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Challenges of renewable integration in Kosovo: A technical study of balancing reserve needs

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ABSTRACT

The integration of renewable energy sources (RES), particularl y wind power, into national power systems introduces significant operational and technical challenges, especially in countries with limited system flexibility, such as Kosovo. This study examines the impact of wind power on Kosovo's balancing reserve requirements using high-resolution operational data from two existing wind farms – Kitka (32.4 MW) and Selac (103.4 MW). The analysis assesses short-term variability and forecast errors across 1-minute, 15-minute, and hourly intervals. The standard deviation (σ) of wind power variability was applied to estimate the impact on short-term reserves. This method is effective for estimating reserve requirements resulting from wind power integration, provided that operational data from wind farms is available. A confidence level of ±4σ is applied to capture over 99% of potential imbalances, in line with EU network code requirements. Additionally, the results are compared with both the variability and the unpredictability of wind power output. The findings indicate that the current wind capacities already cause substantial system imbalances, requiring additional frequency restoration reserves (FRR) of +31 MW (upward) and -40 MW (downward), with forecasting errors and variability reaching ±35% of installed capacity within 15-minute intervals. Scenario-based modeling, aligned with Kosovo's national energy strategy – which targets 600 MW of installed wind capacity by 2031 – suggest that future balancing reserve needs may rise to 129.6 MW (upward) and 156.6 MW (downward). Although the analysis focuses solely on operational data from WPP and excludes factors like demand fluctuations, outages, or market trading, it provides valuable into the operational challenges facing Kosovo's power system. The results point to an urgent need for investments in system flexibility, including battery energy storage, and enhanced regional cooperation to strengthen reserve adequacy and ensure grid stability.

Keywords: balancing reserves, capacity, forecasting errors, integration of wind power plant, variation of power.

INTRODUCTION

Countries worldwide are making significant advancements in renewable energy development. Kosovo has also adopted an ambitious energy strategy aimed at substantially reducing its dependence on lignite-based energy production and transitioning toward renewable sources. Currently, more than 90% of Kosovo's electricity demand is met by thermal power plants using coal as the primary resource.

In 2022, the Government of Kosovo developed a national energy strategy focused on reducing coal-based electricity generation and replacing it with renewable energy sources such as wind and solar power. Given Kosovo's peak electricity demand of approximately 1500 MW and annual consumption of 6.5 TWh (ERO, 2024), the strategy envisions installing 1400 MW of wind and solar capacity by 2031 [Ministry of Economy, 2022].

A key challenge in Kosovo's power system is the lack of flexibility from generation resources, which limits the availability of reserves. Unlike Kosovo, Albania's electricity generation is unique in the European Union, with over 90% coming from hydropower, making its system highly flexible. In 2020, when Kosovo's Transmission System Operator (TSO) established a Load-Frequency Control (LFC) block with Albania's TSO, it was agreed that all system balancing reserves would be imported from Albania using cross-border capacities. Both TSOs agreed on cross-border exchanges of reserves and ensured that the reserves were determined based on a common dimensioning approach. The common dimensioning of reserves for LFC blocks in the EU is presented in the paper [Knorr at al., 2019, ACER, 2023]. Furthermore, dynamic dimensioning of reserves is analyses in paper [De Vos et al., 2019].

While large-scale integration of renewable energy sources is technically possible to connect to the grid, it requires additional system flexibility and increased balancing reserves. The transition to wind and solar power capacities presents challenges related to system balancing reserves on one side and costs of the reserves on the other side. Unlike conventional generation from coal, hydro, or gas, wind and solar generation are intermittent, leading to higher imbalances and increased forecasting errors. To maintain system stability, Kosovo's TSO must continuously assess and procure sufficient balancing reserve capacity and balancing energy to mitigate variability and uncertainty (prediction errors).

Wind and solar power generation introduce significant variability and forecast uncertainty, posing challenges to power system operations. Addressing these challenges requires enhanced system flexibility, which depends on existing infrastructure and the level of RES integration. This paper analyzes the increasing need for additional balancing reserves capacity due to the integration of wind energy into Kosovo's power system. The energy and power generated from wind fluctuate continuously over various time scales, including minutes, 15-minute intervals, hours, days, weeks, and years.

As per system operation guideline ENTSO-E [ENTSO-E, 2017] and Load Frequency Control and Reserves Policy [ENTSO-E, 2024] the minimum recommended amount of automatic frequency restoration reserve (aFRR) based on system imbalances depends on load variations, schedule changes, and the behavior of generating units. The minimum recommended amount of aFRR has to ensure:

The positive aFRR (upward reserve) must be greater than the 1st percentile of the difference between:

- The 1-minute average ACEol (open-loop Area Control Error, excluding mFRR and RR contributions).
- The 15-minute average ACEol of the LFC Block for the same quarter-hour.
- The negative aFRR (downward reserve) must be greater than the 99th percentile of the same difference.

Two factors increase the need for balancing reserve capacities in power systems with renewable energy sources (RES): variability and uncertainty.

Variability refers to the expected changes in electricity production by wind power plants due to fluctuations in wind speed. Variability affects both load and generation, especially with renewable energy sources (RES). Daily load profiles reflect regular energy use patterns, while Wind Parks output varies with wind speed. Variability is measured by the rate of change in power or load over specific periods (MW/min, MW/15min and MW/h). Forecasting inaccuracy refers to errors in predicting energy generation (in this case, RES generation forecasts), which result in real-time imbalances between the scheduled nomination program (e.g., one day ahead, intraday) and the actual real-time generation from RES. This uncertainty arises from inaccuracies in predicting generation. An important aspect in reducing variability lies in diversifying RES by technology, including wind power (WP) and photovoltaics (PV), as well as by geographic distribution. Larger countries have more capability to manage variability than smaller countries such as Kosovo. Geographically distributing wind or solar parks more widely can help to mitigate variability.

The impact of uncertainty can be minimized by aggregating the imbalances from various wind power plants (WPPs) and PV plants located in different regions, due to variations in wind and solar radiation. From the TSO's viewpoint, forecasting errors, particularly those from wind and solar generation, are visible at the system level. The TSO uses a scheduling program throughout the day to balance the system, addressing deviations in both generation and load from the nominated program. When imbalances happen in control area which area control error is positive or negative due to variability and forecasting uncertainty, system operators must activate balancing reserves to correct the imbalances and to bring the in control in values of nomination. With high penetration of renewable resources, the imbalances of the system are higher and the need for balancing reserves capacities and energy is higher, and planning of the reserves is more complicated which significantly affects the reliability and efficiency of the system. Global studies have shown that in the effects of variability and uncertainty manifest in the increased need for Frequency Restoration Reserve (FRR), respectively aFRR (automatic Frequency Restoration Reserves) and mFRR (manually Frequency Restoration Reserves) [Energinet, 2023], [ENTSO-E, 2024]. The significant increase in wind capacity causes greater fluctuations in their generation within the power system, leading to a higher demand for balancing resources. These effects are most pronounced within the 1–15 minute and 1-hour time frames. Figure 1 illustrates the process of determining aFRR and mFRR regulating reserves. The FRR resources must cover imbalances caused by load fluctuations, forecasting errors, generation variability, incidents (such a highest generation capacity or load, N-1 criteria) [Elia, 2018, 2024].

FRR are determined using either a deterministic or a probabilistic methodology, depending on the system operator's approach. In the probabilistic approach, the reserve size is calculated to cover almost all expected imbalances – both positive and negative – excluding the extreme values that occur in less than 1% and more than 99% of cases (ENTSO-E, Annex 1: Policy on Load-Frequency Control and Reserves, 2024).

As shown in Figure 1, the manually activated mFRR is determined according to the following principle:

$$mFRR = FRR - aFRR \quad (1)$$

The method of dimensioning of the Balancing reserves capacity and time period of organization of the balancing market is very important for cost optimization of reserve capacity. In papers [Kippelt et al., 2013] and [Costilla-Enriquez et al., 2023] are discussed about methods developed for dynamic dimensioning of balancing reserve capacity because of renewable integration. Review different methodology used by TSOs for dimensioning of the reserve capacity were analyses in paper [Bongers et al., 2021], and dynamic reserve sizing method using nonparametric distributions as a forecast error in paper [Bucksteeg et al., 2016]. The flexibility reserve ancillary service and its impact in operation was presented in paper [Krad et al., 2017].

MATERIALS AND METHODS

To assess the impact of RES integration on Kosovo's power system and its balancing reserve capacity, this paper develops scenarios based on different levels of RES integration. To determine the impact of wind resources on the increase in balancing reserve capacity needs, historical data on generation and imbalances from specific power plants currently in operation will be used. The data series used will have a time resolution of 1

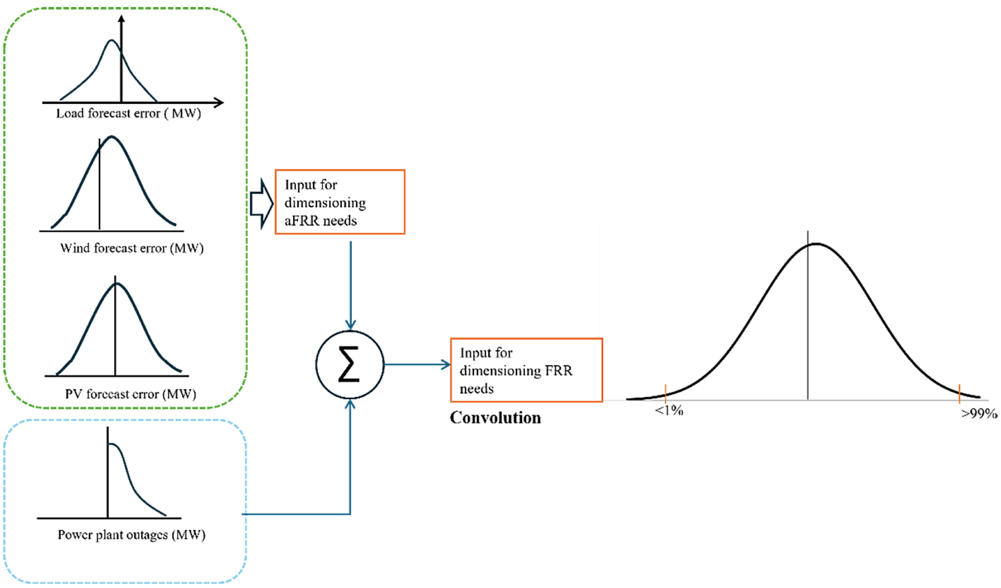

Figure 1. Probabilistic dimensioning of TSO balancing reserves [Hirth & Ziegenhagen, 2015]

minute, 15 minutes, or 1 hour, covering two years of operation. The impact assessment is conducted for several scenarios of RES development as it is foreseen on strategy of energy.

Table 1 presents the methodology for collecting data from existing Wind plants, and future scenarios to determine additional reserve needs and new future scenarios

The methodology considers wind forecasting errors, excluding imbalances caused by consumption, trading, and outages. Furthermore, the standard deviation, normal distribution function, and histogram will be used to evaluate variability, as well as significant deviations caused by uncertainties during the planning phase.

All figures and tables presented in this paper are generated using the methodologies mentioned earlier, based on measurement data, which serve as input for the respective analyses [KOSTT, 2024].

Reserves in the power system are defined to cover variations and uncertainty within a certain confidence level, such as 99% of all possible fluctuations. The standard deviation formula was applied to quantify the average deviation from the mean, accounting for forecast errors and inherent variability.

$$\sigma = \sqrt{\frac{\sum(x_i - \mu)^2}{n}} \tag{2}$$

where: x_i – observed random values and μ – mean value.

To cover 99.99% of all variations, a range of ±4σ was applied.

To calculate the imbalances of wind power plants (WPPs), the error between forecasted and real-time production was calculated by comparing the predicted generation to the actual generation for each time period (usually hourly or Quarter-hourly). The calculation of imbalances is done using the following formula:

$$\Delta Pi = P_{m,i} - P_{n,i} \tag{3}$$

where: ΔP_i – the imbalance (error) for the i-th time period, $\Delta P_{m,i}$ – the forecasted (predicted) power output for the i-th time period, $\Delta P_{n,i}$ – the real-time (actual) power output for the i-th time period.

RESULTS AND DISCUSIONS

The level of variability and uncertainty for WPP in operation

To assess the variability and uncertainty of wind power plants in the power system, operational data has been collected over a two-year period. The WPPs Kitka (32.4 MW) and Selac (103.41 MW), with a combined capacity of 135.8 MW and load factors between 30% and 32%, have been in operation since 2018 and 2021. Wind power production is continuously fluctuating, with variations occurring on minute, hourly, daily, seasonal, and yearly timescales. This paper analyzes the short-term variations in wind power generation within the power system. Output power variability and rate of change were analyzed over 1-minute, 15-minute, and 1-hour intervals. Figure 2 shows a 1-minute frequency distribution of power variations, excluding values below 1% and above 99% or over ±3σ. Variability is calculated as the difference between the average of each consecutive 15-minute interval.

$$\Delta P_i = P_i - P_{i-1} \tag{4}$$

Figure 2 shows the one-minute average power variability of WPP Selaci (103.41 MW), while Figure 3 displays the histogram of power variation in MW/min. The critical gradient ranges from -3 MW/min (decrease) to 4 MW/min (increase).

Figure 4 depicts the average power over one hour and the power variation of wind within one minute.

Table 1. Methodology for collecting data from existing WPPs, and future scenarios for determining additional reserve Needs and new Future Scenarios

Analyses of existing WPPs already connected to grid: WPPs:32.5MW and 103.41 MWs	Scenario WPP in 2030: 600 MW
Collection of data from existing Wind Parks (WP): • Wind Parks: 32.4 MW Kitka and 103.41 MW Selac (measured power series for 1 minute average 15 minutes and 1 hour average for the year 2024) and imbalances due to forecasting errors (2024). • Determination of the variability rate, average value, standard deviation, and critical value in the units of power gradient: 1MW/min, MW/15min and MW/1h Assessment of the additional system power requirements for regulating power according to the current state.	• Use of data from existing plants to create the hourly output power correlation for Scenario 2, including the introduction of the variability and uncertainty mitigation factor based on published research. • Evaluation of the additional system power requirements for regulation according to Scenario 2 of RES.

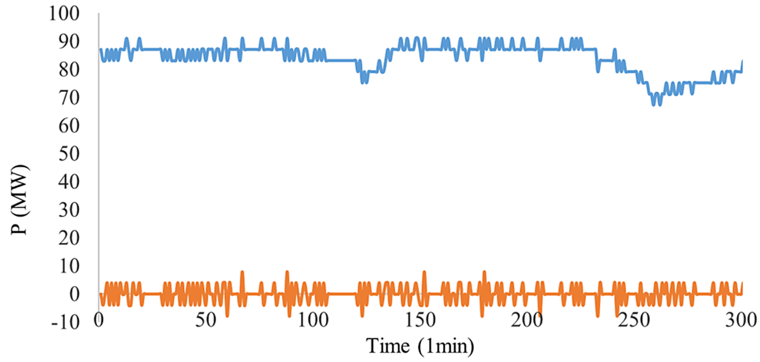

Figure 2. Average power variability of WPPs per minute of WPP Selaci (103.41 MW)

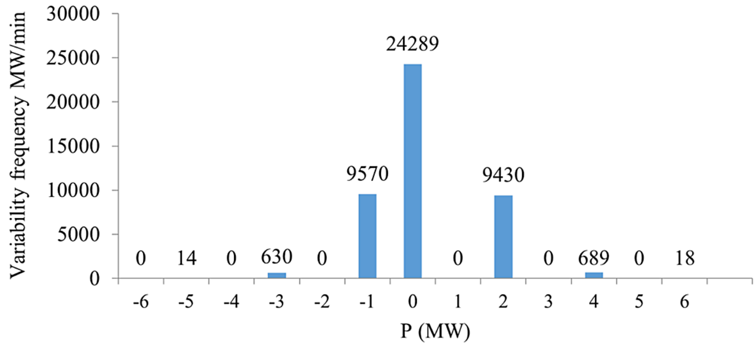

Figure 3. Histogram of average power variability of WPPs per minute

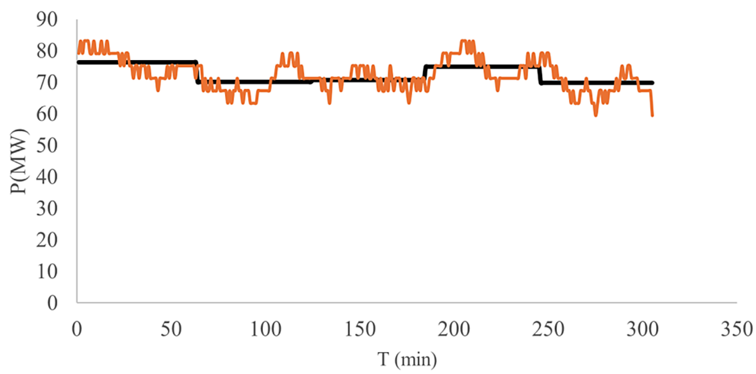

Figure 4. Average power over one hour and 1 min power variation of WPP

Similarly, it analyses the gradient of changes in the average power production output of WPPs installed in Kosovo at 15-minute intervals. The 15-minute variability of WPPs is shown in Figure 5.

The standard deviation and percentage of variability are presented in Table 2. The ratio of variability for all WPPs observed by the TSO is ±10% of the installed capacity.

Furthermore, uncertainty includes the forecast errors made by WPPs in the day-ahead schedule, as well as the continuous updates to the energy production program, compared to the actual real-time output of the WPPs. Any deviation between the real-time output and the nominated program results in an imbalance, which is managed by the TSO. This is important for determining the frequency restoration reserves needed to cover imbalances caused by WPPs in the TSO.

This paper assesses the impact of the operation of WPPs on the power system of Kosovo by analyzing the performance of existing WPPs and their associated uncertainties. A probabilistic approach method, which is based on probability density functions (PDFs), is used for analyzing

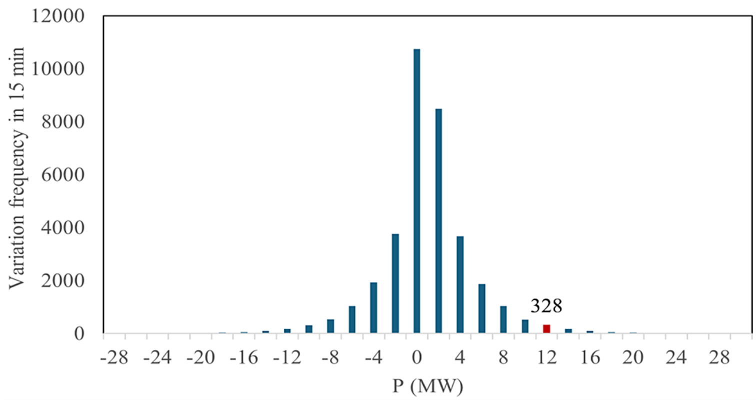

Figure 5. WPP variability in Kosovo every 15 minutes

Table 2. Variability of WPP

Wind power plant	Installed capacity (MW)	Standard deviation σ	Uncertainty probability ≤ 1%	Uncertainty probability ≥ 99%	Ratio of Uncertainty to install capacity	
WPP Kitka	32.4	1.84	-4.285	4.283	-13%	13%
WPP Selac	103.41	4.054	-12	11.9	-11%	11%
Sum of WPP1+WPP2	135.81		-16.285	16.183	-24%	24%
Total capacity operation	135.81	4.48	-14	12	-10%	9%

reserve needs. This method utilizes historical data from the operation of WPPs to evaluate short-term forecast errors over 15-minute and 60-minute intervals. Standard deviation calculations exclude events with probabilities lower than 1% and higher than 99%.

Figure 6 and 7 present the results for both WPPs and the total WPP forecast errors.

In a power system, the total power deviation or aggregated WPP deviation is important. Figure 8 shows the total deviation of WPPs over 15 minutes, which is necessary for determining the FRR required by the TSO to manage imbalances caused by forecast errors.

The results presented in Figures 6, 7, and 8 indicate that the level of imbalances (forecasting errors) in WPP over a 15-minute period is higher when assessed individually than when considering the total capacity. Excluding values below the 1st percentile and above the 99th percentile, the imbalance levels for the 32.5 MW WPP range from -10.3 MW/15 min to 11.3 MW/15 min, while for the 103.41 MW WPP, they range from -30 MW/15 min to 37 MW/15 min.

The level of imbalances of WPPs increases with longer monitoring intervals. In a 1-minute interval, the power output varies by about ±3–4% of the installed capacity per minute. Over 15 minutes, it can be until ±35% of the Installed capacity.

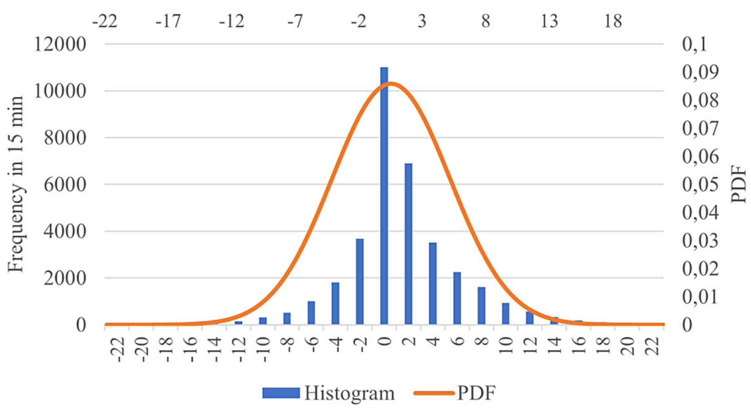

Figure 6. WPP imbalance probability in Kitka every 15 minutes

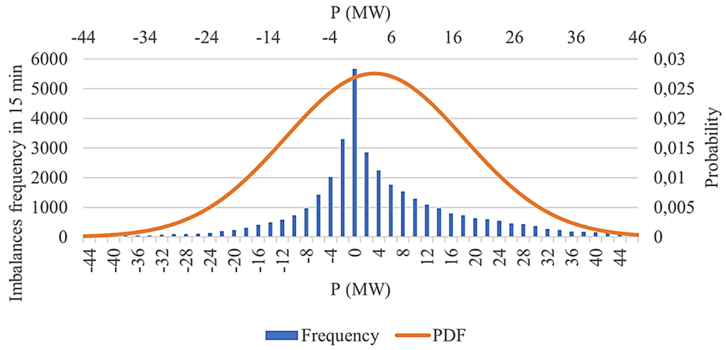

Figure 7. Imbalances of WPP in SOWI every 15 minutes

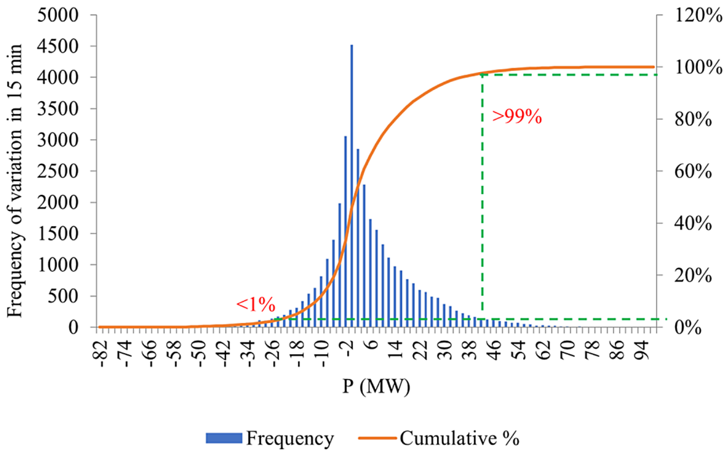

Figure 8. Total power imbalances of WPPs in the Kosovo power system as observed by the TSO

Table 3 shows the forecasting errors of individual WPPs and the total, relative to installed capacity. Overall imbalances, both positive and negative, are lower than the sum of individual WPP errors, with a neutralization effect of about 20%.

Currently, the scheduling nominations for WPPs is done on an hourly basis, while cross-border nominations occur every 15 minutes. To maintain system balance, FRR reserves should be sized to cover real-time deviations within 15-minute timeframe. The ramp rate should be determined based on the average power change per minute.

This analysis also covers the hourly performance of WPPs. Figure 9 shows the imbalances of WPPs over one hour, with compensation between WPPs mitigating deviations – when one reduces power, another increases it. Figure 10 presents the probability of distribution of imbalances.

The overall level of imbalances caused by forecasting errors on individual WPPs and as total imbalances viewed by TSO, in absolute values and as a percentage of total capacity, is presented in Table 4.

Assessment of the impact of current WPPs on regulating reserves of the system

Based on 2023–2024 data, the TSO needs to increase reserves by +32 MW (upward) and

Table 3. Standard deviation and deviation from scheduling program (forecasting errors) for both WPPs

WPP	Installed capacity (MW)	Mean	Standard deviation σ	Uncertainty probability ≤ 1%	Uncertainty probability ≥ 99%	Ratio of Uncertainty to install capacity	
WPP Kitka	32.4	0.54	0.54	-10.27	11.34	-32%	35%
WPP Selac	103.41	3.25	3.25	-30.43	36.92	-29%	35%
Sum WPP1 + WPP2	135.81			-40.70	48.27	-30%	35%
Total capacity operation	137.6	3.78	3.78	-32.84	40.41	-24%	29%

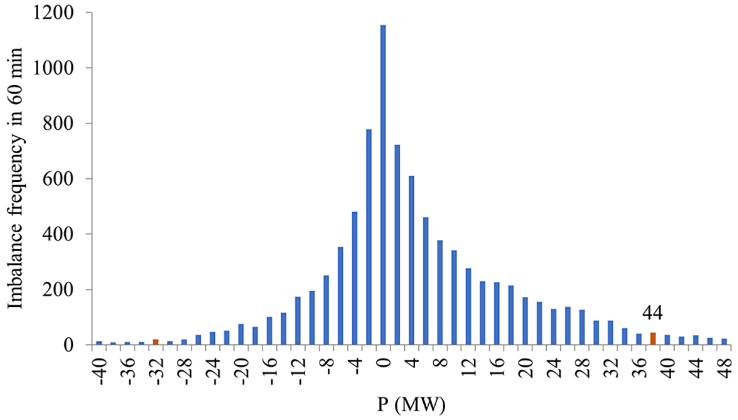

Figure 9. Histogram of imbalances caused by forecast errors of WPPs in Kosovo

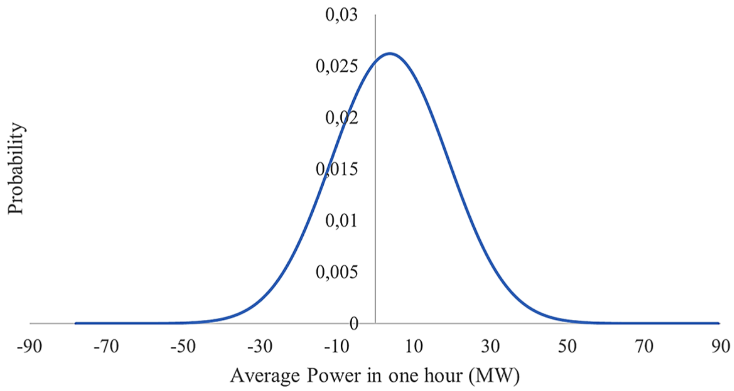

Figure 10. Normal distribution curve: 1-hour imbalance probabilities caused by WPPs in the Kosovo power system

Table 4. Standard deviation for forecasted errors for both WPPs with time interval one hour

WPP	Installed capacity (MW)	Mean	Standard deviation σ	Uncertainty probability ≤ 1%	Uncertainty probability ≥ 99%	Ratio of Uncertainty to install capacity	
WPP Kitka	32.4	0.54	4.37	-9.62	10.70	-30%	33%
WPP Selac	103.41	3.24	14.03	-29.40	35.89	-28%	34%
Sum of WPP1+WPP2	135.81			-39.03	46.59	-28%	34%
Total capacity operation	135.81	3.78	15.24	-31.67	39.23	-23%	29%

-40 MW (downward) due to power variations, which can reach ±10%. Negative imbalances signal MW shortages, requiring more upward reserves, while a +40 MW increase from WPPs needs extra downward regulation. aFRR addresses dynamic imbalances, while mFRR corrects longer-lasting ones, with allocation depending on imbalance type.

Currently, the TSO of Kosovo determines reserve requirements using a deterministic approach, as outlined in [ENTSO-E, 2017]. The total aFRR reserves required for the system amount to ±43 MW, with WPP variability contributing to a 100% increase in reserve requirements compared to the existing system. According to [Xu et al., 2019] the reserve capacity can be different and reduced if methods for prediction of wind power is different, and time prediction is lower than one hour in our case for 15-min instead of 1-h predictions. In paper [Holttinen et al., 2013], power systems with high wind penetration are shown to experience increased variability and uncertainty, necessitating the determination of the required additional operating reserve.

To enhance the analysis, three representative days were selected to assess forecast performance at the Kitka (32.5 MW) and Selaci (102.5 MW) wind farms, as shown in Figure 11. The need for balancing capacity (Frequency Restoration Reserves) is driven by variability and forecast errors. Figure 12 presents the Imbalance Duration Curve, which ranks the level of imbalances throughout the year from maximum to zero. It is evident that, to fully cover all deviations caused by WPPs, the TSO must ensure sufficient upward and downward reserves, equal to the maximum deviations on both the positive and negative sides.

Future scenario assessment and impact on system regulating reserves

The system was analyzed under the scenario 600 MW wind power plants installed in the system. Initially, the amortization coefficients for wind were determined. In addition to the Kitka and Selaci wind project, other wind projects were considered, located in different geographic areas in Kosovo. The amortization coefficients for variability were determined based on historical data's on Kosovo numerous studies conducted worldwide on this issue. As the projects are combined, the rate of change (gradient) of power and net imbalances observed from TSO level decreases due to the amortization effect from geographical distribution. For our analysis, we will use the same amortization coefficients, variability factors, and uncertainties 0.8. The meaning of these coefficients is that the variability and uncertainty of the combined projects will be 20% for scenario 2.

With amortization factor 0.8 the level variability is about -21.6% and +26.1% which means the impact of required additional FRR for balancing the system +21.6% upward reserves capacity and -26.1% downward reserves capacities. In absolute terms, additional FRR for upward reserves is about 129.6 MW and 156.6 MW. Normally, to properly assess the required upward and downward reserves from a system perspective, it is necessary to evaluate the total generation capacity (including RES, conventional power plants

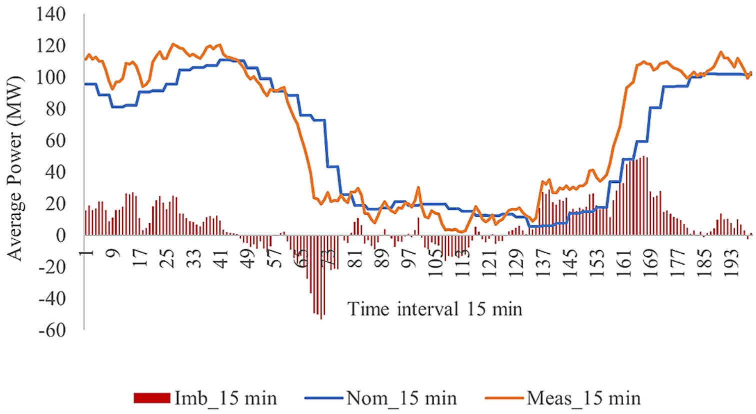

Figure 11. Comparison of 15-minute measured and forecasted wind power, along with the resulting imbalances in Kosovo's power

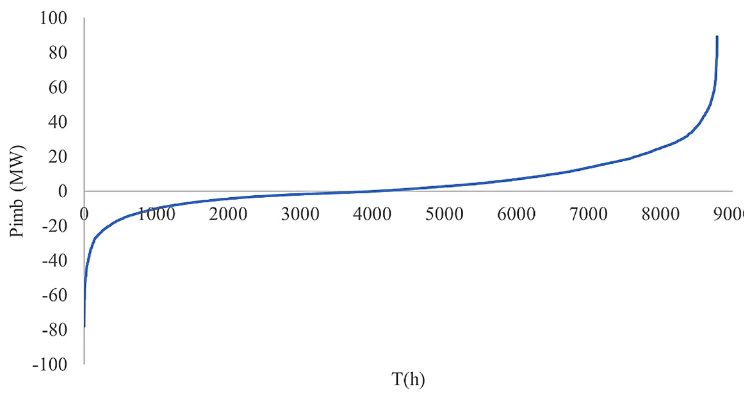

Figure 12. Imbalance duration Curve for WPPs in the Kosovo power system.

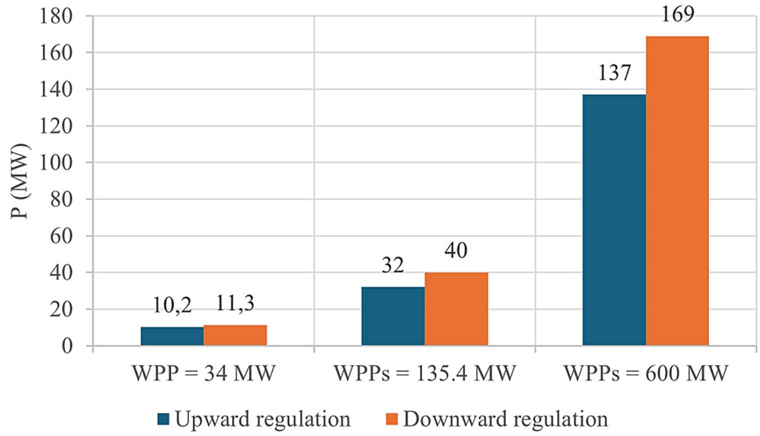

Figure 13. Required upward and downward regulation power as a function of total installed WPPs capacity in the Kosovo power system

such as coal, gas, etc.) and the load. In Figure 13 shows how the need for upward and downward regulation (balancing reserves) increases with installed WPPs capacity in the system.

CONCLUSIONS

The current aFRR and mFRR reserve needs are based on load variations and the largest generation unit or load loss. Integrating wind and solar energy will increase the demand for these reserves, creating a challenge for the System Operator to maintain balance in real time per ENTSO-E requirements. This requirement becomes more critical given the limited upward and downward regulating capacity currently available within Kosovo's power system.

The main factors contributing to the increased need for regulating power are the variability (fluctuations) in wind power output and forecast uncertainty. Variability necessitates regulating units capable of compensating for power fluctuations (both upward and downward) to ensure that the system's ACE remains within the tolerable limits set by EU network code.

This paper analyzes the impact of these two factors on reserve requirements, focusing on the current situation with 135.8 MW of installed wind capacity and the future implementation of the national energy strategy, which envisions 600 MW of WPP capacity – equivalent to 40% of Kosovo's peak load. The geographical distribution of wind farms and the low probability of simultaneous fluctuations will play a crucial role, as the need for regulating reserves will not increase proportionally to the installed wind power capacity.

Technical analysis of the current situation shows that wind variability and imbalances caused by forecast errors have led to an increase in aFRR + mFRR requirements in the range of +31 MW (upward) and -40 MW (downward). Under the scenario of 600 MW of installed wind power, Frequency restoration reserves FRR = aFRR + mFRR) requirements are expected to rise to approximately 129 MW (upward regulation) and 1567 MW (downward regulation). This represents a significant reserve requirement for a small country like Kosovo, highlighting the urgent need for the TSO to address the impact of renewable energy sources (RES) on system performance and reserve costs. Given the inflexible nature of Kosovo's power system, the TSO and country must accelerate investments in battery energy storage systems (BESS) to provide a viable solution within the next five- ten years. Additionally, enhancing cooperation with regional TSOs for reserve exchanges will be critical in ensuring system stability and cost-effectiveness.

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