COMPARATIVE STUDY OF RENEWABLE ENERGY SOURCES: POWER CHARACTERISTICS AND CAPACITY FACTOR

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This article presents a comparative analysis of renewable energy sources, focusing on the characteristics of active and reactive power (P and Q) and the capacity factor. Using measurements from photovoltaic and wind power plants in Romania, the study highlights the variability of generation curves based on specific climatic conditions. The paper's originality lies in the comparative evaluation of the performance of these sources, emphasizing their integration into power systems and offering new perspectives for optimizing the use of renewable resources.

Keywords: renewable energy sources; power systems; generation curves; photovoltaic power plants; wind power plants; energy storage

1. Introduction

In the global transition towards a sustainable energy system and depletion of conventional energy resources (coal, oil, and natural gas), renewable energy sources (RES) have become essential for diversifying the energy mix. Among the most widely used RES are solar and wind energy, due to their high availability and technological advancements in recent decades. The integration of these sources into Power Systems (PS) requires a detailed analysis of generation characteristics, particularly active and reactive power (P and Q), as well as the capacity factor, an essential indicator of system productivity [1].

According to specialized studies, variations in electricity production from solar and wind energy sources significantly impact the stability of electrical grids, making the analysis of active and reactive power generation curves over time, as well as the evaluation of the capacity factor (CF), for effective integration into the PS [2, 3].

This paper aims to conduct a comparative analysis of solar and wind RES in Romania, focusing on active and reactive power generation curves over time and determining the capacity factor. By using production data from photovoltaic and wind power plants, the research examines performance differences and operational

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characteristics in the context of renewable energy integration in the context of integrating renewable energy into power systems.

2. Generation curves P, Q = F(t) for solar and wind energy sources

2.1. Analysis of generation curves P, Q = F(t) for a photovoltaic power plant

The productivity of photovoltaic power plants (PVPP) depends on various factors, including solar irradiance, temperature, dust accumulation, panel characteristics, inverter performance, and installation angle [4]. A thorough analysis of these elements helps optimize performance, reduce energy losses, and improve overall profitability.

The performance of photovoltaic panels is significantly influenced by variations in irradiance and temperature, factors that shape the characteristics of the current-voltage and power-voltage curves. According to the study [5], the use of the PV Array block in Simulink enables detailed simulation of the behavior of photovoltaic devices under different operating conditions. This includes consideration of parameters such as incident irradiance, operating temperature, the series and shunt resistances of the panels, and the diode ideality factor.

The simulation results have shown that as irradiance decreases, the maximum power output of the panels is reduced, accompanied by a decrease in both open-circuit voltage and short-circuit current. An increase in temperature leads to a drop in the overall efficiency of the panel, primarily due to the reduction in open-circuit voltage [5]. These observations are used for understanding the performance of photovoltaic power plants under varying climatic conditions.

The technical parameters of solar panels that strongly influence the performance of photovoltaic power plants include series and shunt resistance, diode ideality factor, and other parameters that determine system productivity [6]. Simulations performed on AFP-60-245W solar panels have shown that a low shunt resistance leads to significant current losses, reducing the maximum power output. On the other hand, a low ideality factor minimizes recombination losses, contributing to higher overall efficiency [6]. These aspects are essential for optimizing the P=F(t) curves and improving the capacity factor.

PVPP converts the energy of solar irradiance into electrical energy [7]. The production of electricity is characterized by two main components, P and Q:
P – active electrical power generated by the photovoltaic power plant, used to produce mechanical work, light, heat, or other forms of energy [W];
Q – reactive electrical power, necessary for maintaining the electric and magnetic fields of electrical equipment [VAr].

The active electrical power generated by a PVPP can be expressed by the relation [7]:

$$P\ (t) = n \cdot A \cdot G(t) \cdot \eta_T\ [W] \quad (1)$$

where:
$P_{(t)}$ - active electrical power generated at time t;
n - the number of photovoltaic panels;
A - area of a photovoltaic panel [m^2];
G - the level of solar irradiance at time t [W/m^2];
η_T - efficiency of converting solar irradiance into electrical energy by the solar panel [%].

The PVPP generates only active electrical power, while the reactive electrical power injected or absorbed by a PVPP is determined by the interface of inverter according to the grid operator's requirements. Its value depends on the grid's operating conditions. This can be expressed by the relation (2), which is valid only in a purely sinusoidal regime:

$$Q\ (t) = \frac{P(t)}{PF} \cdot \sqrt{1 - PF^2} \quad (2)$$

where:
$P_{(t)}$ – active electrical power generated at time t [W];
PF – power factor [%].

Additionally, the PVPP can operate under several control modes [7]:

- Dynamic active power control (P/f) – adjusting P according to the frequency value in the power grid;
- Dynamic reactive power control (Q/U) – adjusting Q based on the voltage at the connection point;
- Power factor control (PF control) – complying with the requirements of the grid operator;
- Dynamic reactive power-active power control (Q/P) – adjusting Q based on generation of P;
- Active power setpoint (P) – where P is a set value;
- Reactive power setpoint (Q) – where Q is a set value.

For power grid operators, these control modes are essential for maintaining stability and reliability in power systems with high renewable integration. They regulate frequency and voltage in real-time, ensuring reliable operation while minimizing losses and optimizing energy production [8].

To study the P and Q curves as functions of time, hourly production values from a PVPP located in the southern region of Romania were used, a location favorable for electricity production from solar energy sources. The PVPP has an installed capacity of 45 MW, injects the generated electricity into the 110 kV distribution network, and operates under the dynamic reactive power control mode (Q/U). The active power curve P = F(t) represents the power generated by the PV installation according to the conditions of the analyzed time interval, while the reactive power curve Q = F(t) is imposed by the grid operator's requirements and depends on the network conditions.

The measurements were conducted to analyze the hourly values of the active and reactive powers generated by the studied PVPP over four distinct days, considering both the electricity demand within the power grid and the meteorological parameters that directly influence electricity production. The first and the last days were working days, while days 2 and 3 were non-working days, an essential aspect from the perspective of electricity demand within the power system.

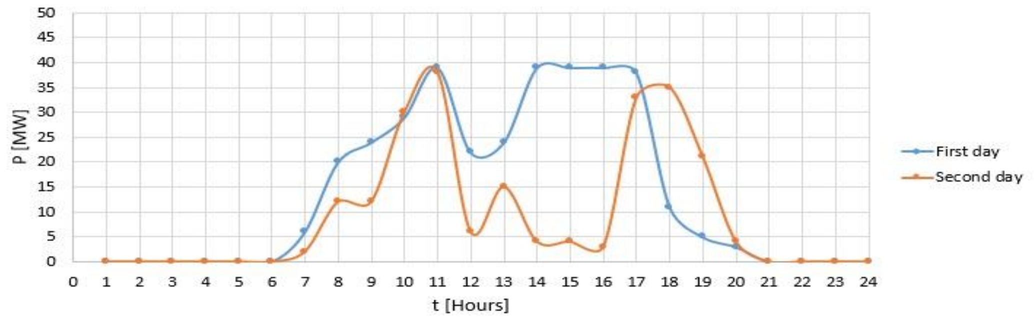

Fig. 1. Active power generation curves P = F(t) for the first and second days

In Fig. 1, the generation curves P = F(t) for the first and second days within the analyzed time interval are illustrated covering the 0-24 hour period on a summer day. These curves highlight the general pattern of active power production generated by the PVPP, characterized by a gradual increase during the early hours of the day, reaching a peak production around noon, followed by a gradual decline in the evening as the sun sets.

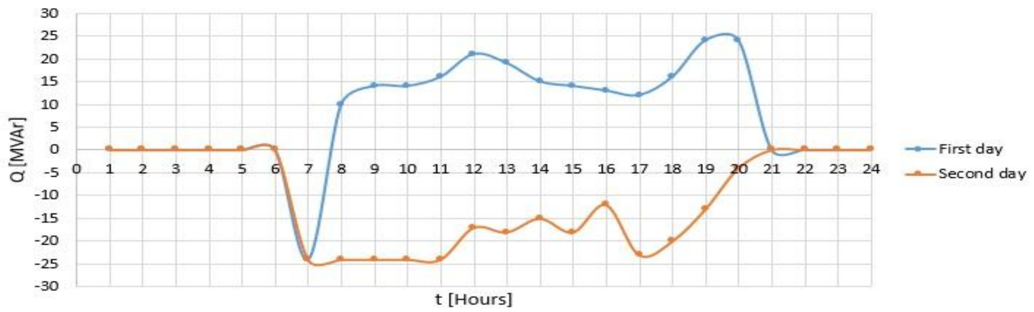

Fig. 2. Reactive power generation curves Q = F(t) for the first and second days

Fig. 2 illustrates the evolution of the reactive power curves injected into or absorbed from the power grid by the PVPP over 24 hours, for two distinct summer days. The first day is a working day, while the second day is a non-working day.

By comparing them, significant differences in the PVPP's behavior are highlighted, caused by variations in electricity demand and its contribution to voltage regulation in the power grid. On the first day, reactive power is injected, while on the second day, reactive power is absorbed to maintain the voltage within permissible limits.

2.2. Analysis of generation curves P, Q = F(t) for a wind power plant

The electricity production of WPP is characterized by two main components: active electrical power (P) [W] and reactive electrical power (Q) [VAr]. The WPP used in this study is equipped with a synchronous generator connected to the grid via a full-scale power converter.

The generation curves of active and reactive power as a function of time are directly influenced by the variability of electricity production. These curves depend on factors such as wind speed and direction, air temperature and pressure, and precipitation [9].

The active electric power produced by a wind turbine at the moment *t* can be expressed as [9]:

$$P = \frac{1}{2} \cdot \rho \cdot A \cdot v^3 \cdot \eta \, [\mathrm{W}] \tag{3}$$

where,

ρ - air density [kg/m^3]

A - area swept by the turbine blades[m^2];

v - wind speed [m/s];

η - wind turbine efficiency [%].

Reactive power and operating modes for WPP can be expressed similarly to those of PVPP. However, due to the complexity of wind systems, their reliability and maintenance play a crucial role in ensuring consistent energy production. Reliability is defined as the probability that the system will function without failure under specified conditions over a given period. The main failure modes of wind power systems include faults in turbine blades due to changes in surface roughness, failures in the gearbox caused by extreme loads, and generator issues related to insulation degradation [10].

To study the generation curves of active and reactive power as functions of time, the hourly electricity production values of a WPP located in the southeastern region of Romania were used. This region is recognized for its favorable conditions for the installation of wind power plants.

The WPP analyzed in this study has an installed capacity of 90 MW and is operated under the dynamic reactive power control mode (Q/U).

The measurements were conducted to analyze the hourly values of the active and reactive powers generated by the WPP over three consecutive days providing a detailed analysis of the WPP's performance.

On the first and second days, the weather conditions were favorable, leading to high electricity production. On the third day, unfavorable weather conditions, characterized by lower wind speeds, caused a significant decrease in electricity production. Furthermore, failures in mechanical components such as bearings and shafts due to fatigue stress can further impact the generation curves and overall system performance [10].

In Fig. 3, the generation curves P = F(t) for the analyzed WPP over the three days of recordings are highlighted. This analysis emphasizes the direct influence of wind speed variations on electricity production and highlights the importance of efficiently managing meteorological resources to ensure the stable operation of the power system and ensure continuity in the electricity supply to users.

Fig. 3. Active power generation curves P = F(t) for the first, second, and third days

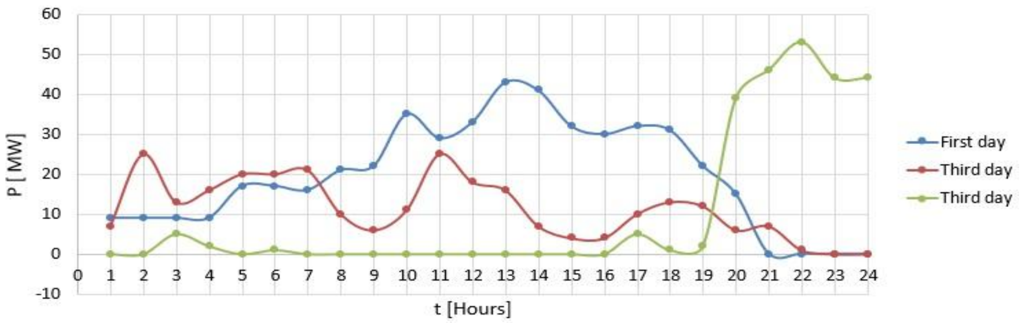

Fig. 4 illustrates the evolution of the reactive power of the WPP during the analyzed period and reflects the important role of the WPP in voltage regulation within the power system, where the reactive power is imposed by the grid operator according to the network conditions. The daily variations in reactive power highlight the WPP's contribution to voltage regulation in the power grid.

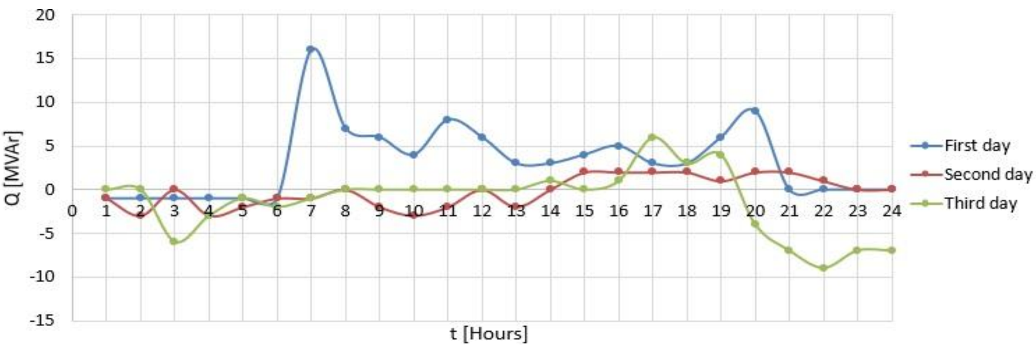

Fig. 4. Reactive power generation curves Q = F(t) for the first, second and third days

On working days, due to the high electricity demand, the WPP injected reactive power to increase voltage levels. On non-working days, characterized by lower electricity demand, reactive power absorption was necessary to prevent overvoltages thus contributing to the stability of the power system.

3. Capacity factor – annual electricity production for photovoltaic and wind power plants

The capacity factor (CF) represents the ratio between the actual electrical energy produced by a power plant over a given period (usually one year) and the maximum possible energy it could have produced during that period if it had operated continuously at its nominal power [11].

The capacity factor of a renewable energy power plant can be expressed as [11]:

$$CF = \frac{Actual\ energy\ produced}{Maximum\ possible\ energy} \cdot 100\ [\%] \quad (4)$$

The capacity factor is an essential indicator for evaluating the performance and productivity of wind power plants and photovoltaic power plants. It reflects the proportion of actual electrical energy produced by a power plant relative to the theoretical maximum energy it could have generated if it operated at maximum capacity.

Calculating the electrical energy produced by a power plant involves considering important parameters such as meteorological factors, the efficiency of electrical equipment, system losses, and local environmental conditions.

General formula for calculating electrical energy [11]:

$$E = P_{nom} \times t \times CF\ [Wh] \quad (5)$$

where,
P_{nom} - nominal electrical power of the power plant [W];
t - operating duration of the power plant [h];
CF - capacity factor [%].

3.1. Determination of the capacity factor and annual electricity production for a photovoltaic power plant

To determine the annual electricity production and the capacity factor, recordings from a photovoltaic power plant with an installed capacity of 45 MW were used, through daily monitoring of electricity production.

In Fig. 5, the electricity production and the capacity factor of the analyzed photovoltaic power plant are presented for each month over a year. Electricity production steadily increases starting in January and becomes significant from March as solar irradiance intensifies and days become longer, reaching a production peak in May of approximately 7,500 MWh. The analysis of the capacity factor for the PVPP reveals significant variation throughout the year, with a maximum of 22.51% in May and a minimum of 5.51% in December, reflecting the inherent seasonality of solar energy. The annual average capacity factor of 15.17% indicates that the PVPP operated at an average of 15.17% of its maximum capacity over the entire year, emphasizing the importance of introducing energy storage systems during periods with favorable weather conditions.

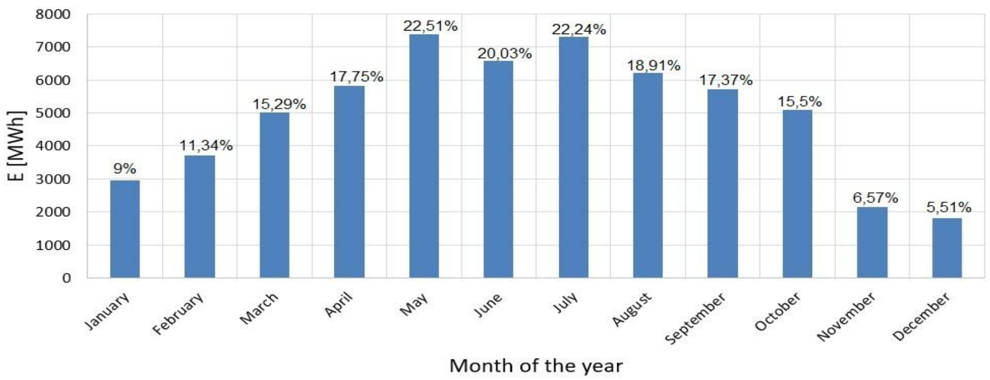

Fig. 5. Monthly electricity production and the capacity factor over a year for the studied photovoltaic power plant

The highest production levels are recorded during the summer months, particularly in May and July, when operating conditions are optimal. From August, there is a decline in electricity production due to the gradual shortening of daylight hours and changing weather conditions. This decline became more pronounced during the autumn months (September and October), reaching below 2,000 MWh in December. A clear seasonality in electricity production is observed, with maximum values during the spring-summer period and minimum values during the autumn-winter period.

The analysis of daily electricity production for May and December, shown in Figs. 6 and 7, highlights the seasonal differences in the operation of the photovoltaic power plant. Over the monitored year, the analyzed photovoltaic power plant generated a total of 59,797.4 MWh, corresponding to an average capacity factor of 15.17% and a utilization duration of maximum power of 1,328.86 hours per year, with an average daily production of 238 MWh in May and 58 MWh in December. This capacity factor is an essential indicator of the productivity of solar resource use and reflects the proportion of the total annual time during which the power plant operates at its maximum electrical power.

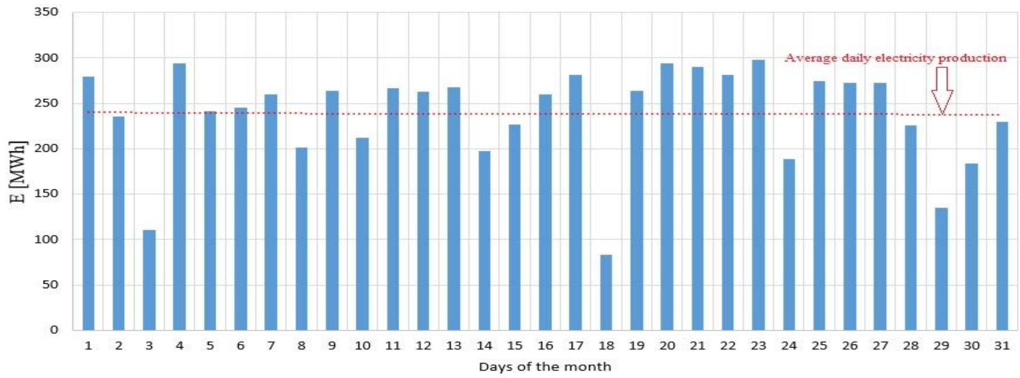

Fig. 6. Daily electricity production for May

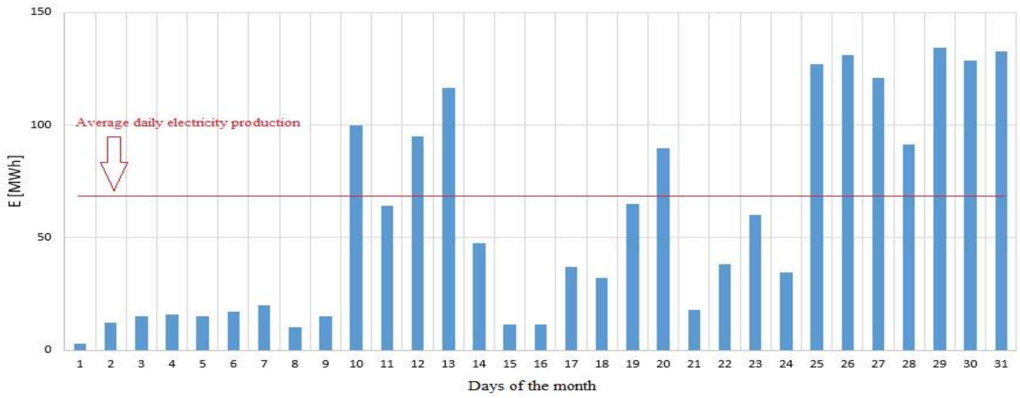

Fig. 7. Daily electricity production for December

To enhance the capacity factor and the annual energy production of photovoltaic power plants, several optimization measures can be implemented. The proper selection of the installation site, taking into account local solar irradiance levels and climatic conditions, is essential for maximizing solar energy capture [5]. Additionally, the optimal positioning and tilt angle of the panels can significantly impact the electricity production, as these factors determine the amount of sunlight incident on the panels throughout the day and year. Minimizing shading effects, either through careful spatial arrangement or by avoiding obstacles such as nearby buildings or vegetation, further reduces power losses. Periodic maintenance is very important, ensuring that panels remain clean and free of debris, as accumulated dust or dirt can degrade performance over time [5]. These measures, when implemented effectively, contribute to a higher capacity factor by improving the panels exposure to sunlight and maintaining optimal performance.

The presence of shading can have a significant impact on the capacity factor of photovoltaic systems by limiting their ability to operate at optimal power output [5]. Partial shading conditions create imbalances in the current flow, leading to reduced power generation even in otherwise favorable conditions. Simulation results have demonstrated the strategic placement of panels, combined with the use of bypass diodes and tracking systems, can mitigate these effects and improve the capacity factor by allowing more consistent power production throughout the year [5].

These findings suggest that optimizing installation conditions and shading mitigation strategies is essential for maximizing the capacity factor.

3.2. Determination of the capacity factor and annual electricity production for a wind power plant

To determine the annual electricity production and the capacity factor, recordings from a wind power plant with an installed capacity of 50 MW were used through daily monitoring of electricity production. These data allow a detailed analysis of the variability of wind energy sources under different meteorological conditions.

In Fig. 8, the electricity production and the capacity factor of the wind power plant are presented for each month over a year, highlighting a seasonality in electricity production, with a peak of approximately 20,000 MWh in January due to increased wind speeds.

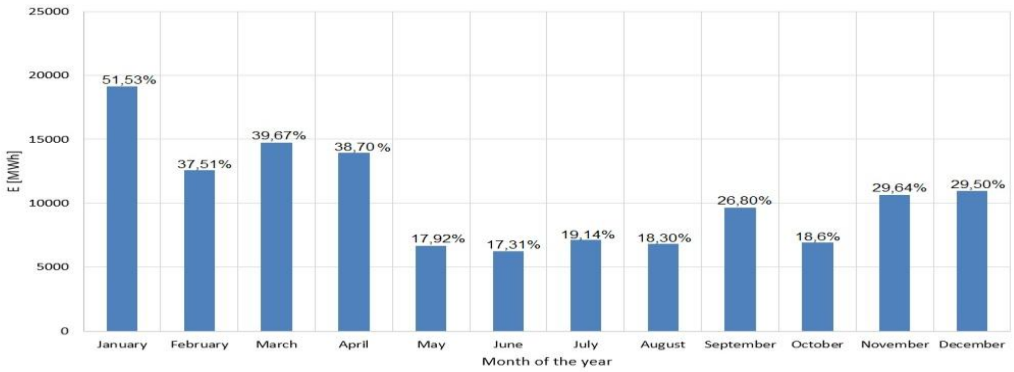

Fig. 8. Monthly electricity production and the capacity factor over a year for the studied wind power plant

In February and March, a decrease in production is observed, followed by a moderate recovery. During the summer months, meteorological phenomena such as breezes and daytime winds can contribute to a stable but lower level of energy production. Starting in October, electricity production steadily increases, reaching 10,000 MWh in December due to the intensification of wind speeds characteristic of the cold season.

According to Fig. 8, throughout the year, the analyzed WPP generated 125,492 MWh, corresponding to an average capacity factor of 28.65% and an annual operating duration of 2,572.46 hours. The capacity factor reflects the WPP's average performance in harnessing wind resources, indicating an average utilization of approximately 30% of its maximum capacity. The higher values during the winter and spring months, contrasted with the lower values in the summer months, confirm the significant influence of meteorological conditions on production. This highlights the need for planning and optimizing wind resources according to seasonal fluctuations.

The daily electricity production for June and January, presented in Figs. 9 and 10, highlights the contrast between the months with the lowest and highest electricity production generated by the analyzed WPP. In January, due to the high and consistent wind speeds characteristic of the cold season, electricity production varied between 400 MWh and 1,200 MWh per day, with an average daily production of 238 MWh, while in June, electricity production decreased significantly, ranging between 20 MWh and 600 MWh due to the reduced wind intensity typical of the summer period, when favorable atmospheric phenomena for electricity generation are less frequent and the average daily production was 58 MWh.

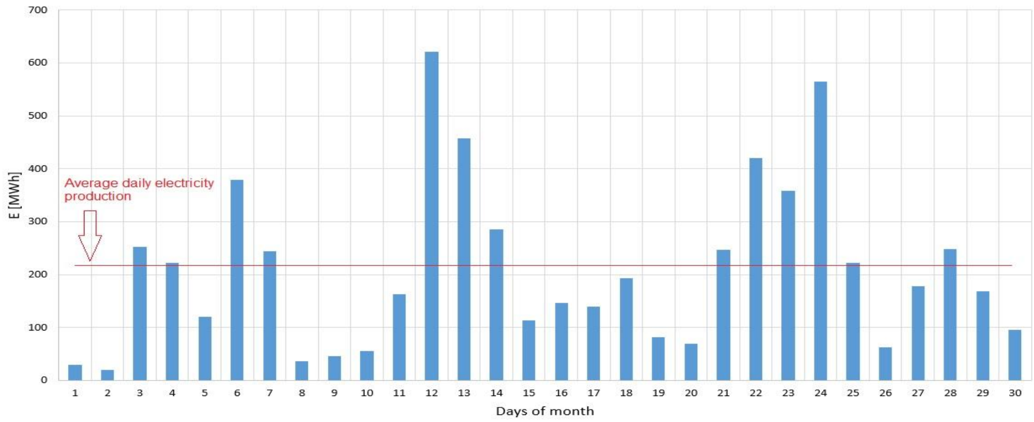

Fig. 9. Daily electricity production for June

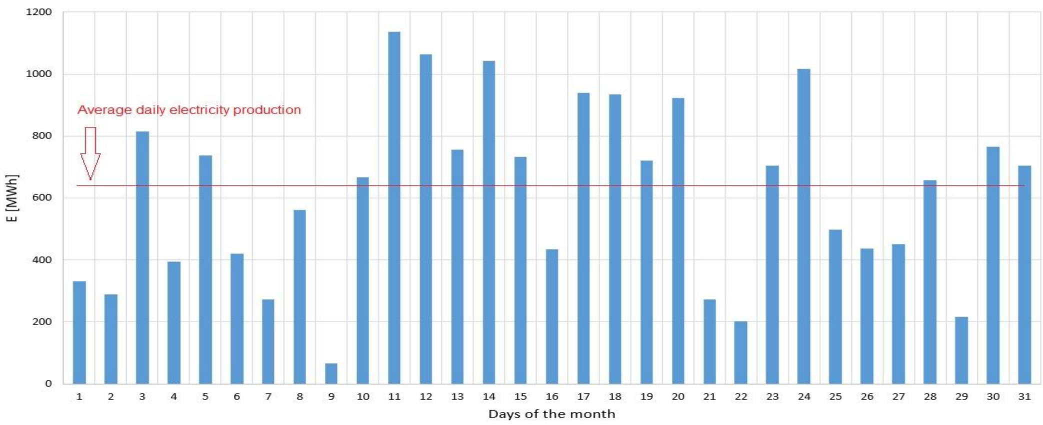

Fig. 10. Daily electricity production for January

Ensuring a stable capacity factor requires the implementation of effective reliability and maintenance strategies. Wind power plants are subject to mechanical stress, which can lead to failures in key components such as turbine blades, gearboxes, and generators. Predictive maintenance, involving real-time monitoring through SCADA systems, vibration analysis, and thermal imaging, has proven to reduce downtime and improve the overall efficiency of wind power systems. Additionally, periodic inspections and preventive maintenance measures play a crucial role in extending the operational life of turbines and minimizing unexpected failures [10].

Furthermore, research has shown that optimizing wind farm layouts to reduce wake effects, enhance pitch and yaw control, and integrate energy storage systems can significantly increase the annual electricity production and the capacity factor. The modernization of existing turbines with advanced aerodynamic design and improved power electronics has also been demonstrated to contribute to overall efficiency gains. Such measures have led to capacity factor improvements of up to 5-10% in several case studies, highlighting their importance in maximizing wind source utilization [10].

3.3. Comparative analysis of photovoltaic power plant and wind power performance

Table 1 presents a summary of the key differences between photovoltaic (PVPP) and wind (WPP) power plants, based on the analyzed data. These differences highlight the distinct operational profiles, capacity factors, seasonal behaviors, and power control characteristics of each technology.

Table 1

Comparative analysis of PVPP and WPP

Parameter	PVPP	WPP
Installed capacity	45 MW	50 MW
Primary resource	Solar irradiance	Wind speed
Energy production profile	Predictable daily cycle, seasonal variation	Highly variable, less predictable
Seasonal peak	May – July	January – April
Capacity factor (yearly avg.)	15.17%	28.65%
Max. monthly production	~7,500 MWh (May)	~20,000 MWh (January)
Daily variation	Smooth curve with midday peak	Irregular
Control mode	Dynamic reactive power control (Q/U)	Dynamic reactive power control (Q/U)
Generation predictability	Higher (based on irradiance forecast)	Lower (wind is more variable)
Maintenance complexity	Lower	Higher (mechanical wear, moving parts)

The differences highlighted in the table above underline the distinct operational behaviors of the two types of renewable power plants. The photovoltaic power plant (PVPP) has a predictable energy production profile, with a clearly defined daily variation and a peak production in the period of May – July, due to the intensification of solar irradiance. In contrast, the wind power plant (WPP) presents a much more pronounced variability, with a seasonal maximum in the period of January – April, corresponding to an intensification of the wind conditions. This seasonal complementarity between the two sources can be exploited to ensure a more constant energy production throughout the year.

The annual capacity factor is significantly higher in the case of WPP (28.65%) compared to PVPP (15.17%), reflecting a more efficient use of the available natural resources. Both power plants operate under a dynamic reactive power control (Q/U) regime [7], imposed by the grid operator, but the challenges related to system integration differ. PVPP benefits from high generation predictability, based on irradiance forecast, while WPP requires more careful management of rapid production fluctuations, caused by unstable weather conditions. Thus, the planning and operation of these sources must be adapted to the specific characteristics of each technology, because each source has its role in the electric power system, and a wind power plant cannot be replaced by a photovoltaic power plant without affecting the functional balance of the network.

4. The role of energy storage in enhancing capacity factor and renewable energy integration

The integration of battery energy storage systems (BESS) in renewable energy power plants has become a crucial strategy for addressing the variability of solar and wind energy production. By storing excess energy during periods of high generation and discharging it when production is low, BESS helps improve the capacity factor of RES, ensuring a more stable and reliable electricity supply [12].

A significant challenge in renewable energy integration is the curtailment of excess energy when production exceeds grid capacity. This issue arises due to transmission constraints, minimum generation levels of conventional power plants, or back feeding limitations in distribution networks. In this context, BESS plays a key role by capturing surplus energy and redistributing it when demand is high, thereby minimizing energy losses and maximizing economic benefits [13]. Additionally, integrating storage systems reduces dependency on conventional power sources during periods of low renewable generation, contributing to a more resilient and flexible power system.

Beyond mitigating curtailment, BESS also provides essential grid services, including frequency regulation. Power imbalances between supply and demand can cause frequency deviations, impacting grid stability. Traditionally, these imbalances were managed using fast-response conventional generators. However, BESS offers a more efficient alternative due to its rapid response time and ability to adjust power output almost instantaneously.

Another advantage of BESS is its contribution to optimizing energy dispatch strategies. By strategically storing and releasing energy, storage systems help align electricity generation with demand patterns, improving the economic efficiency of renewable energy projects [13].

The economic feasibility of BESS deployment largely depends on multiple revenue streams. In some regions, the initial cost of battery storage remains a barrier to widespread adoption, particularly in markets where subsidies and incentives are limited. However, studies have shown that optimizing BESS sizing and integrating it into frequency regulation markets can significantly improve financial viability.

A practical example of BESS implementation can be observed in a case study of a 50 MW photovoltaic power plant equipped with a 25.6 MW / 46.9 MWh BESS [13]. The deployment of energy storage in this facility improved system performance, reduced energy curtailment, and enhanced overall financial performance. The ability to store and later sell excess energy increased the project's net present value, demonstrating the potential of BESS to optimize renewable energy utilization. Similar findings have been reported in wind power applications, where storage has been used to smooth generation profiles and provide grid stability support, reinforcing the economic and technical benefits of integrating BESS in renewable energy projects.

Integrating BESS into renewable power plants could increase the capacity factor, minimizing energy curtailment, and ensuring grid stability. By enabling better energy dispatch, helping to balance frequency fluctuations, and optimizing economic efficiency BESS contributes to a more reliable and resilient power system.

5. Conclusions

This study includes an original analysis of generation curves for both PVPP and WPP based on real data production, highlighting the impact of meteorological conditions on power generation in Romania.

The comparative evaluation of the generation curves P, Q = F(t) highlights significant differences in the evolution of active and reactive power for the analyzed power plants. While the P = F(t) curves reflect variations in the effectively generated energy, the Q = F(t) curves indicate how each power plant contributes to maintaining voltage within admissible limits and ensuring grid stability. The PVPP presents a predictable daily curve, with a gradual increase in the morning, a peak around noon, and a progressive decrease until sunset. This regular pattern facilitates planning of the power system. In contrast, the WPP presents highly variable power curves, with frequent and irregular fluctuations, caused by sudden changes in wind conditions.

Moreover, the WPP also contributes during the night by absorbing reactive power, suporting voltage regulation even in the absence of active power generation. This is possible by the full-scale power converter, which allows independent control of the reactive power flow, even when the turbine is not producing active power. As a result, modern wind turbines can support the operation of the grid even during low-wind periods by adjusting the local voltage level. Therefore, the characteristics of the generation curves must be analyzed in parallel with indicators such as the capacity factor when assessing the potential for integrating RES into the grid.

The assessment of the capacity factor for PVPP and WPP technologies provides insights into their productivity and seasonal variations. Although the WPP has an installed power of only 5 MW higher than the PVPP analyzed in this study, the WPP produced more than twice as much electricity. This results in a more consitent electricity generation pattern, as observed in the analyzed region, where wind availability has led to significantly higher energy production.

Considering that the higher capacity factor for the WPP (approximately 28.65%) compared to the PVPP (15.17%) highlights the more efficient use of wind resources, especially in regions with favorable meteorological conditions, it suggests that wind technology is more effective in exploiting natural resources over a longer period of the year. In contrast, the electricity production of PVPPs is limited to periods of intense sunlight.

Although both types of power plants are affected by seasonality, WPPs tend to have higher production during the winter and spring months, when winds are stronger, while PVPPs reach maximum electricity production during the summer months, when solar irradiance is at its peak. This complementarity can be leveraged in energy mixes to ensure more consistent electricity production throughout the year.

The analysis of photovoltaic and wind power plants demonstrates the crucial role of BESS in improving renewable energy utilization. Since solar and wind generation are highly variable, energy storage helps smooth fluctuations, increase the capacity factor, and ensure a more stable electricity supply. The wind power plant had a higher capacity factor due to the steadier nature of wind resources, while the PVPP showed stronger seasonal variations. However, with BESS, both technologies can operate more efficiently by reducing curtailment and maximizing annual energy production. This demonstrates that energy storage is essential for balancing renewable generation and enhancing the reliability of the power system.

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