for the period 2020–2023 and annual consumption for 2023 (as shown in Figure 5.), the model of electricity production and consumption, assuming the shutdown of the Pljevlja coal-fired power plant and the construction of the proposed wind farms under the WB criteria, is illustrated in Figure 16.

Based on the results illustrated in Figure 16, it can be concluded that the construction of fixed wind farms, coupled with the permanent shutdown of the Pljevlja coal-fired power plant, following the WB criteria, would not entirely enable Montenegro's power system to meet the required electricity production, leaving a deficit of approximately 270 GWh.

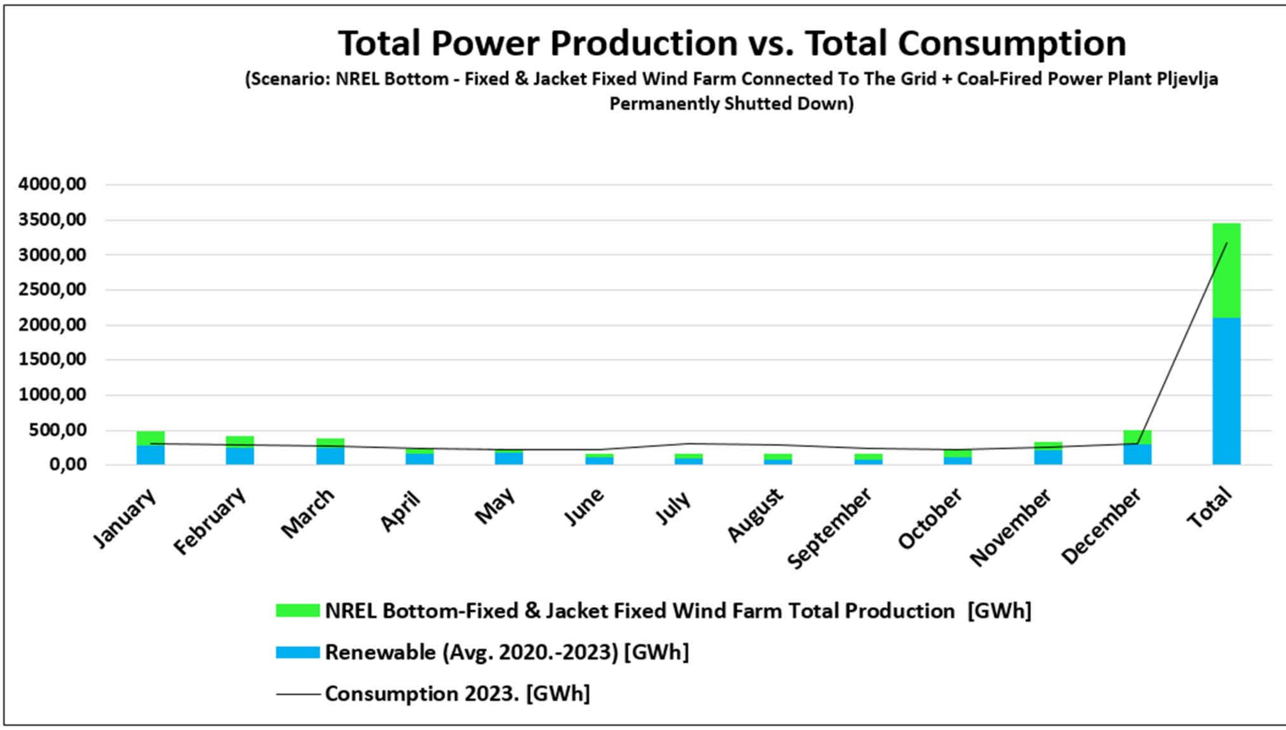
For the given scenario, using the average monthly electricity production model for the period 2020–2023 and the annual consumption for 2023, as presented in Figure 5, the electricity production and consumption model with the permanent shutdown of the Pljevlja coal-fired power plant and the construction of the proposed wind farms following the NREL criteria is depicted in Figure 17.

Based on the results shown in Figure 17, it can be concluded that the construction of a fixed wind farm under the NREL criteria, combined with the permanent shutdown of the Pljevlja coal-fired power plant, would enable Montenegro's power system to meet the total annual electricity production requirements, with a surplus of 270 GWh. However, a production deficit would occur on a monthly basis during June, July, August, and September.



Month	January	February	March	April	May	June	July	August	September	October	November	December	Total
Renewable (Avg. 2020.-2023) [GWh]	281,65	244,39	253,53	158,65	172,33	106,19	97,44	81,90	83,81	112,53	210,58	299,25	2102,25
WB Bottom - Fixed & Jacket Fixed Wind Farm Total Production [GWh]	119,31	102,82	81,04	42,64	32,61	32,61	38,43	50,33	46,34	70,39	72,44	119,50	808,48
Total Power Production [GWh]	400,96	347,21	334,57	201,29	204,95	138,81	135,87	132,24	130,15	182,92	283,02	418,75	2910,73
Consumption 2023. [GWh]	307,44	290,06	271,35	245,46	217,31	226,74	299,96	293,85	231,78	219,41	262,45	313,31	3179,12

Figure 16 WB Bottom-Fixed & Jacket Fixed Wind Farms Connected to the Grid + Coal-Fired Power Plant Permanently Shut Down



Month	January	February	March	April	May	June	July	August	September	October	November	December	Total
Renewable (Avg. 2020.-2023) [GWh]	281,65	244,39	253,53	158,65	172,33	106,19	97,44	81,90	83,81	112,53	210,58	299,25	2102,25
NREL Bottom-Fixed & Jacket Fixed Wind Farm Total Production [GWh]	198,85	171,36	135,07	71,07	54,36	54,36	64,05	83,89	77,24	117,32	120,74	199,17	1347,47
Total Power Production [GWh]	480,50	415,75	388,59	229,72	226,69	160,55	161,49	165,80	161,05	229,85	331,32	498,42	3449,72
Consumption 2023. [GWh]	307,44	290,06	271,35	245,46	217,31	226,74	299,96	293,85	231,78	219,41	262,45	313,31	3179,12

Figure 17 NREL Bottom-Fixed & Jacket Wind Farm Connected to the Grid + Coal-Fired Power Plant Permanently Shut Down

4.2 Scenario No. 2

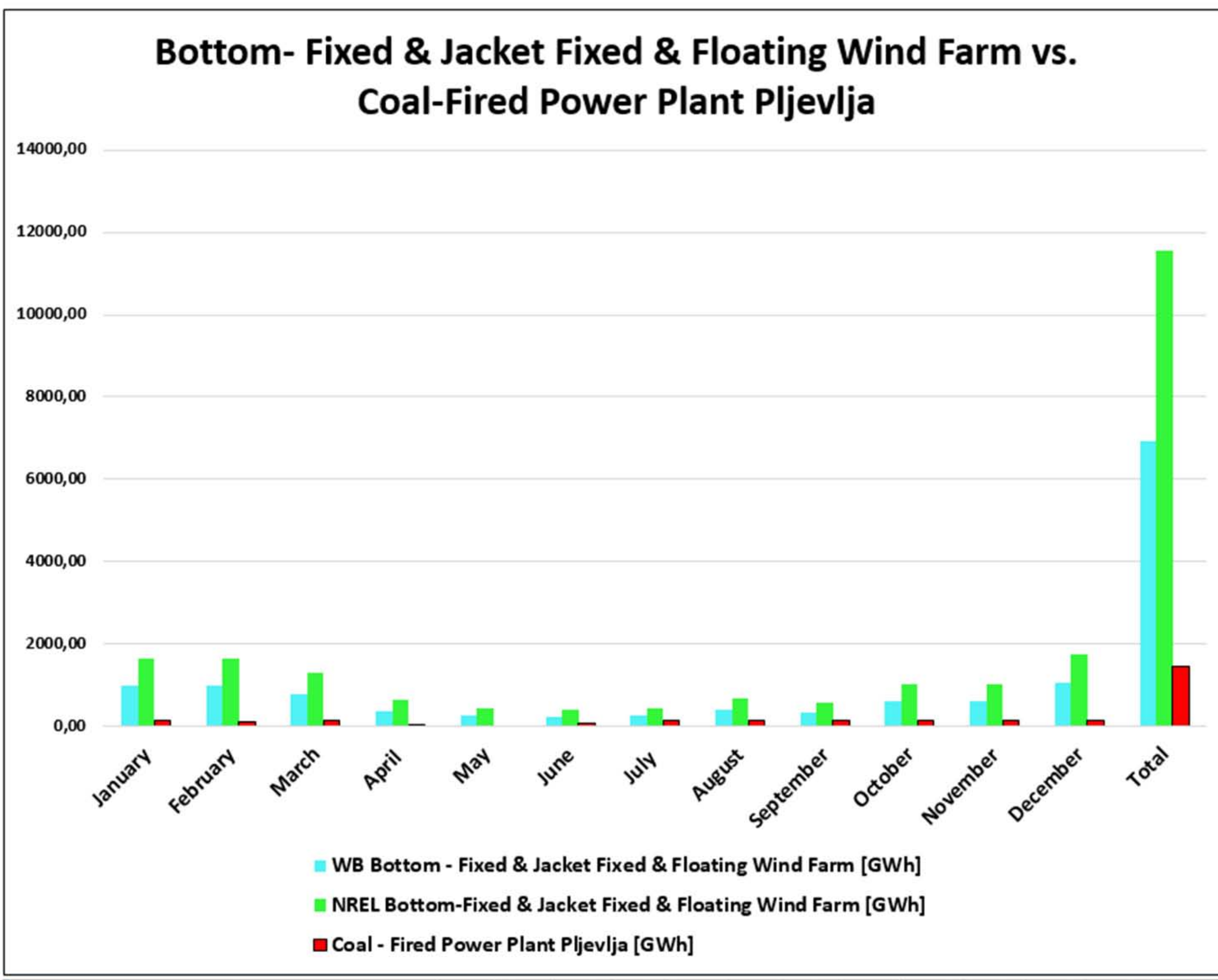
Bottom-fixed, jacket-fixed, and floating wind farms connected to the grid, while the Pljevlja coal-fired power plant is permanently shut down

Based on the results presented in Chapter 3, the comparison of the annual electricity production of the Pljevlja coal-fired power plant with the expected production that could be achieved through the construction of a fixed wind farm (bottom-fixed, jacket-fixed, and floating wind farm) is shown in Figure 18.

Based on the data presented in Figure 18, it can be concluded that the construction of the wind farm, according to both criteria (WB and NREL), would fully replace the electricity production of the Pljevlja coal-fired power plant.

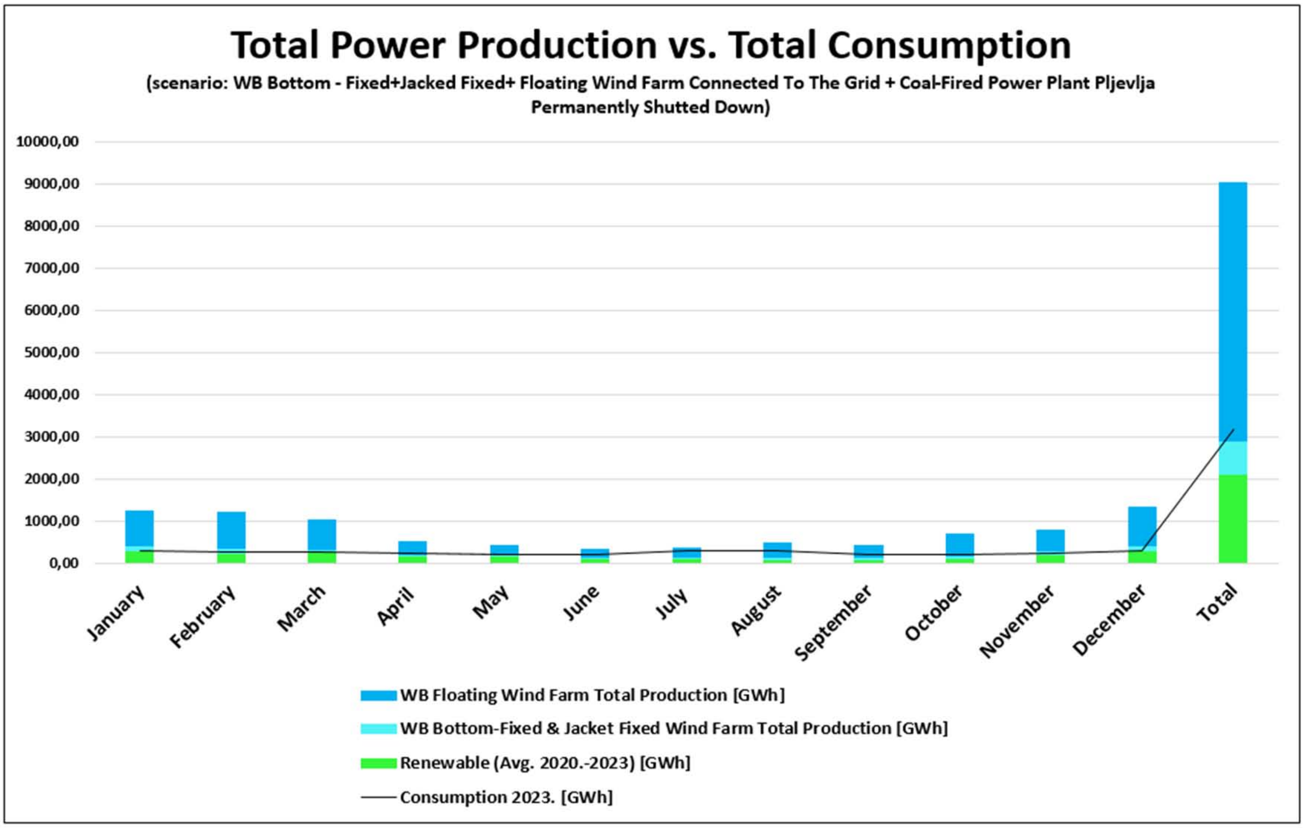
For the specified scenario, based on the model of average monthly electricity production for the period 2020–2023 and annual consumption for 2023, as shown in Figure 5, the model for electricity production and consumption, with the permanent shutdown of the Pljevlja coal-fired power plant and the construction of the respective wind farm according to the WB criterion, is presented in Figure 19.

Based on the results from Figure 19, it can be concluded that the construction of the respective wind farm according to the WB criteria, with the permanent shutdown of the Pljevlja coal-fired power plant, could enable the Montenegrin electricity system to fully meet the total annual electricity consumption, both on an annual and monthly basis, with a surplus of 5862,4 GWh.



Month	January	February	March	April	May	June	July	August	September	October	November	December	Total
WB Bottom - Fixed & Jacket Fixed & Floating Wind Farm [GWh]	982,67	987,40	786,66	380,87	261,36	236,28	275,98	411,61	351,86	607,48	609,53	1047,58	6939,27
NREL Bottom-Fixed & Jacket Fixed & Floating Wind Farm [GWh]	1637,78	1645,67	1311,09	634,78	435,60	393,80	459,96	686,02	586,43	1012,46	1015,88	1745,97	11565,44
Coal - Fired Power Plant Pljevlja [GWh]	155,65	131,67	152,37	50,52	0,00	71,18	149,42	140,95	139,22	153,71	151,48	154,85	1451,03

Figure 18 Bottom-Fixed & Jacket Fixed & Floating Wind Farm vs. Coal Fired Power Plant Pljevlja

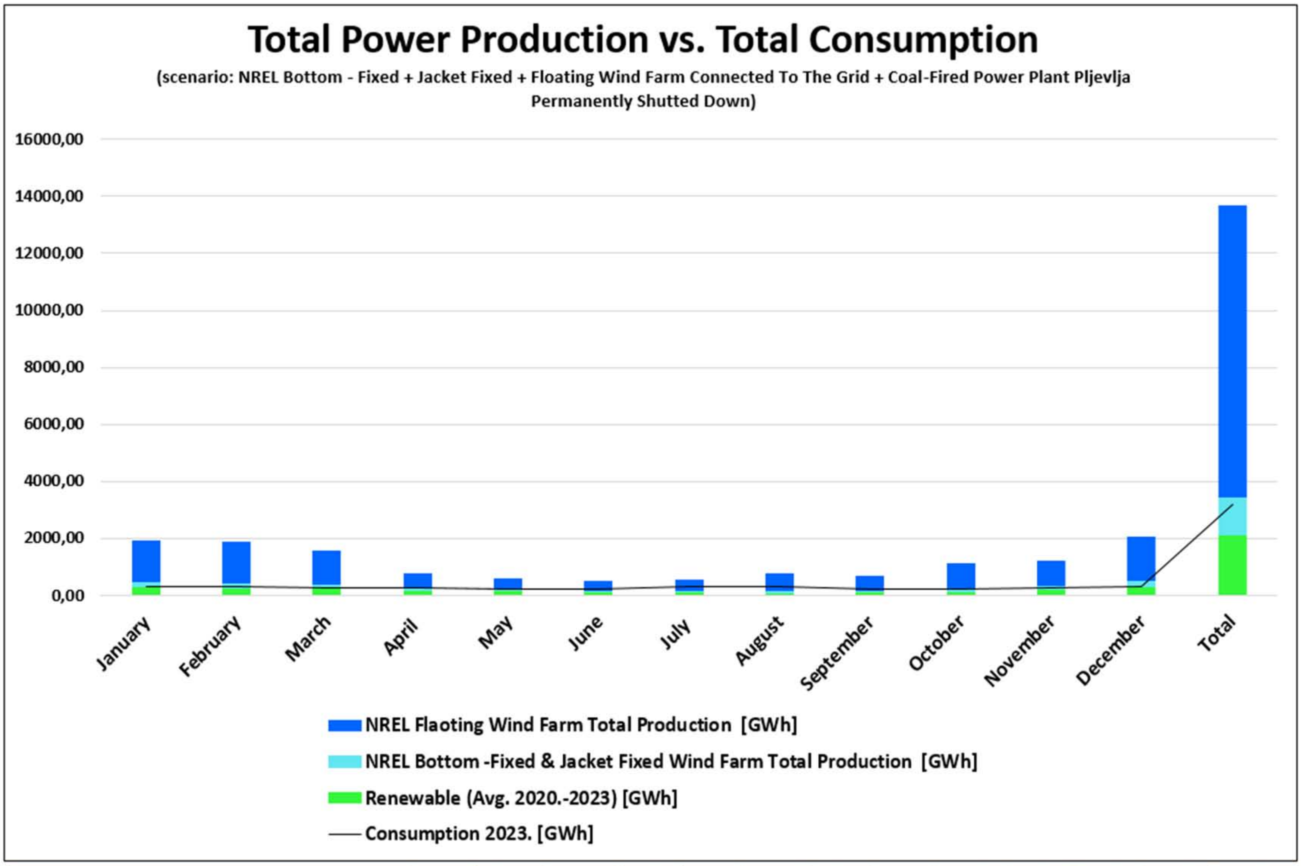


Month	January	February	March	April	May	June	July	August	September	October	November	December	Total
Renewable (Avg. 2020.-2023) [GWh]	281,65	244,39	253,53	158,65	172,33	106,19	97,44	81,90	83,81	112,53	210,58	299,25	**2102,25**
WB Bottom-Fixed & Jacket Fixed Wind Farm Total Production [GWh]	119,31	102,82	81,04	42,64	32,61	32,61	38,43	50,33	46,34	70,39	72,44	119,50	**808,48**
WB Floating Wind Farm Total Production [GWh]	863,36	884,59	705,62	338,22	228,75	203,66	237,54	361,28	305,52	537,09	537,09	928,08	**6130,78**
Total Power Production [GWh]	1264,31	1231,80	1040,18	539,52	433,70	342,47	373,41	493,52	435,67	720,00	820,11	1346,84	9041,52
Consumption 2023. [GWh]	307,44	290,06	271,35	245,46	217,31	226,74	299,96	293,85	231,78	219,41	262,45	313,31	3179,12

Figure 19 Scenario No2: WB Bottom – Fixed & Jacket Wind Farm & Floating Wind Farm connected to the grid + Coal Fired Power Plant Permanently Shut down

For the specified scenario, based on the model of average monthly electricity production for the period 2020–2023 and the annual consumption for 2023, as shown in Figure 5, the model for electricity production and consumption, with the permanent shutdown of the Pljevlja coal-fired power plant and the construction of the respective wind farm according to the NREL criteria, is presented in Figure 20.

Based on the results from Figure 20, it can be concluded that the construction of the respective wind farm according to the NREL criteria, with the permanent shutdown of the Pljevlja coal-fired power plant, could enable the Montenegrin electricity system to fully meet the total annual electricity consumption, both on an annual and monthly basis, with a surplus of 10488,57 GWh of electricity.



Month	January	February	March	April	May	June	July	August	September	October	November	December	Total
Renewable (Avg. 2020.-2023) [GWh]	281,65	244,39	253,53	158,65	172,33	106,19	97,44	81,90	83,81	112,53	210,58	299,25	**2102,25**
NREL Bottom -Fixed & Jacket Fixed Wind Farm Total Production [GWh]	198,85	171,36	135,07	71,07	54,36	54,36	64,05	83,89	77,24	117,32	120,74	199,17	**1347,47**
NREL Flaoting Wind Farm Total Production [GWh]	1438,93	1474,31	1176,03	563,70	381,25	339,44	395,91	602,13	509,19	895,14	895,14	1546,80	10217,97
Total Power Production [GWh]	1919,43	1890,07	1564,62	793,43	607,94	499,99	557,40	767,92	670,24	1124,99	1226,46	2045,23	13667,69
Consumption 2023. [GWh]	307,44	290,06	271,35	245,46	217,31	226,74	299,96	293,85	231,78	219,41	262,45	313,31	3179,12

Figure 20 Scenario No2: NREL Bottom-Fixed & Jacket Wind Farm & Floating Wind Farm connected to the grid + Coal Fired Power Plant Permanently Shut down

5 Conclusions

This study offers the first scientific evaluation of the potential for offshore wind energy production in Montenegro, specifically focusing on capacity factor estimations and the potential for replacing coal-based electricity generation. The results highlight the significant role that offshore wind farms could play in Montenegro's energy transition, supporting its commitment to decarbonization and its integration into the European energy market.

The research analyzed two scenarios: the first involved the construction of bottom-fixed and jacket-fixed offshore wind farms at depths of up to 60 meters, while the second expanded the development to include floating wind farms. Given the current technology maturity and construction costs, it is anticipated that the first fixed offshore wind farm will be established at depths of up to 60 meters.

The findings suggest that, based on the WB criteria, fixed offshore wind farms could replace more than half of the electricity generated by the Pljevlja coal-fired power plant, using the reference data for electricity production in Montenegro from 2023. Under the NREL criteria, this replacement could be nearly complete. However, a full replacement of Pljevlja's electricity generation, along with surplus production on both an annual and monthly basis, would only be achievable with the adoption of modern floating wind farm technology. These advancements would result in significant surplus electricity production, based on the reference data for electricity production in Montenegro from 2023.

These findings are significant within the context of Montenegro's energy strategy. This study confirms that offshore wind power has the potential to become a cornerstone of the country's renewable energy mix. It would help ensure long-term energy security, enable independence from fossil fuels, and enable electricity exports. The research strongly emphasizes the importance of initiating the construction of offshore wind farms in Montenegro, a crucial step for maintaining energy stability, meeting environmental obligations, and positioning the country as a regional leader in renewable energy.

The entire research of this paper is based on the analysis of the Global Wind Atlas database, which, in addition to historical wind speed data, utilizes mathematical models to generate output values. The paper also incorporates the adopted model of the IEA 15 MW wind turbine. Primarily, future research should focus on measuring the necessary meteorological parameters using lidars installed on floating buoys, in order to obtain in-situ values for wind parameters.

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