



Influence of seasonal air density fluctuations on wind speed distribution in complex terrains in the context of energy yield

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Received: 9 June 2023 / Revised: 3 October 2023 / Accepted: 21 October 2023 / Published online: 14 November 2023

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Abstract Given the variable nature of wind speed and the importance of accurately determining the energy that can be generated at a given site, understanding the wind speed at different time scales is crucial. In addition to differences within a very short period (i.e., hourly and daily), these changes are also pronounced throughout the seasons. They are affected by the atmospheric conditions and the terrain’s complexity. Therefore, this study investigates the seasonal wind speed variability and its impact on the potential energy generation in a representative study case of Koznica, the mountainous region in Kosovo. The wind speed measurements campaign started in May 2019 and ended in April 2020; the measurements were made at a 10 min time scale. Ground measurements show that the wind direction is mainly northwest and southeast. Then, the wind speed and potential energy generation variability analysis were conducted for three different measurement heights. The results show that winter and spring have the highest potential wind energy capacity with an average speed of 6.7 m/s. In comparison, the average wind speed is 6.12 m/s. Potential energy generation for each season (i.e., spring, summer, autumn, and winter) is as follows: 64,396.7, 22,040.3, 42,539.3, and 46,417.2 MWh/year, respectively, while the average capacity factor is 25%. Solution-oriented findings from this study might provide valuable insights to policymakers and investors regarding wind power energy

exploration in Kosovo and other places with similar geoclimatic conditions.

Keywords Energy in Kosovo · Energy strategy · Energy transition · Renewable energy · Wind energy

Abbreviations

P_w	Extracted power from the wind (W)
ρ	Air density (approximately 1.2 kg/m ³ at 20 °C at sea level) (kg/m ³)
A	Area of a wind turbine (m ²)
w	Wind velocity (m/s) (velocity can be controlled between 3 to 30 m/s) (m/s)
P_{iso}	Power produced by an isolated wind turbine under the same wind condition (W)
N	Number of wind turbines (l)
P_{tot}	Total power from all wind turbines (W)
E_{el}	Electrical energy output (Wh/kWh)
C_P	Power coefficient (%)
τ	Number of hours during the year (hour)
$w(h_2)$	The wind speed at different height (m/s)
$w(h_1)$	The wind speed at reference height (m/s)
h_1	The reference height level (m)
h_2	The height level that need to calculate (m)
h_0	The roughness length (m)

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1 Introduction

Wind energy or wind farms are an environmentally friendly form of energy generation. Despite the advantage of environmentally friendly energy generation, wind speed

and direction fluctuations remain challenging for optimal wind farm locations (Pryor and Barthelmie 2010). The growth of wind farms worldwide is a global trend (Moemken et al. 2018). Generally, it is a resource that can be used for free and highly depends on weather and climate (Gallego et al. 2011). Therefore, many sophisticated models have been developed to increase the certainty of prediction within the preliminary energy that can be generated (Baños et al. 2011; Foley et al. 2012). Rossby waves, pressure gradients, jet streams, and local weather conditions are the main factors affecting wind speed alteration (Schäfler et al. 2020). In addition to this dependence, the change in wind intensity is also affected by the turbulence that occurs as part of the interaction of air masses with the edges of blades (Elgendi et al. 2023). Of course, alterations caused by seasonal and climatic changes also have a crucial impact (Kim et al. 2020).

Considering all factors affecting wind energy development, statistical methods are usually used to predict the energy that can be generated (Hanifi et al. 2020). These methods include predictions for different time scales. As much as the energy prediction system has evolved over these periods, significant changes are observed when comparing each farm's predicted and actual energy, especially as the seasons change (Lledó et al. 2019). The main reason for accurately predicting the potential wind energy generation at a given prospective wind farm is related to the risk that such an imbalance in wind energy generation can cause in the power grid (Amroune 2022). For example, to function stably, the transmission grid must not be subject to significant fluctuations in voltage and current (Akin-sanola et al. 2017; Tavner et al. 2013). Optimizing and controlling the generated energy fluctuations are even more complex when dealing with hybrid energy generation systems (Peng et al. 2013). Tahiri et al. (2021) developed an innovative approach to predicting the energy produced by the system consisting of wind and solar energy. Goyal et al. (2022) show that the pressure is more pronounced at the edges of the blades, which affects the flow separation and further the creation of the corresponding vortices. Ismaiel (2023) shows that the possible shocks from atmospheric turbulence should also be constantly monitored in addition to monitoring the main air parameters. In mountainous areas, as in the case considered in this study, wind farms are largely influenced by the (Abolude and Zhou 2017; Navarro Diaz et al. 2021). Therefore, to calculate the potential energy generation at a prospective wind farm, the capacity of the wind turbines must be known, or the total capacity must be determined (Pishgar-Komleh and Akram 2017; Wang 2012). The potential wind energy generation can be computed for different time scales, such as minutes, hours, and respective days (Mohammadi and Mostafaei-pour 2013). The study of Ren et al. (2018) shows that in the

context of the changes in wind intensity during the seasons, the wind characteristics, such as direction, remain unchanged in spring, summer, and autumn. Only in winter, a significant change in wind direction is also reported in other literature (Gallego et al. 2011; Lledó et al. 2019). Similarly, the change of seasons is also studied in the work of Lledó et al. (2019), who investigate the changes in the capacity factor over the seasons. Such a change directly affects the energy generated.

In addition, the work of Jin and Virk (2019) and Hau (2013) shows that the analysis of turbine placement in a wind farm should consider that terrains with harsh winters are not preferred despite the high potential during the winter season. The weather conditions can cause a large ice load on the turbine structures. Moreover, Abolude and Zhou (2017) and Wang (2012) show that the electronic system of the met mast is less reliable during the winter season. Thus, this study calculates the optimal possible power generation based on the wind speed data measured at each position where the wind turbines will be installed. Then, the power coefficient is calculated for the total number of turbines installed. The average wind speed for the Koznica wind farm at 80 m measurement height is 6.12 m/s. Four wind turbines with an installed power of 7.5 MW per wind turbine are planned in this park. The strategy for placing the turbines follows the methodology of keeping the 3D distance between them to ensure the working conditions by avoiding the wake effect as much as possible. In addition to the distances that must be maintained between the turbines, it is necessary to maintain a distance of 2.5D from the measuring mast.

Thus, for an optimal configuration of wind turbines in a park, the energy that can be generated in the months of change of each season is studied. The goal is to get an idea of the change in wind energy during the change of seasons in the year of the measurements made. For a wind farm to be profitable, no matter where it is built, the characteristics of the wind must be well-known (Wang et al. 2019). Thus, wind speed and direction measurements are essential once the location is determined. In this study, for the first time, an analysis considering the maximum capacity of wind turbines is performed to calculate the capacity factor at the beginning of each season. Many studies have been conducted on wind speed changes during the seasons (Akpınar and Akpınar 2005; Guo et al. 2011; Jiang et al. 2010).

Nevertheless, studies dealing with the changes in critical months and their comparison have not been conducted. So far, to the best of our knowledge, the studies that have been conducted have considered the complete changes during a season but not the intermediate phase. The intermediate phase means significant changes in the wind parameters that pass from one season to another. In addition, the terrain of the case considered in this study has a complex

topography, making these changes even more significant. Using the same methodology as done in the studies of Abolude and Zhou (2017) and Huang et al. (2019), this study extends these previous findings to the intermediate or transitional phase of the seasons. In this respect, this study represents an innovation because the form of the analysis approach considers not only the change in the wind speed parameter but also the change in air density for considered periods. This allows a more accurate analysis of the potential wind energy generation for the chosen study case.

The idea here is that the months in which the most remarkable change is observed should be considered when the seasons change. Another element related to the placement of turbines is that, due to the impossibility of using them for other purposes, hilly and not flat terrain is usually used for the placement of wind farms. This placement approach applies to most European countries and beyond (Elgendi et al. 2023). The variability of wind parameters during the transition from season to season depends on the characteristics of the terrain. Thus, for terrains like Koznica, in terms of complexity, it can be assumed that these changes between seasons are almost the same. Of course, the climatology of the area covered by the analysis has an influence here.

Moreover, this variability applies to all countries with such climate conditions. In most of the analyses performed, the measurements were made at meteorological stations with a measurement height of 10 m. In our case, the seasonal variability of the measurement height is of even greater importance since no extrapolation was performed. However, the results of the specific terrain accurate measurements were considered. The transition phases from one season to another remain crucial for predicting the potential wind energy generation. The analyses by different authors in this context have considered the seasonal periods in their total duration, not even the month known as the transition month. The behavior of air masses in these transitional periods is very stochastic, especially in winter (Jin and Virk 2019). These stochastic changes play a significant role in determining the average velocity during a given season. They are, therefore, of great importance in the analysis. This is because as the seasons change, not only does the energy generated change but so does the energy consumed by people in the form of electricity and heating. This study compares a mountainous, moderately complex terrain farm, among others. The paper is structured as follows. Section 2 presents the study case, the data set measurement of the met mast, and the study's methodology. Section 3 shows the main findings from this study and their relevance in a broad perspective regarding wind energy exploitation in other cases with similar geo-climate conditions. Finally, Sect. 4 presents the main conclusions and some future work recommendations.

2 Material and methods

2.1 Study case and wind data

The climate of Kosovo is predominantly continental, resulting in warm summers and cold winters with Mediterranean and Alpine influences (i.e., the average temperature within the country ranges from + 30 °C (summer) to − 10 °C (winter)) (Gavrilov et al. 2018). However, there are differences in temperature and rainfall distribution due to considerable differences in elevations in certain parts of the country. The location of the mast used for the measurements of the wind speed at 80, 60, and 40 m heights and the average wind speed at 80 m height above the ground at the measurement point is shown in Fig. 1.

The measurement mast is located at E 529096.8 m, N 4716324.7 m. Based on placement coordinates 1 (E 529057 m, N 4715890 m), 2 (E 529084 m, N 4716514 m), 3 (E 528958 m, N 4716943 m), 4 (E 529630 m, N 4717140 m). Figure 2 shows the possible scheme of turbine placement in the wind farm in Koznica, which includes four turbines with an installed power of 7.5 MW each.

Wind direction is also crucial for evaluating wind energy potential (Gruber et al. 2019). In this context, wind

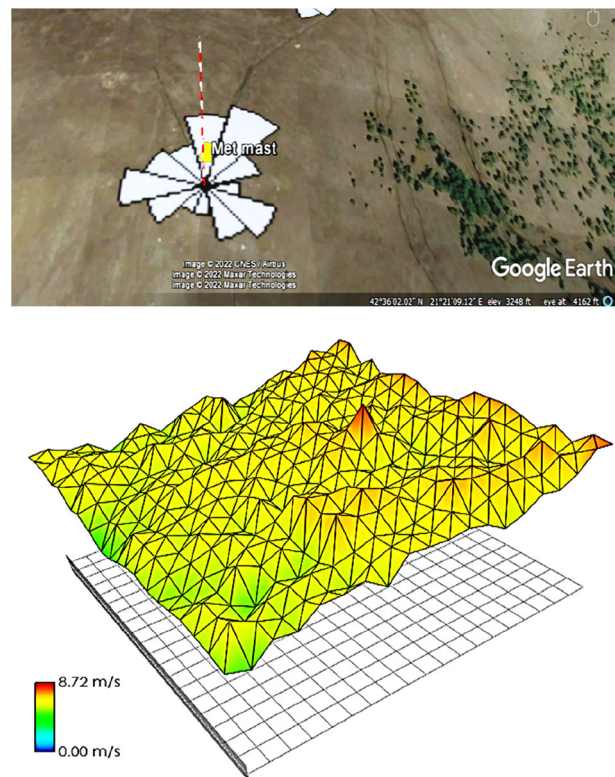
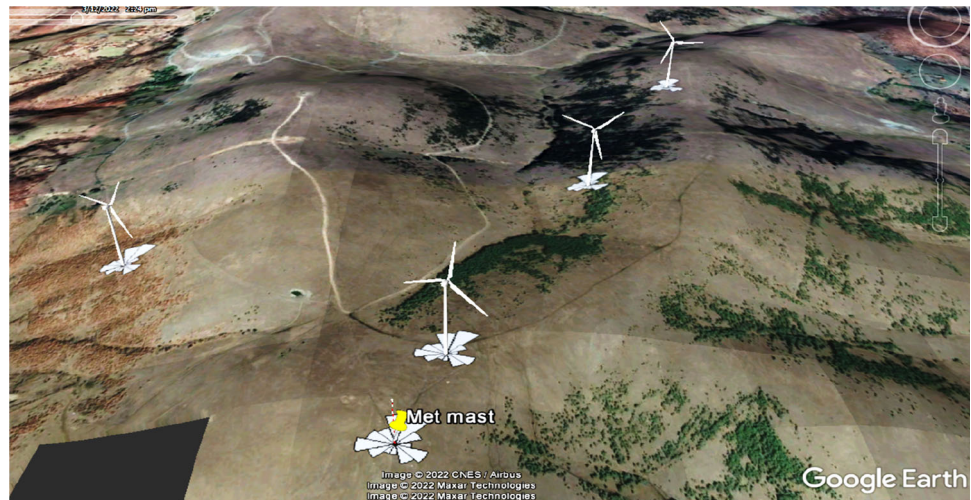


Fig. 1 Met mast location (upper) and mean wind speed distribution (lower) in Koznica, 80 m above the ground

Fig. 2 Koznica wind farm, placement of wind turbines



turbines should be placed in a specific location in the prevailing wind direction (Liu and Ho 2016).

For this study, data records are available for a whole year, from which the data for the indicated months were selected, namely 4213 records. They are presented in 10 min values as averages. Almost 60 h were not considered (i.e., about 0.54% of the total measurement period) because the electronic system was not functioning. Also, on some days, the anemometer was frozen. The overall data availability is 93%, considering the one-year period for which the calculations are performed. The measurement period at the study site lasted one year. Table 1 shows the change in wind speed, measured at 80 m above the ground, for each season and presents the seasonal changes.

The higher the turbine is placed, the greater the amount of energy that can be extracted. The lowest wind speed occurs in summer and autumn. Different computer models are used to calculate all these, including capacity factor, energy, wake losses, aerodynamic efficiency, and other feasibility parameters. The model widely used in the industry field is WAsP V11.4, which gives accurate results no matter how complex the terrain is. It is enough to have at least nine annual measurements of wind data, including wind speed every 10 min, then wind direction, standard deviation of wind speed, air temperature, and pressure.

The highest height of the measurements was 80 m, which is not equal to the hub height of the wind turbines. As a result, speed extrapolations should be carried out

based on the currently known terrain conditions. In the current case, the measurements of wind data were directly extrapolated to the hub height of the turbines specified by the manufacturer through the WAsP software, which is also based on the power law as follows in Eq. 1 (Pourasl and Khojastehnezhad 2021):

$$w_{h_2} = w_{h_1} \cdot \frac{\ln\left(\frac{h_2}{h_0}\right)}{\ln\left(\frac{h_1}{h_0}\right)} \quad (1)$$

where $w(h_2)$ = the wind speed at different heights, $w(h_1)$ = the wind speed at reference height, h_1 = the reference height level h_2 = the height level that must calculate h_0 = the roughness length. Terrain roughness indicates the influence of obstacles and the terrain contours; it has a role in changing the flow of air masses direction and, in this way, the wind speed intensity (*Roughness Length*, n.d.).

2.2 Energy generation estimation

Wind speed is the most crucial element in wind energy analysis (Tascikaraoglu and Uzunoglu 2014). A potential diameter of 127 m is assumed for this case. The capacity factor for such an installed capacity of wind turbines is first calculated for all months considered in the analysis. Then, the average speed for each season is determined to calculate the capacity factor. The power that can be obtained from a wind turbine is calculated according to Eq. 2:

$$P = \frac{1}{2} \cdot \rho \cdot A \cdot w^3 \quad (2)$$

P is the output power, ρ is the air density, A is the swept area, and w is the wind speed. The main goal of operating a wind turbine is to extract as much energy as possible. An ideal energy conversion process is impossible due to the system's aerodynamic, mechanical, and electrical losses

Table 1 Mean wind speed data for each season at 80 m height

Season	w_{average} , m/s
Spring	6.732
Summer	4.709
Autumn	5.863
Winter	6.036

(Hau 2013). The power coefficient for a given number of turbines N is calculated as follows, Eq. 3:

$$C_p = \frac{P_{tot}}{N \cdot P_{iso}} \quad (3)$$

P_{tot} —is the total power of wind turbines in a farm, N —is the number of wind turbines in a farm, P_{iso} —is the power output from one wind turbine and C_p —is the power coefficient. The calculation of electrical output power, as a function of wind speed, is done using Eq. 4:

$$E_{el} = \frac{1}{2} \cdot \rho \cdot A \cdot w^3 \cdot \tau \quad (4)$$

E_{el} —electrical energy output, τ time of operation of wind turbines. Energy yield calculations are performed with a capacity factor by analyzing the number of working hours per year (Charabi et al. 2019; Hau 2013). Optimizing the placement of turbines in a wind farm is a complex problem that requires considering the effects of the terrain's topography and the relative positions where the turbines are placed (Elgendi et al. 2023). Thus, in this context, many variables related to the optimization process apply to each wind farm (Amroune 2022; Foley et al. 2012). The period of the performed measurements is one full year. In achieving the most accurate results, three years, and in this context, will be more acceptable results. During this process, it is assumed that there would be a smaller variability from winter to spring and a larger one from summer to autumn. This is important for power generation planners in the respective countries to ensure that power needs are met depending on availability. This means planning the coverage of energy needs from other renewable or conventional sources based on the potential from the wind energy analyses from this study.

3 Results and discussion

In the context of showing monthly changes and seasonal transitions, other parameters besides the intensity change are important (Mortensen et al. 2014; Taslimi-Renani et al. 2016). In this context, the wind direction and the duration of a specific wind speed intensity representation are also important.

The differences observed during the seasons in the place under consideration concern pressure and temperature. The variation of these parameters affects the variation of air density and velocity (Abolude and Zhou 2017). Air density and velocity depend on temperature, humidity, and air pressure, independent of terrain complexity (Turnipseed et al. 2002). Added to the differences in the conditions' parameters is the air's direction, which changes as the

previously mentioned parameters change, but also due to topography and obstacles in the terrain.

As an essential point for a wind farm, it reflects the most common directions of wind speed at a given site, as shown in Fig. 3. As shown, the wind directions are mainly to the north and south.

Figure 4 shows the intensity changes of maximum, average, and minimum wind speed each month, measured 80 m above the ground. Figure 4 (upper part) shows significant wind energy potential in the spring season. This stability of the speed can be understood as a positive indicator for the operation of the wind turbines regarding the coverage of energy needs at this time. During the spring season, there are frequent cases in which the wind speed is around 25 m/s. The case is different when considering the summer season. The stability of the wind speed also characterizes this season. However, its intensity is lower here, as seen in Fig. 4 (lower part). Combined with hydropower, which has a high potential for water resources until late summer (i.e., there is a considerable number of hydropower plants in Kosovo), and solar energy (i.e., due to the increasing hours of sunshine during the summer season), this potential would provide good renewable energy coverage.

Wind and water energy decrease in summer, but solar energy reaches its maximum. The average, maximum, and minimum wind speed measurements are displayed at only 80 m height due to the higher potential and ease of use. In the case of autumn and winter, a different situation is described in Fig. 5. Summer conditions usually influence a pronounced lack of wind in the initial phase.

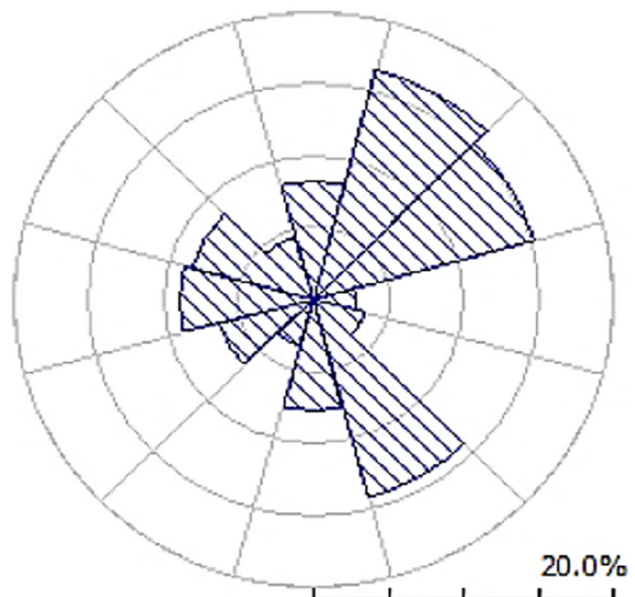


Fig. 3 Windrose of wind direction for Koznica wind farm

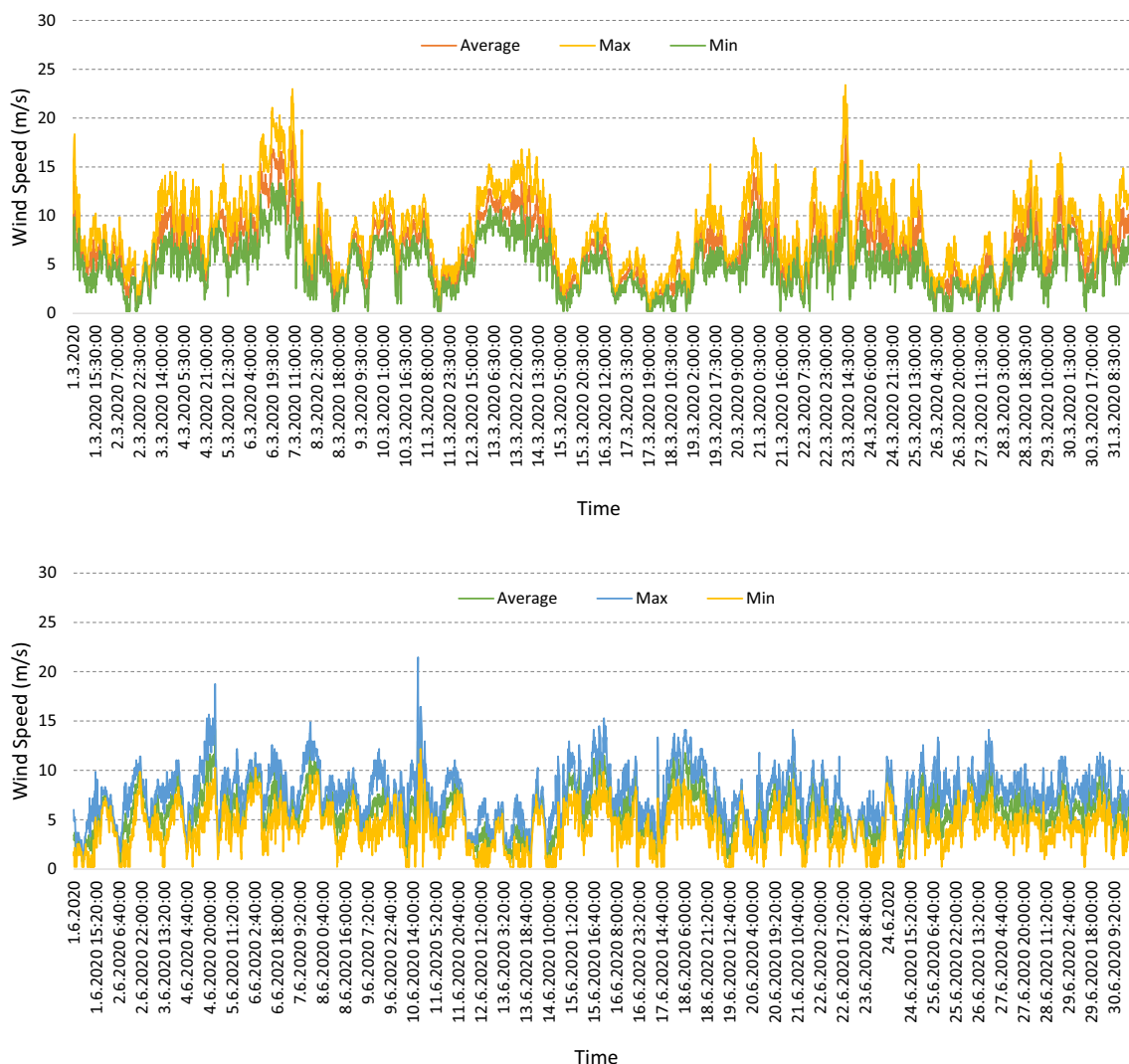


Fig. 4 Wind speed variation in a 10 min time scale during Spring (upper) and Summer (lower) seasons, measured at a height of 80 m

A low and unstable intensity characterizes seasons such as autumn and winter. Another issue is the northern winds that mainly characterize the winter season. These speed values are negative due to the direction toward the north, as shown in Fig. 5.

The increase in electricity demand in Kosovo from year to year is 5–8%, based on the Energy Regulatory Office of Kosovo data (ZRRE 2023). The highest increase in electricity demand is observed during the winter. At the same time, in the winter, the wind potential is relatively high; thus, maximizing the exploitation of wind energy would fulfill a considerable amount of the electricity demand. In that regard, integrating wind with hydropower would enhance the power system's flexibility. In addition, Figs. 6, 7, 8, 9 show wind speed histograms for measurement heights at 80, 60, and 40 m for the critical months of each season: March, June, September, and December. These measurements show that spring and winter seasons have

the greatest potential. Autumn is an average operating value; summer decreases significantly. The wind turbines start operating in the 3–5 m/s range, while they have the optimal working range of 11–15 m/s. From the histograms shown in Fig. 6, which are from measurements in March, there are more cases where the wind speed is 7–10 m/s.

When studying wind energy and its potential, the regime caused by the winds is also essential. For a specific location, the sustainability of wind energy generation means an average level of speed but high availability throughout the year, as is the case now for March.

The histogram in Fig. 7 for June shows a significant representation of speeds in the interval of 0.2–1 m/s and 2.5 to 5 m/s, respectively. As shown earlier, June represents the month with the lowest usable speeds. The case of stability of the speed necessary for operation, known as a cut in wind speed, is only partially achieved in June. The transition from the spring to the summer is expected to be

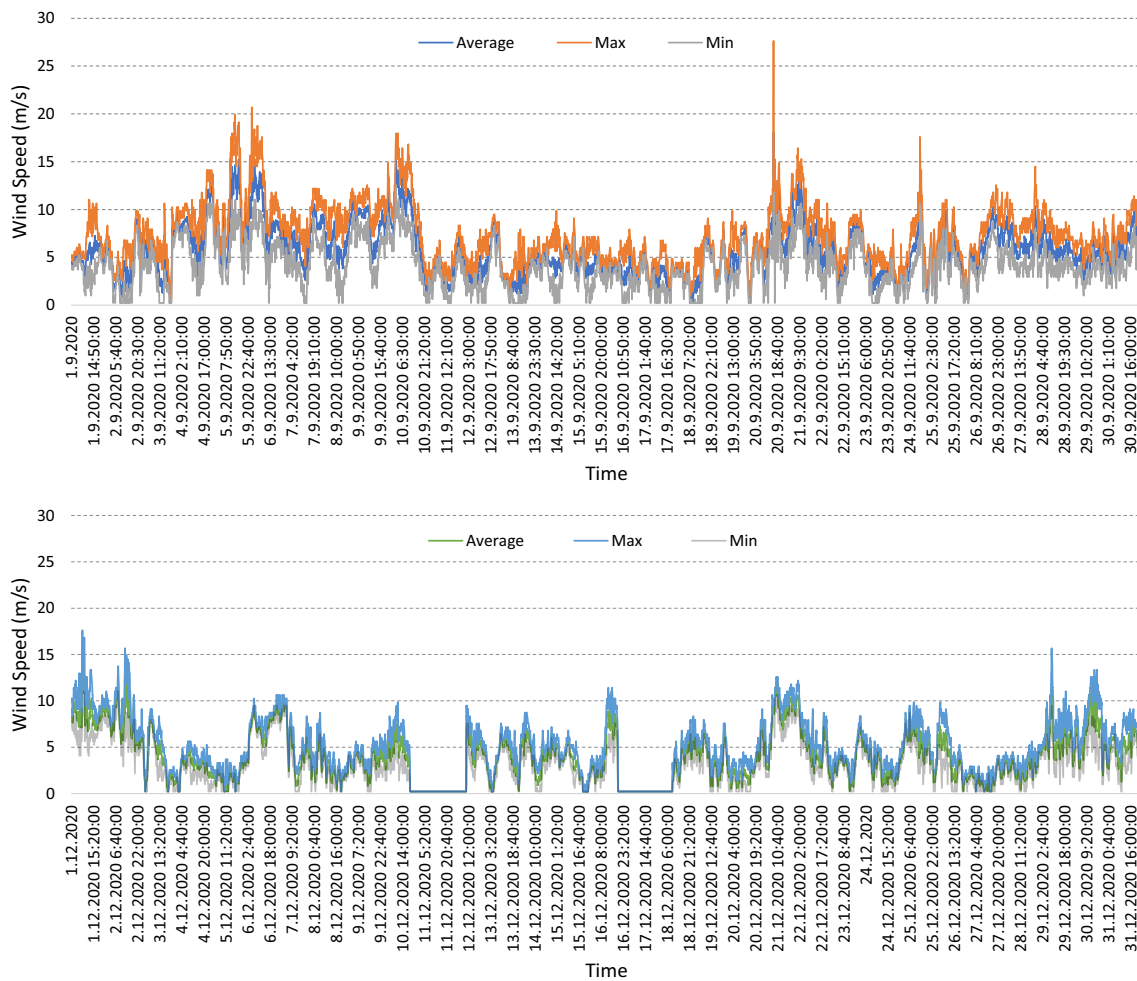


Fig. 5 Wind speed variation in a 10-min time scale during Autumn (upper) and Winter (lower) seasons, measured at the height of 80 m

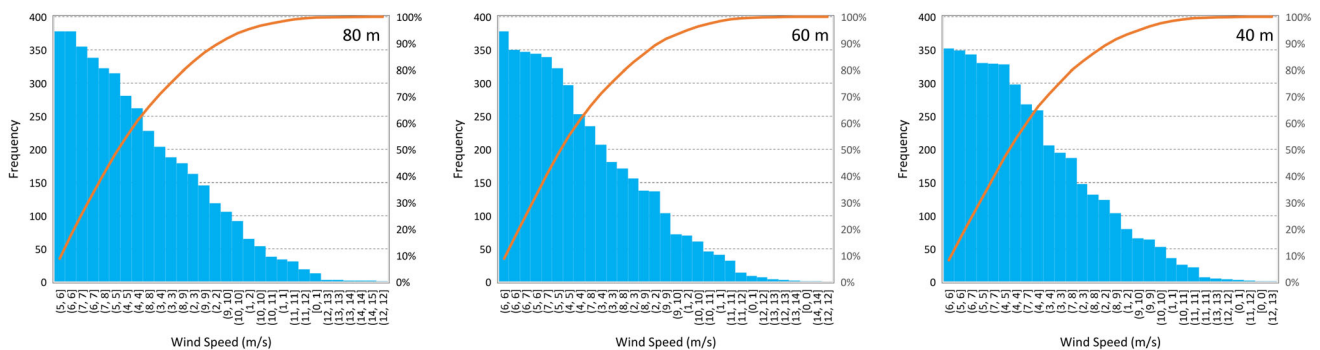


Fig. 6 Histogram of wind speed distribution measured at 80, 60, and 40 m height for March

accompanied by a reduction in the availability of high speeds. For the highest measuring height, 80 m, the availability of speeds from 5–6 m/s is 350–400 h during the year. The optimal speed values of 12–13 m/s are minimal in appearance during this month.

The histograms in Fig. 8 for September show more cases where the wind speed for all measuring heights is 2–6 m/s. The transition process from summer to autumn,

specifically September, is characterized by more hours during the year when the wind speed is 4–5 m/s. Likewise, the optimal speed values of 11–13 m/s also have small hours of their appearance. On average, there are 50–60 h during the year that this range of speeds occurs during this month. Naturally, from the highest measurement height, there is a reduction in working hours for other measurement heights, such as 60 and 40 m. At the measuring

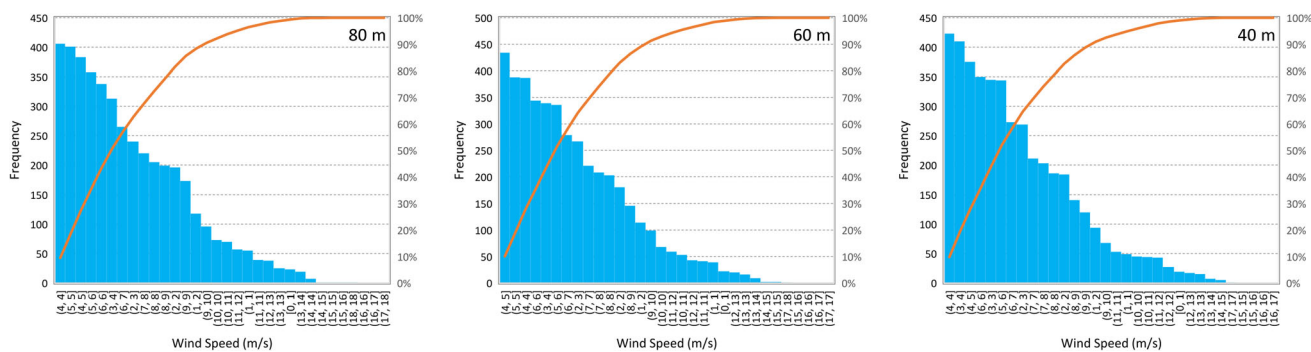


Fig. 7 Histogram of wind speed distribution measured at 80, 60, and 40 m heights for June

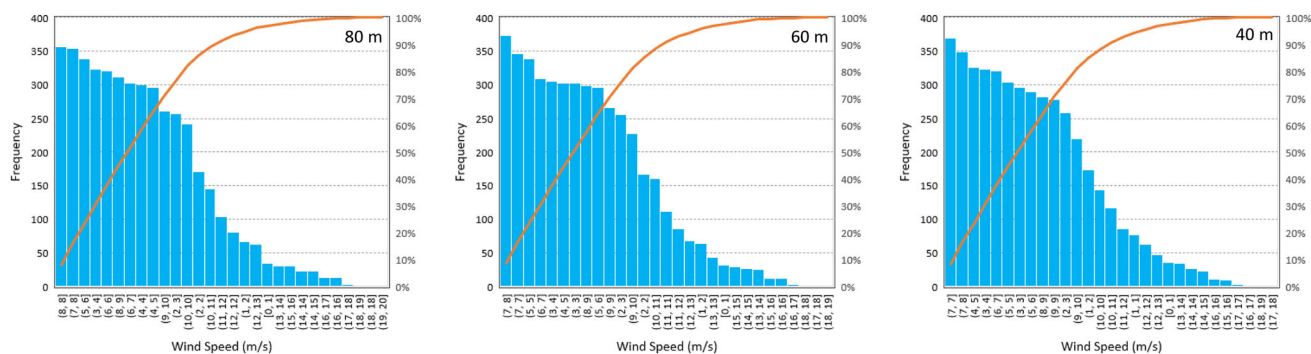


Fig. 8 Histogram of wind speed distribution measured at heights of 80, 60, and 40 m for September

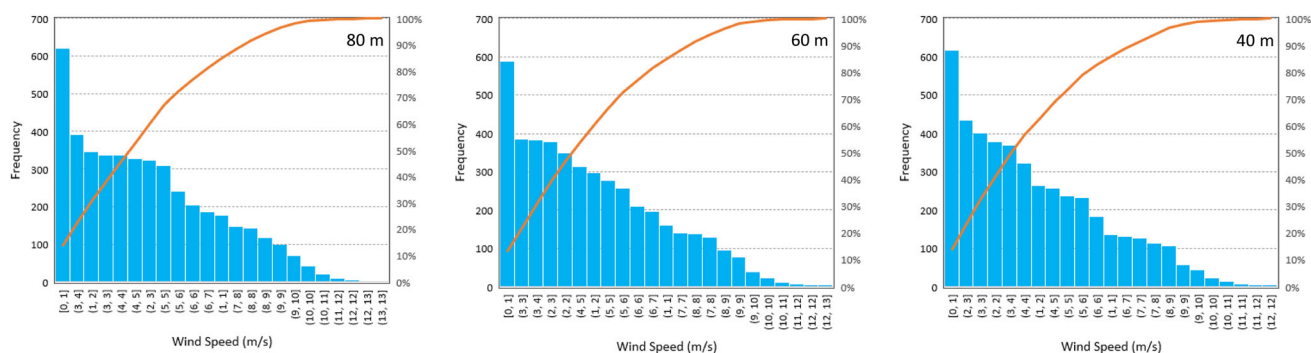


Fig. 9 Histogram of wind speed distribution measured at 80, 60, and 40 m heights for December

height of 60 m, 4–5 m/s speeds are in about 450 h during the year, an increase of 50 h more compared to the previous case. As for the optimal operating speeds of the turbines, the number of hours during the year is reduced by about 35 per year. The measurement level of 40 m is also in almost the same condition. In this case, the cut-in speeds are dominant, with about 420 h during the year, while the optimal operating speeds are about 15–20 h a year.

From the histograms shown in Fig. 9, it is evident that there are a larger number of cases where the wind speed at all altitudes is 5–8.9 m/s. The working regime of the wind starts to change in December. In this case, the frequency of presentation of cut-in wind speed is about 600 h during the

year. This makes this month the month with the highest number of working hours. Regarding the optimal operating speed of the turbines, of 11–13 m/s, the appearance of this interval is about 10–15 h, as presented in Fig. 9.

The wind is variable, which affects wind energy generation since wind power generation requires regular and robust airflow (Wang 2012). Based on the aerodynamic efficiency, mathematically defined earlier in this paper, the higher the wind speed, the higher the aerodynamic efficiency, and the higher the overall turbine efficiency (Turnipseed et al. 2002). The results of the capacity factor for each season are shown in Fig. 10. Here, the highest capacity factor was obtained in spring and winter. This is

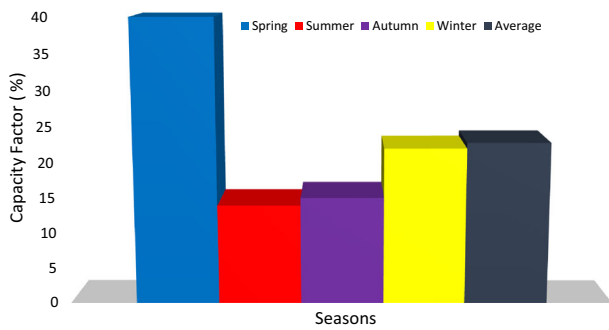


Fig. 10 The average capacity factor for each season

important because these seasons are characterized by the highest energy demand, especially for countries like Kosovo, where a large part of the heating demand is covered by electricity. From Fig. 10, it is shown a capacity factor (CF) value of about 40% in spring, which is the highest during the year. The lowest value of CF was reached in summer, around 15%. Average values are in autumn and winter. Thus, an average CF value of 22.77% was reached.

According to the Energy Regulatory Commission, the maximum capacity of a wind farm operating under a permit is 35 MW (ZRRE 2023). Four turbines can operate in the selected site based on the initial maximum capacity for a single turbine of 7.5 MW. However, the maximum capacity of 35 MW is not precisely met. The energy generated monthly can be determined using the manufacturer’s data for the installed turbines, the corresponding number of units, and the turbine’s capacity factor. The energy generated each month can be determined using the manufacturer’s specifications for the installed turbines, the corresponding number of units, and the coefficient of performance. The number of operating hours and the energy generated are shown in Fig. 11. The capacity factor is

strongly related to the number of operating hours and energy generated. As shown in Fig. 11, the number of operating hours of wind turbines is proportional to CF. The electricity produced considering CF during the spring season is 105,120 MWh, according to the summer season 36,792 MWh, 39,682.8 MWh according to the autumn season, while in winter, it is 57,816 MWh. In the average value, the annual energy produced during the year is 59,852.7 MWh.

As discussed previously, the maximum allowed installation capacity is 35 MW, which is not exhausting for the selected study case. In this case, the value is not exhausted, 35 MW for a wind farm with the current selection. This leaves the possibility to increase the efficiency of the parks, i. e., to use turbines with different capacities that increase the overall efficiency by up to 2%. Figure 12 shows how energy production varies from season to season. The largest change in energy produced is from spring to summer, 68,328.38 MWh. Among the research goals is to contribute to the idea of covering energy needs throughout the seasons in a country. With the data of Fig. 10, the distinctness of the abundance of energy needs is seen. As shown in Fig. 12, the biggest difference in the energy produced is from spring to summer, in a negative sense, because the energy production from wind turbines in summer decreases considerably. Likewise, there is a difference in energy generation from summer to autumn, but it is a slight difference. Also, there is a big difference in the positive sense from autumn to winter, where the amount of electricity produced increases significantly. In the average value, the difference in annual energy according to the consideration of CF based on the year’s seasons is 11,316.825 MWh.

Another change from season to season is from summer to fall, with a total of -2890.05 MWh. Of course, this is only an approximate way of calculating the energy yield. The results become much more realistic if analyzing a

Fig. 11 Energy generated by the wind farm and the number of working hours in the respective season

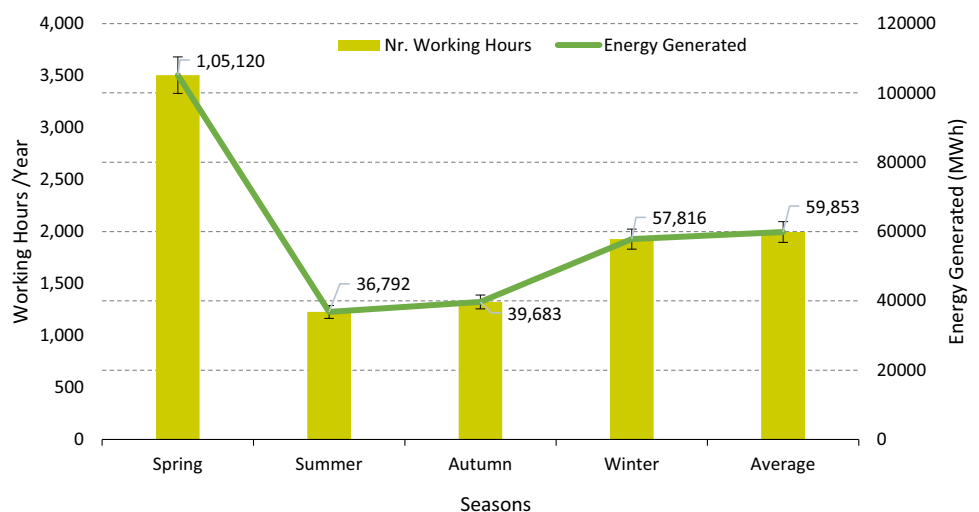
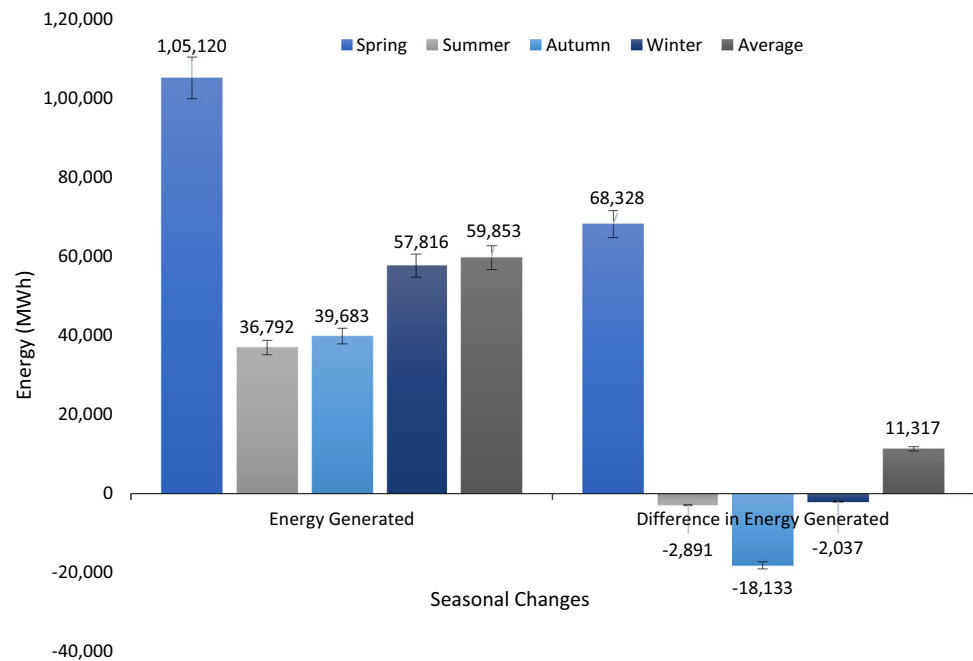


Fig. 12 Energy generated by the wind farm in the respective season and the difference from season to season



disturbing phenomenon, the lag effect (Lledó et al. 2019). Based on the Energy Strategy of the Republic of Kosovo (ME 2022), which favors the production of solar energy, and considering that the biggest change in energy production is from spring to summer, a hybrid system for wind and solar energy would fill the gap created by the lack of wind energy.

The poor energy situation with growing demand and air pollution is still worrying. According to the Energy Strategy of the Republic of Kosovo (ME 2022), approved in 2023, maximum coverage with renewable sources and battery storage is foreseen.

Since the late twentieth century, with the rapid growth of the world economy, the energy demand has also increased rapidly (Jiang et al. 2010). The power industry massively expands wind resources exploitation to meet the increasing electricity demand. Wind energy is clean, renewable, and abundant, providing environmentally friendly electricity that can be used on a large scale. Nevertheless, there are several challenges regarding the optimal exploitation of wind energy.

Thus, starting from the idea of this study to deal with the seasonal transitional phase, the key contribution that offers this study can be discussed. The transitional phase of the seasons is maximally like the respective seasons. The potential of generating energy from the wind is maximum in the spring and winter; in contrast, it is considerably reduced during summer and autumn. Although electricity generation depends on many factors other than wind conditions, the capacity factor (CF) is an appropriate indicator to quantify the impact of wind speed variations on

electricity generation (Lledó et al. 2019). The analysis proposed in this case is helpful because it applies a seasonal CF to estimate the potential annual energy generation. The analysis conducted in this study considers the average energy generation for all seasons in the selected study case. Despite some assumptions about aerodynamic, mechanical, and electrical efficiencies, the applied approach provides reliable results.

The most essential element is the wind speed histograms for all measurement heights, especially at 80 m. From this histogram presented in Figs. 6, 7, 8, 9, it was found that:

- For March, the speed of 0–1 m/s appears about 25 h a year, 5–6 m/s with about 290 h a year, and the extreme speed of 20 m/s not every hour, only intervals of a few minutes.
- For June, the speed of 0–1 m/s appears about 26 h a year, the speed of 5–6 m/s with about 375 h a year, and the extreme speed of 20 m/s was unavailable.
- For September, the speed of 0–1 m/s appears about 23 h a year, 5–6 m/s with about 360 h a year, and the extreme speed of 20 m/s was unavailable.
- For December, the speed of 0–1 m/s appears to be about 620 h a year, the speed of 5–6 m/s with about 250 h a year, and the extreme speed of 20 m/s was unavailable.

This study can be expanded even further by including analyses of the main factors that influence such pronounced changes in wind speed. As well as the effect of climate change on changing air flows/currents. As an additional effect to the work in question, drafting the energy

production strategy in Kosovo based on the seasonal availability of wind energy in the country can be added. The final assessment of seasonal changes by correcting an entire season should be based on the whole season, including the season's start and end day (Akpinar and Akpinar 2005). It is also important to consider similar studies (Baker et al. 1990) and other studies that show the fluctuating nature of wind speed over time and the solution to tackle such fluctuations in the power grid (Katsarava and Gaschler 2023). In that regard, hybridizing the power system (Jurasz et al. 2020) and storage solutions (Malika et al. 2022) would enhance the electricity supply and improve the flexibility of the entire power system.

4 Conclusions

The great importance of air parameter variability comes from the transitional phase from season to season. Understanding the seasonal changes in wind speed and its impact on energy generation is particularly important for stakeholders dealing with power generation and planning. The difference in this study is that the whole season was not considered, but only the transitory phase of the seasons. This study analyzed the variation of wind speed during seasonal change. The study was conducted in complex mountainous terrain in Kosovo. The study is conducted in the context of the correlation of wind speed, capacity factor, and potential energy generation. These analyses are performed for a specific type of turbine, considering the operating parameters specified by the manufacturer. The following main conclusions can be drawn from this study:

- With an average capacity factor of 25%, i.e., with 2190 operating hours per year, the potential energy generation for the wind speed measured at 80 m height for each season (i.e., spring, summer, autumn, and winter) is 64,396.66, 22,040.28, 42,539.34, and 46,417.18 MWh/year, respectively.
- The potential of wind energy during the passage through the change of seasons is at an intermediate level. This value is along each measurement altitude, and the intensity increases linearly with altitude. In the comparison of the energy that, according to the measurements, can be produced at 40, 60, and 80 m heights, differences are observed: from 80 to 60 energy generation decreased by about 7–8%, while from 60 to 40 m, it decreased by about 10–15%.
- To achieve a higher level of energy generation and safety in the operation of turbines regardless of the season, it is first necessary to define the optimal placement of turbines in each farm regardless of climatic conditions in the respective site.

- The comparison of the results obtained cannot be called seasonal differences but the designation of the changes in wind speed at the beginning of each season. Of course, there are higher wind speeds in winter. However, the analysis performed here applies to the critical months of transition from one season to another, which is an important indicator.
- Overall, wind speed is highest from the beginning of winter (December) to the end of spring (June). The difference in energy generation is 65% from spring to summer, then from summer to autumn, 8%, and 31% from autumn to winter.

This study may be expanded in the future in the context of analyses related to the possibility of an energy system mixed with other available types of renewable energy, which would lead to a greater reduction of dependence on coal-based power plants of Kosovo's power system. Working on intelligent systems that respond quickly to power fluctuations would add value to future work in this area. Considering the fluctuations in the wind farm and the impact on the power grid, a hybridization of the system with a pumped storage power plant should be considered for more flexible operation. The hybridization of the power system would smooth the fluctuations in wind power generation and provide consumers with a more stable energy supply.

Acknowledgements Alban Kuriqi is grateful for the Foundation for Science and Technology's support through funding UIDB/04625/2020 from the research unit CERIS.

Funding Open access funding provided by FCT/IFCCN (b-on).

Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request through a material transfer agreement.

Declarations

Conflict of interests The authors declare no competing interests.

Ethical approval Ethics approval is not applicable.

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