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Power Variability of Wind and Solar Production Portfolio in the Republic of Croatia (March 2023)

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Summary **— In this work, we analysed multi-annual data set of wind and solar production portfolio with different power frequency approaches and averaging methods in order to characterize power production variability at different temporal scales. All the methods have their advantages depending on their scale and purpose, but also some shortcomings that limit their use. For the purposes of this work, we selected the method of explicit derivation as the most appropriate for the fast power change frequency analysis and characterization. The variability of power production from wind and solar power plants in Croatia is strongly present on an hourly, daily and seasonal level, while on an annual level the variability is much less pronounced. Since current electricity production and consumption must remain in balance to maintain the stability of the power network, this variability of production can pose significant challenges for the inclusion of large amounts of wind and solar energy in the power system of the Republic of Croatia. A particular challenge for the power system in terms of production variability is the fast change in power. Fast power change affects the quality of production forecasting and consequently causes higher imbalance costs. The impact on the management and balancing of the power system is particularly challenging.**

Keywords **— fast power change, solar power plants, variability of electricity production, wind power plants**

I. Introduction

CROATIAN ENERGY MARKET OPERATOR Ltd. (HROTE) in accordance with the Law on the Renewable Energy Sources and High-Efficiency Cogeneration ("Official Gazette", number: 138/21) is designated as the manager of the ECO balance group with the obligation to forecast the production of ECO balance group, payment of balancing costs for ECO balance group and sale of electricity from ECO balance group.

The installed capacity of wind power plants (WPP) in the Republic of Croatia is growing rapidly, on 31 December 2021 it was 989.5 MW, while in the ECO balance group there was 712 MW of installed power of WPP on the same day. Considering that the largest share of the installed power of WPP in the Republic of Croatia is in the ECO balance group, for the purposes of this paper, data of production of WPP (the same applies to solar power plants) from the ECO balance group will be used as representative for the Republic of Croatia.

The construction of solar power plants (SPP) in the Republic of Croatia is currently lagging behind WPP, but significant increase in the installed power of SPP is expected in the next few years. On 31 December 2021, the installed capacity of SPP that are part of the ECO balance group was 55.9 MW.

The variability of electricity production from WPP and SPP is expressed on an hourly, daily and seasonal level, while on an annual level the variability is less pronounced [1]. A particular challenge for the power system in terms of production variability is the fast change in power. Fast power change affects the quality of production forecasting and consequently causes higher imbalance costs, and the impact on the management and balancing of the power system is particularly pronounced [2], [3].

Considering the biggest share of the installed power of WPP in total power of all plants that are part of ECO balance group, the quality of WPP production forecasting has the greatest impact on the balancing costs for the ECO balance group. In 2021, HRK 53.56 million of balancing costs were charged to ECO balance group, and according to HROTE's estimation, WPP used more than 97% of all the costs. The achieved quality of WPP forecast for a day ahead in 2021 was 4.92% MAE (35.5 MWh/h) with a maximum positive error (production greater than plan) of +268 MWh/h and with a maximum negative error (production less than plan) of -221 MWh/h. With forecasting WPP production on the day of delivery, the total WPP forecasting error was reduced for 25%, from an average of 35.6 MWh/h to 26.7 MWh/h, that is, from MAE 4.92% to MAE 3.70%. The paper will specifically analyse the quality of the WPP forecast, in case of fast power change, for a day ahead and on the day of delivery.

The achieved quality of SPP production forecast for a day ahead in 2021 was 1.73% MAE (<1 MWh/h) with a maximum positive error of 10 MWh/h and with a maximum negative error of -16 MWh/h.

The paper presents an analysis of the frequency of fast power change, WPP and SPP ramp events, individually and in total, which are part of the ECO balance group, the amount and distribution of fast power change in time. The impact of fast power change on the entire power system will also be considered and analysed in paper. For the purposes of the analysis, historical 15-minute, hourly and 2-hour data of WPP and SPP production were used for the first

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three years and four months of ECO balance group operation, and additionally, an analysis was made for a shorter period based on minute data of WPP production.

II. Literature Overview

Wind and solar power production variability, identification of fast power change events and how they affect the quality of production forecasting and power system management was widely studied subject due to strong impact on the grid integration, flexibility requirements and accuracy of wind and solar power forecasts.

In research article [4] a wind energy Ramp Tool and Metric (RT&M) was developed with description of multiple methods how to identify events of fast power change. The RT&M integrates skill of multiple forecast models over a matrix of ramp events of varying amplitudes and durations, with range of power thresholds and window lengths.

Report [5] presents an overview of current fast power change (ramp) definitions and state-of-the-art approaches in ramp event forecasting. Multiple ramp definitions are quoted in report and ramp forecasting models are described.

In paper [6] an analysis of time series of load, wind, PV and the resulting net load is presented in scenarios for Europe that allow to quantify flexibility requirements in future power systems with high shares of variable generation in scenarios for Europe that allow to quantify flexibility requirements in future power systems with high shares of variable generation. Ramp properties of wind and PV generation in Europe are described with comparison of expected range of largest wind and solar power ramps on hourly level.

Article [12] and study [13] are focused on assessment of the possibility of the integration of wind power plants specifically into the electric power system of the Republic of Croatia. Since wind power variations affects power system requirements in ancillary services, an assessment of fluctuation in the power output of wind power plants is made. Based on model data an assumption is made of maximum hourly fluctuation on entire expected wind portfolio in the Republic of Croatia.

III. Description of the Method and Input Data

According to [4], the analysis of the frequency of events of fast power change of WPP and SPP, individually and collectively, can be performed according to three described methods:

A. → Fixed-time interval method – the method with constant time intervals

The method with constant time intervals records the change in power between the initial and final power values of a given time interval, which can be bigger or smaller than the given power change value. Due to the simplicity of implementation, the method itself has several disadvantages, such as the occurrence of larger power changes within the observed interval and overlapping positive and negative power changes, where only a change in one direction, either positive or negative, is recorded. In the case when we analyse 15-minute power data of WPP in a time period of 2 hours, the comparison will be made only of the first and last 15-minute intervals. Within the analysed interval there may be larger power changes, but they will not be considered.

B. → Minimum - maximum method - the method of the lowest and highest value

Considering the shortcomings of the previous method, the lowest and highest value method identifies the lowest and highest value in each time interval and thus identifies the most cases with fast power change. In the case when we analyse 15-minute power data of WPP in a time period of 2 hours, we will compare each 15-minute interval and look for the lowest and highest value of all 15-minute intervals in the 2-hour time period.

C. → Explicit derivation method

The method compares each interval with the adjacent interval of a given time period and looks for a power change that is above the given power change value. The method analyses all power values within a given time interval. In the case when we analyse 15-minute power data of WPP in a time period of 2 hours, each 15-minute interval is compared with the next 15-minute interval, and if the power change is greater than the set value, it is recorded as a fast power change event.

Although a fast power change can be easily identified visually, there is no consensus on the accepted formal definition of a fast power change, and it can be characterized according to three features: direction, magnitude and duration [5], [6], [7], [8].

The highest rates of change in WPP power depend on the geographical size of the observed country. In medium-sized and large countries, the maximum hourly change in the WPP power is in the range of 6-10% of the installed WPP capacity, while in smaller countries it is in the range of 11-18%. SPP have a power change equal to or close to 0 for almost half of the hours because they have no production during the night hours, and in most countries the maximum power change at the hourly level is in the range of 18-25% of the installed capacity [9].

For the purposes of this work, the method of explicit derivation was used, with the fact that the distribution of all changes in power will be shown without clearly determining the threshold that would determine the fast power change for the observed time period.

The input data for calculating the power change of WPP and SPP are historical 15-minute data on the production of WPP and SPP for the period from January 1, 2019 to May 1, 2022, from which hourly and two-hourly historical data were obtained. For a shorter time period from March 2, 2022 to June 17, 2022, an analysis of the power change of the WPP was made for one-minute and 5-minute intervals.

IV. Results and Interpretation

As stated in the previous chapter, the paper will analyse the power change based on the method of explicit derivation according to which the power change is equal to the difference between the power in interval i and the power in the previous i-1 interval in relation to the total installed capacity (1).

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

Additionally in chapter 4.B. for the hourly time interval for WPP, a threshold for fast power change was determined (10% of the installed capacity of the WPP), and the quality of forecasting was determined for such a determined fast power change.

A. → Analysis of WPP and SPP power change distribution

Figures 1-3 show the distribution of all changes in WPP power at the 2-hour, hourly and 15-minute levels.

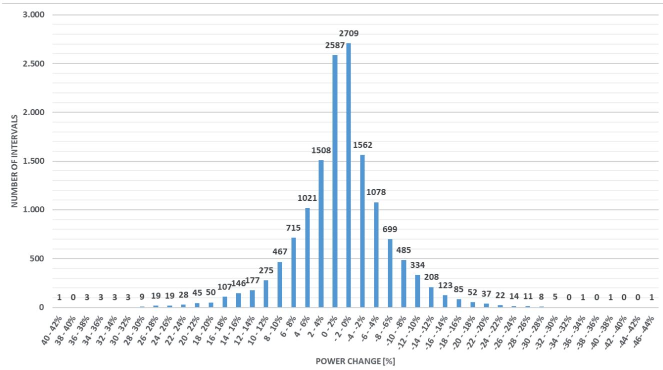

Fig. 1. Distribution of the WPP power change intervals at the 2-hour level

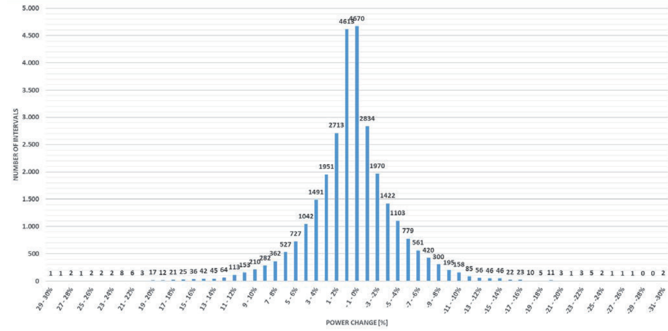

Fig. 2. Distribution of the WPP power change intervals at the hourly level

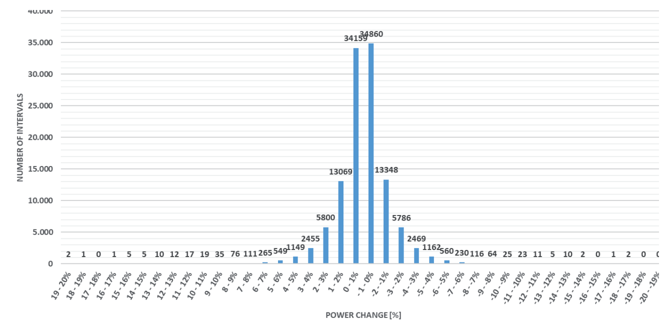

Fig. 3. Distribution of the WPP power change intervals at the 15-minute level

At the 2-hour interval, the largest power increase was recorded in the amount of +40.2% of the installed capacity, and the largest decrease was -45.4%. At the hourly interval, the previously described range is +29.7% and -30.8%, and at the 15-minute level +19.6 and -17.5%. If we compare the results of the research under [9], according to which in smaller countries the maximum WPP power change on an hourly level is in the range of 11-18%, we can conclude that significantly larger power changes occur in the Republic of Croatia than the average. The characteristics of the wind and the concentration of WPP in a relatively small area are the main cause for extremely fast WPP power changes in the Republic of Croatia.

Figure 4 shows the normal distribution of WPP power changes at 2-hour, hourly and 15-minute levels.

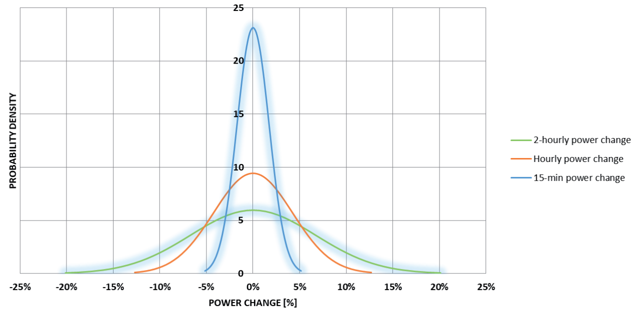

Fig. 4. Comparative presentation of the normal distribution of the WPP power change at the 2-hour, hourly and 15-minute levels

The data in Figure 4 for each time period are in the range 0% +/- 3% standard deviation of all data and include 98.4% of all data, so for a 2-hour period they are in the range +/-20.1%, for an hour period in the range +/-12.7%, and for a 15-min period in the range +/-5.2% of the installed WPP capacity.

Figures 5 and 6 show the distribution of WPP power changes at the minute and 5-minute levels for the period from March 2, 2022 to June 17, 2022.

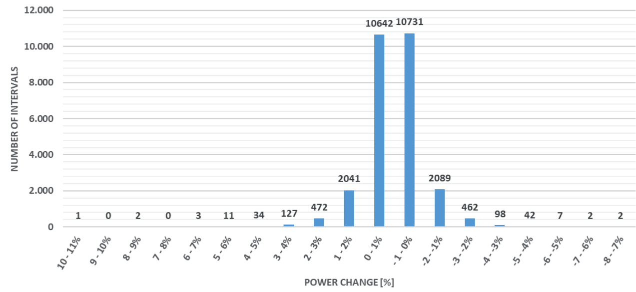

Fig. 5. Distribution of the WPP power change intervals at the 5-minute level

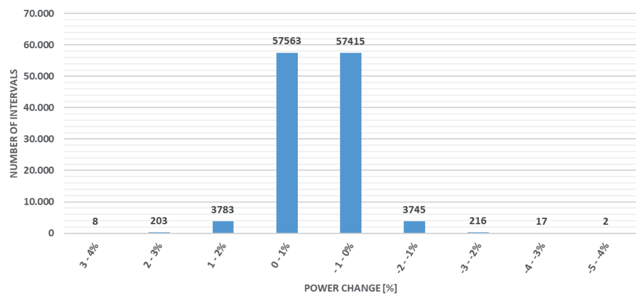

Fig. 6. Distribution of the WPP power change intervals at the 1-minute level

The largest change in WPP power at the 5-minute level is +10.3% and -7.2%, while at the 1-minute level it is in the range of +3.6% and -4.6% of the installed WPP capacity.

Figure 7 shows the distribution of the change in WPP power at the hourly level of more than 10% of the installed WPP capacity within a day.

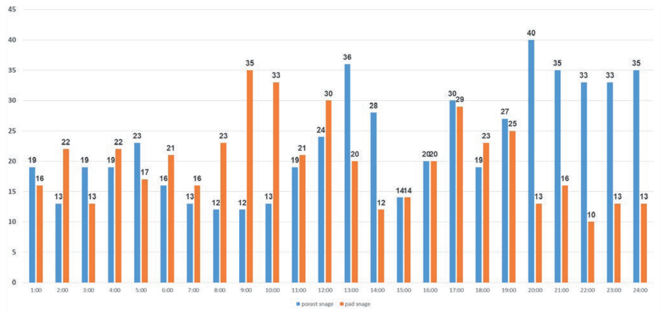

Fig. 7. Distribution of fast WPP power change intervals within a day

It can be seen from Figure 7 that the fast increase in WPP power on an hourly basis is most common towards the end of the day (20:00 to 24:00), while the fast decrease in WPP power is most common in the morning hours (9:00 to 10:00). No analysis was performed for other time levels and thresholds of power increase, but the authors assume that similar results would be obtained. Similar results are shown in paper [10] where fast wind power change in California, USA is analised.

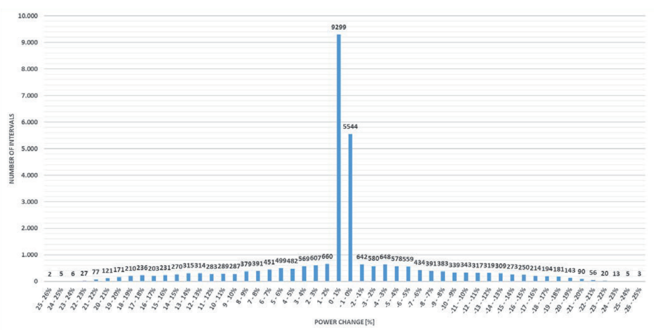

Fig. 8. Distribution of SPP power change intervals at hourly level

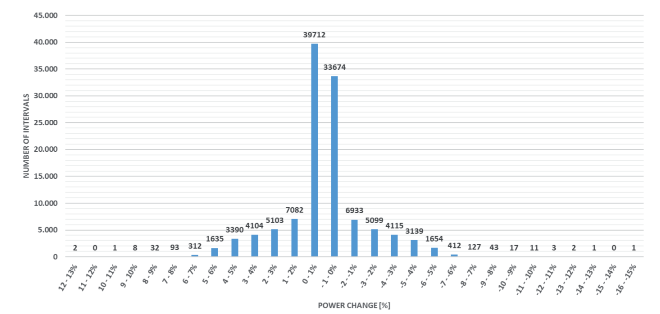

Fig. 9. Distribution of SPP power change intervals at 15-minute level

Figures 8 and 9 show the distribution of all SPP power changes at hourly and 15-minute levels. The largest change in SPP power at the hourly level is +25.1% and -25.9%, while at the 15-minute level it is in the range of +12.3% and -15.6%, of the installed SPP capacity. Compared to the research results under [9], according to which the maximum power change on an hourly level is in the range of 18-25% of the installed capacity, it follows that the maximum power change of SPP in the Republic of Croatia is at the upper limit of the specified range. The paper additionally analysed the distribution of the power change for a hypothetical case according to which the installed SPP capacity in the previous period would have been 13 times higher (increase from 54 to 698 MW), which would have made the installed SPP capacity roughly equal to the WPP capacity. Increased SPP capacity was made in simplified way where existing historical dana was linearly increased in all hours.

Figures 10 and 11 show the distribution of all power changes for the previously described hypothetical case at hourly and 15-minute levels.

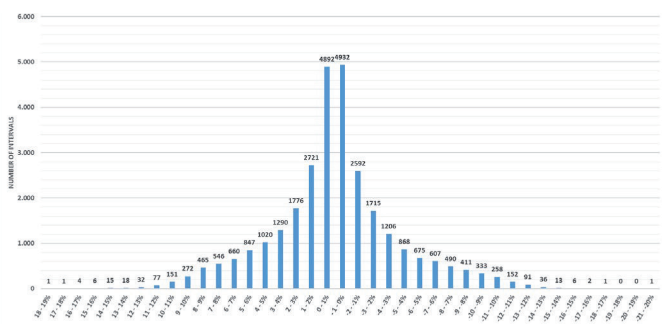

Fig. 10. Distribution of the power change intervals for the hypothetical case of a combination of WPP and SPP at the hourly level

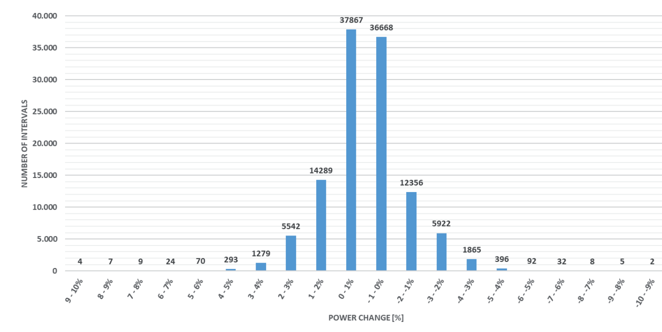

Fig. 11. Distribution of the power change intervals for the hypothetical case of a combination of WPP and SPP at the 15-minute level

The largest change in SPP and WPP power for the specified hypothetical case at the hourly level is +18.0% and -20.9%, while at the 15-minute level it is in the range of +9.8% and -9.0% of the installed SPP and WPP capacity.

B. → WPP forecasts under conditions of fast power change

From January 1, 2019, HROTE plans the production of WPP on the day of delivery in a way that it corrects the WPP production plan made on the previous day for the day of delivery several times a day (hourly). The correction of the WPP forecast is coordinated with the allocation of cross-border transmission capacities, so it is done at least one hour before the delivery hour.

In this chapter, we will analyse the quality of WPP forecasts for a day ahead and on the day of delivery (intraday) in the case of fast WPP power change on an hourly basis. For the purposes of the following analysis, any change greater than 10% of the installed capacity of all WPP will be considered as a fast power change. Table 1 shows the quality of the WPP production forecast with fast power changes on an hourly basis in the period from January 1, 2019 to May 1, 2022.

Table I

WPP Foorecast Quality in Case of Power Change

Change in WPP power	Number of intervals	WPP day-ahead forecast quality MAE [%]	WPP intraday forecast quality MAE [%]	Difference [%]
>0%	14458	5.06%	4.17%	-17.56%
>10% <15%	413	9.12%	8.34%	-8.63%
>15% <20%	111	12.21%	11.48%	-5.97%
>20%	28	14.36%	14.96%	**4.21%**
<0%	14719	4.85%	4.05%	-16.46%
>-10% <-15%	387	7.77%	7.25%	-6.69%
>-15% <-20%	71	9.86%	9.40%	-4.62%
>-20%	19	11.48%	12.65%	**10.25%**

With the increase in power at the hourly level, HROTE achieved a total forecast quality of 5.06% MAE (Mean Absolute Error) for the day ahead, while in the intraday the forecast error was reduced by 17.56%, to 4.17% MAE. In the hourly power drop on the day of delivery, the error was reduced by 16.46%, from 4.85% to 4.05% MAE. With fast power changes (>10% of the installed capacity), significantly worse forecast quality was achieved, and an additional drop in forecast quality was noticeable with faster power changes. With faster power changes, a drop in the quality of forecast corrections on the day of delivery is also noticeable. In contrast to all hours, where the total forecast was improved by 16.46% and 17.56%, significantly lower levels of forecast quality improvement were achieved with fast power changes. With extreme power changes, even worse quality of the WPP forecast was achieved in the intraday than was a day ahead. The reason for the worsening of the forecast in the intraday is that on the day of delivery the forecast is planned at least an hour in advance, which in the conditions of unstable weather resulting in fast power change can be considered a relatively long period for replanning WPP production. If it were possible to plan closer to the delivery time and for shorter balancing periods, it would be possible to improve the quality of the WPP forecast in case of fast power change [11].

V. Application Of Results

This paper presents empirical data on the variability of WPP and SPP production at different time intervals, using the method of explicit derivation. Since the installed power of SPP is significantly smaller than the installed power of WPP in the Republic of Croatia, a hybrid system of WPP + SPP with equal shares was hypothetically set up based on real data. The goal of the mentioned hybrid system is to enable the analysis of the impact of the technological portfolio on the production of electrical energy, i.e. the hybridization of production.

Although many studies on the possibility of integrating variable sources into the Croatian electric power system (EPS) have been made, they are, as a rule, based on model data of WPP (and SPP) operation. This work aims to contribute to the understanding of the characteristics of the operation of WPP and SPP, primarily their real variability based on the operation data of the power plants included in the ECO balance group. That would lead to facilitation of similar future analyses and enabling easier planning of the necessary measures and interventions in the system, with the aim of greater integration of RES in the Republic of Croatia.

VI. Conclusion

The analysis of the actual variations of production from the ECO balance group WPPs (on a representative sample of 712 MW, during about 3.5 years of analysed data), showed that the model assumptions that were used for the analysis of the necessary interventions in the EPS were adequate and well evaluated. By the same token, these assumptions were somewhat conservative since the frequency of real power changes is somewhat lower than the modelled ones. Necessary interventions in the EPS were required due to the greater integration of variable energy sources (please refer to reference: [12], [13]).

The WPP and SPP operation performance shows the following characteristics of technology specific and whole portfolio power variability:

– expected hourly change of WPP power within the interval from -31% to +30% of installed WPP capacity, whereby 99% of hourly variations of WPP power are within the range of -13.8% to +14.8% of installed WPP capacity, while changes greater than ± 10% of the installed capacity (fast changes in WPP power) can be expected in 3.5% of cases;

– expected hourly change of SPP power is within the interval from -26% to +26% of installed SPP capacity, with 99% of hourly variations of SPP power being within the interval of -20.4% to +20.7% of installed SPP capacity;

– the expected hourly change of a hypothetical hybrid system with similar shares of WPP + SPP is smaller, whereby 99% of the hourly power variations of such a system are within the interval from -12% to +11% of the installed WPP + SPP capacity.

Hourly variations of less than ±10% of installed capacity should not be a problem from the production planning and system balancing point of view. However, hourly changes greater than ±10% of the installed capacity (although relatively rare) represent a special challenge. From the point of view of the production forecast, the error in the case of fast and intense power changes of more than ±10% is significantly higher and reaches about 15%. As the room for forecast improvement in small and moderate power changes is limited (the day-ahead error is about 5%, while the forecast error for the day of delivery is close to 4%), future efforts in forecast improvement should be directed precisely in the direction of reducing the error in fast and intense change in power, both in terms of their intensity and in terms of the moment of their appearance. In addition, it was shown that production planning, except in the case of extreme (and very rare) power changes, results in smaller production forecast errors. Therefore, planning closer to the actual delivery time and for shorter balancing periods, would lead to additional benefits for the system operator, who could plan the necessary engagements of the available regulatory measures with greater reliability.

The presented frequency of hourly power variations in case of system hybridization with an equal amount of WPP and SPP, suggests that for some future portfolio (i.e. 3000 MW of WPP and SPP by 2030), 99% of hourly production variations would be within the interval from -360 MW to +330 MW. When looking at 15-minute power variations, empirical data shows that:

— the expected 15-min power change of the WPP is smaller than the expected hourly power change and ranges from -17% to +20% of the installed WPP capacity, with 99% of the 15-min variation of the WPP power within the range of -5.7% to +5.9% of installed WPP capacity, while changes greater than ±10% of installed capacity (fast 15-min changes of WPP power) can be expected in 0.11% of cases;

— the expected 15-min change in SPP power is smaller than the expected hourly power change and ranges from -16% to +13% of the installed SPP capacity, with 99% of the 15-min SPP power variation within the range from -6.1% to +5.8% of installed SPP capacity while changes greater than ±10% of installed capacity (fast 15-min changes of power SPP) can be expected in 0.018% of cases;

— the expected 15-min change of a hypothetical hybrid system with similar proportions of WPP + SPP is within the range of -10% to +10% of the installed WPP + SPP capacity, with 99% of the 15-min power variation of such a system within the interval of -3.9 % to +3.8% of installed WPP + SPP capacity.

As can be seen, in 99% of cases at the 15-min level (at which the required secondary regulation in the system is usually estimated), the production variability is significantly lower than the hourly one, especially in the case of hybridization of WPP and SPP production. However, still in extreme cases the variations can be very large. Therefore, such variations are very rare, and it is justified to think about the introduction of a production limitation measure for WPP and SPP in cases of threatened EPS security.

Additionally, WPP variability on 1-minute and 5-minute time interval. The use of high-frequency data provides a deeper understanding of WPP natural variability and performance [14]. High-frequency data is also needed for minute-scale forecasting of WPP that have application in wind turbine and wind farm control, power grid balancing and energy trading and ancillary services [15].

Finally, it should be noted – although it is not explicitly shown in this paper – that the spatial (geographical) diversification of WPP and SPP, including the construction of production facilities on in the continental part of the Republic of Croatia, has favorable effects on the variability of the entire portfolio of power plants. Since that geographical expansion would lead to different regimes of wind and solar radiation, there would be less simultaneity of production. Therefore, in planning the further development of variable sources such as WPP and SPP, this feature should also be considered.

References

[1] C.L. Archer, M.Z. Jacobson, “Geographical and seasonal variability of the global “practical” wind resources”, 2013.

[2] D.-A. Ciupăgeanu, G. Lăzăroi, L. Barelli, „Wind energy integration: Variability analysis and power system impact assessment“, 2019

[3] X. Yao, B. Yi, Y. Yu, Y. Fan, L. Zhu, „Economic analysis of grid integration of variable solar and wind power with conventional power system“, 2020

[4] L. Bianco, I.V. Djalalova, J. M. Wilczak, J. Cline, S. Calvert, E. Konopleva-Akish, C. Finley, J. Freedman, „A Wind Energy Ramp Tool and Metric for Measuring the Skill of Numerical Weather Prediction Models“, 2016.

[5] C. Ferreira, J. Gama, L. Matias, A. Botterud, J. Wang, „A Survey on Wind Power Ramp Forecasting“, 2010.

[6] A. Bossavy, R. Girard, G. Kariniotakis, “Forecasting Uncertainty Related to Ramps of Wind Power Production”, 2012.

[7] A. Florita, B.-M. Hodge, K. Orwig, “Identifying Wind and Solar Ramping Events”, 2013.

[8] J. W. Zack, S. Young, J. Nocera , J. Aymami, and Vidal J. “Development and testing of an innovative short-term large wind ramp forecasting system”, Proc. European Wind Energy Conf. and Exhibition, Warsaw, Poland, European Wind Energy Association, 2010

[9] M. Hubera, D. Dimkovab, T. Hamacher, „Integration of wind and solar power in Europe: Assessmentof flexibility requirements“, 2014.

[10] C. Kamath, “Understanding Wind Ramp Events through Analysis of Historical Data,” pp. 1–6 in Proceedings of the IEEE PES Transmission and Distribution Conference and Expo, New Orleans, La., 2010

[11] Greaves, B., J. Collins, J. Parkes, and A. Tindal, “Temporal Forecast Uncertainty for Ramp Events,” in Proceedings of the European Wind Energy Conference & Exhibition (EWEC), Marseille, France, 2009

[12] D. Bajs, G. Majstrović, “The feasibility of the integration of wind power plants into the electric power system of the Republic of Croatia”, 2008.

[13] D. Bajs, G. Majstrović, S. Knežević, L. Horvath, D. Jakšić, „Analiza potrebnih tehničkih zahvata i aktivnosti u elektroenergetskom sustavu hrvatske s ciljem preuzimanja većeg udjela proizvodnje planiranih VE“, study, Energetski institut Hrvoje Požar, 2010.

[14] E. Gonzalez, B. Stephen, D. Ineld, J. J. Melero, „On the use of high-frequency [1] SCADA data for improved wind turbine performance monitoring“, J. Phys.: Conf. Ser. 926 012009, 2017.

[15] . Würth, L. Valldecabres, E. Simon, C. Möhrlen, B. Uzunoglu, C. Gilbert, G. Giebel, D. Schlipf, A. Kaifel, „Minute-Scale Forecasting ofWind Power—Results from the CollaborativeWorkshop of IEAWind Task 32 and 36“, MDPI, 2019.