A Methodological Approach for Scenario Modeling of the Integrated Wind, Solar, And Small Hydro Power Output to Cost-Effectively Meet the Peak Power Demand in Power Systems

N.R. Rakhmanov[1], G.B. Guliyev[2,*], F.Sh. Ibragimov[2]

[1] Azerbaijan Energy Research and Engineering Design Institute, Baku, Azerbaijan
[2] Azerbaijan Technical University, Baku, Azerbaijan

***Abstract* — This study contributes a methodological framework for identification of a holistic model of power output by multiple renewable power plants integrated into a power system at locations with distinct meteorological and geographical conditions. The scenarios generated based on individual predictions relying on $k-$medoids clustering demonstrate better capturing of the variable nature of the total output from multiple renewable power plants. A case study of the integration of several renewable power plants into a power system is presented to show that the direct prediction of the total output by these green sources proves effective in cutting operational costs of the system, mostly by better serving the peak load demand. The methodological framework proposed in this paper can be used for online management of power systems with several different renewable power plants such as solar power plants, wind farms, and small hydropower plants. This approach also enables the estimation of the contribution of each source to the overall output.**

***Index Terms* — Power system, renewable energy sources, serving electricity demand, online management, load profile, aggregation of renewable power plants.**

* Corresponding author.
E-mail: huseyngulu@mail.ru

DOI: 10.25729/esr.2025.03.0002

Received August 20, 2025. Accepted August 25, 2025. Available online November 28, 2025.

I. Introduction

The drastically increased penetration of renewables is a key factor defining the process of transformation of the power sector. Over the last four decades, the total output of electricity in the world has increased by more than 25% and the global installed capacity of power plants running on renewables reached as much as 3 870 GW in 2023. In 2024, renewables accounted for over 90% of new capacity additions that total about 585 GW [1].

Among all renewables integrated into power systems around the world, wind farms (WF), solar power plants (SPP), and hydropower plants lead in renewable energy production. In 2024, the installed capacity of PV plants was at 1 900 GW, surpassing the capacity of nuclear power plants by a factor of 5 [2]; and that of wind farms reached over 1 000 GW [3]. Unlike conventional electricity sources, wind farms, solar power plants, and small hydropower plants (sHPP) are usually sited in the areas with 'critical' meteorological conditions where winds and solar radiation persist for extended periods of time, thus ensuring the availability of renewable energy potential in these locations. Power output of sHPP, WF, and SPP is indeterminate and stochastic as it depends on meteorological conditions in the areas of their installation. In order to offset the random fluctuations in the power system induced by intermittent renewable generation, the system is provided with an additional source of energy. The choice of the additional source depends on technical and economic capabilities of the system as well as meteorological conditions in given areas [4–7]. Stable and efficient operation of power systems with integrated WF, SPP, and sHPP requires an in-depth analysis of intermittent power generation by these plants. This analysis should be complemented by forecasting models that reflect the current time and factor in meteorological data.

The findings from the scenario analysis of complementarity of wind farms and solar power plants and their use to serve the demand in the power system parts that lack renewable generation are presented in [10–15]. Spatial and temporal changes in climate variables are examined in [16, 17] to prove that the ability to meet the demand in a power system with wind farms and solar power plants can be enhanced by the additional output resulting from complementarity of such plants located in the areas with diverse geographical and climate conditions. The studies [18–20] rely on correlation analysis of different geographical areas with operating wind farms and solar power plants to establish that in areas with higher penetration of wind power than in other areas with lesser penetration of renewables, adding solar power can help meet the demand and offset its intermittency [20–24].

This study presents a methodological framework for identification of scenarios of joint generation for intermittent renewable energy sources placed in the areas with different geographical and weather conditions.

II. Method for Identifying Scenarios of Combined Power Generation in Individual Power System Parts with Wind Farms, Solar Power Plants, and Small Hydropower Plants

A. Cluster Analysis of Changes in the Output of Wind Farms and Solar PV Power Plants Given Meteorological Conditions of Areas and Their Integration

At its core, the identification of aggregated generation relies on cluster analysis of stochastic processes governing intermittent output of wind farms, solar power plants, and hydropower plants to extract clusters with identical parameters that meet some specified criteria.

Establishing relationships for the aggregated power output from wind farms, solar power plants, and hydropower plants connected to the power system in its different areas enables the identification of key defining features of models of such relationships. This approach filters out the effects of individual areas with integrated renewable power plants and groups the points of the power grid topology exhibiting similar patterns of power generation.

Identification of scenarios of combined power output from power plants running on renewable energy is a key step in assessing prospective capacity additions of wind farms, solar power plants, and hydropower plants in the power system during the planning horizon. Cluster analysis proves effective in terms of precision and detail in capturing data on intermittency of renewable energy potential and weather conditions in geographical areas.

This study leverages *k*-medoid clustering to identify patterns in power output of wind farms, solar power plants, and hydropower plants installed in the power system. The *k*-medoid clustering model can have the following form [19]:

$$D = \arg\min \left\{ \sum_{k=1}^{k} \sum_{n=1}^{k} \left(\left\| x_n - C_k \right\|^2 \right) \right\}, \tag{1}$$

$$x_n = \begin{vmatrix} w_{1,1} & w_{1,2} & \cdots & w_{1,i} \\ w_{2,1} & w_{2,2} & \cdots & w_{2,i} \\ \vdots & & & \\ w_{n,1} & w_{n,2} & \cdots & w_{n,i} \end{vmatrix}, \tag{2}$$

where D is the distance between the current values of hourly changes and the medoid of each cluster; C_k is the *k*-th cluster medoid; n is he number of measured parameters; $w_{n,i}$ is power outputs of renewable power plants, power system loads, wind speed, solar radiation, ambient temperature, etc. to be grouped into *k*-clusters $(k < n)$; i is the number of renewable power plants. The clustering algorithm is applied separately to each renewable power plant and the entire area with installed wind farms, solar power plants, and hydropower plants.

B. Algorithm for Choosing the Scenarios of the Most Cost-Effective Capacity Additions of Wind Farms and Solar Power Plants to Meet the Expected Demand Growth in the Power System

The optimization technique applied makes use of linear objective functions to evaluate possible expansion scenarios for wind farm, solar power plant, and hydropower plant capacities installed before 2024. The algorithm that relies on the above method proves exceptionally useful because it is simpler than its alternatives based on heuristic search techniques. The function of demand variability is treated as the “net” load N_{net} (the total demand less the total output by all renewable power plants). The subsequent period of the N_{net} increase by ΔN_{net} implies the expansion of wind

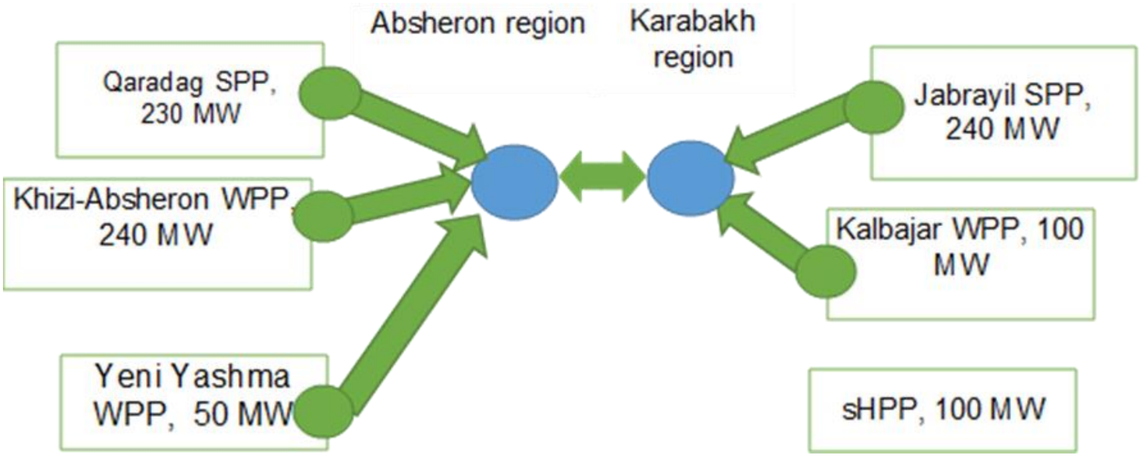


Fig. 1. Overall layout of operating intermittent renewable sources located in two regions of Azerbaijan.

farms, solar power plants, and hydropower plants during the same period combined so as to optimally serve the demand for ΔN_{net}. The objective functions utilized to identify scenarios of expansion for renewable power plants installed in the power system are as follows:

1. The minimum mean square error of the random variable of annual change in the net load (NS_{demand})

$$SO(z) \to \min . \quad (3)$$

2. The minimum mean square error of the net load by hour during the year:

$$SO(z) = \sqrt{\frac{\sum_{t=1}^{T}\left(z(t)-\overline{z}\right)^2}{T-1}} \to \min \ \forall t , \quad (4)$$

where $z(t) = N_{net}(t_{hour})$ is changes in the net load by hour during a single year; $T = 8760$ h; $\overline{z}$ is the average hourly change in load by hour during a single year. Minimization of functions (3) and (4) has the following solutions:

$$z(t_{year}) = N_{net}(t_{year}) \ \forall t_{year} \quad (5)$$

and

$$z(t_{hour}) = N_{net}(t_h) - N_{net}(t_{h-1}) \ \forall t_h . \quad (6)$$

Solutions (5) and (6) meet the constraints on the annual power output of renewable energy plants up to 30% of demand (under the assumption that by 2030 wind farms and solar power plants will serve up to 30% of demand in Azerbaijan's power system):

$$30\left\{\sum_t \frac{P_{(WF+SPP+HPP)}(t)}{N_{net}(t_h)}\right\} \le N_{net\max} \quad (7)$$

subject to

$$N_{net}(t) = P_{demand}(t) - \left(P_{WF}(t) + P_{SPP}(t) + P_{HPP}(t)\right) \forall t , \quad (8)$$

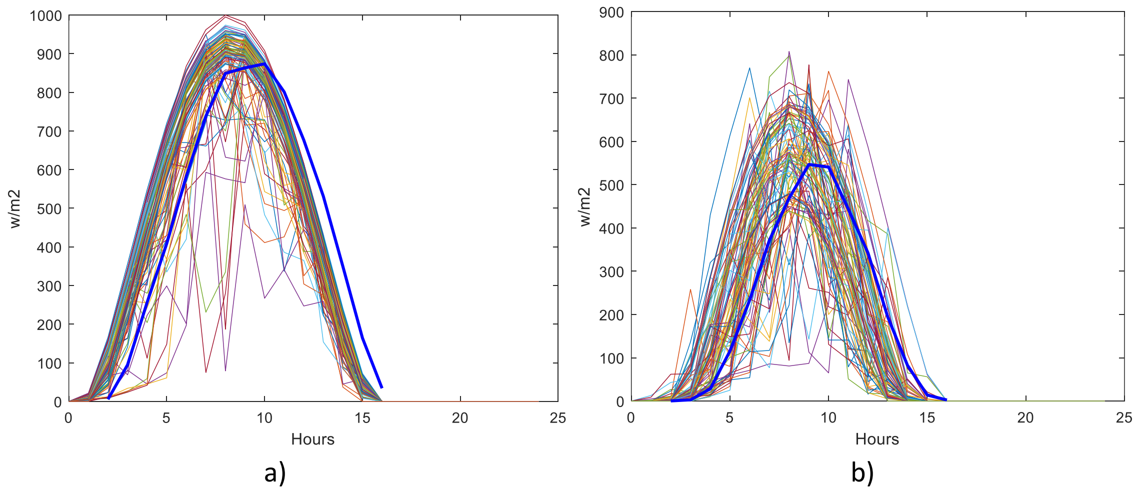


Fig. 2. Clusters of solar radiation in the regions of Absheron (a) and Karabakh (b).

$$P_{WF}(t)+P_{SPP}(t)=\sum_{R}\sum_{it}N_{WF}(it,r_{W})P_{WF}(t,r_{WF})+ +\sum_{r_{SPP}}\sum_{it}N_{SPP}(it,r_{SPP})P_{SPP}(t,r_{SPP})+ +\sum_{r_{HPP}}\sum_{it}N_{HPP}(it,r_{HPP})P_{HPP}(t,r_{HPP}), \forall t,\forall it,\forall r_{WF},\forall r_{SPP}\ , \tag{9}$$

$$VRE_{surplus}(t)=\begin{cases}VRE(t)-S_{demand}(t), & VRE(t)>S_{demand}(t),\\ 0, & VRE(t)\le S_{demand}(t),\end{cases}\ , \tag{10}$$

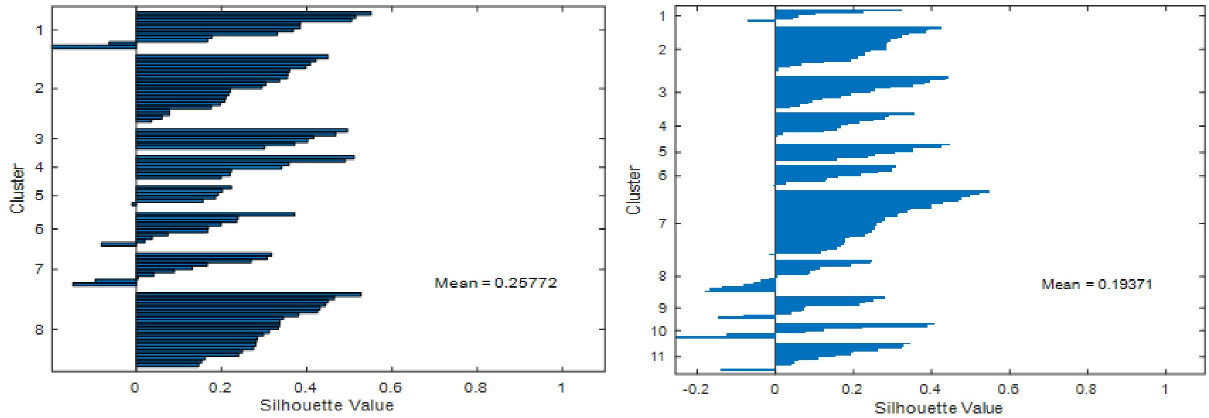
$$z, NL, VRE, VRE_{surplus,}\ N_{WF},\ N_{SPP}, N_{HPP}\in NR, \tag{11}$$

where $t\in[t_1,t_2,...,t_{8760}]$ represents indices of the hourly power output from renewables by time; $it\in[it_1,it_2,...,it_m]$ is the number of renewable energy units at power plants; $r_{SPP}\in[r_{SPP1},r_{SPP2},...,r_{SPPM}]$, $r_{WF}\in[r_{WF1},r_{WF2},...,r_{WFN}]$, and $r_{HPP}\in[r_{HPP1},r_{HPP2},...,r_{HPPK}]$ are the number of areas with installed renewable power plants. $VRE_{surplus}$ is surplus output of renewable power plants; $P_{WF}(t)$, $P_{SPP}(t)$, and $P_{HPP}(t)$ stand for hourly generation from wind farms, solar PV power plants, and hydropower plants. In equations (7)–(11), N_{WF} and N_{SPP} are the number of wind farms and solar power plants as determined by the optimization algorithm for wind and solar power output models.

III. Scenario Analysis of Combined Power Output of Wind Farms and Solar Power Plants for Supply and Demand Planning

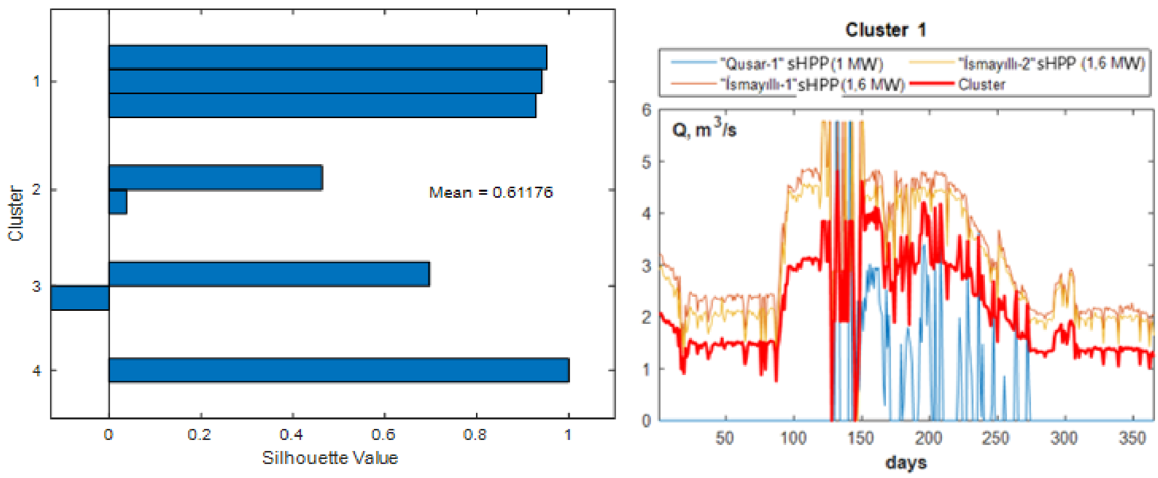
A. Key Data on Meteorological Conditions and Power Output of Wind Farms, Solar Power Plants, and Hydropower Plants in Individual Regions

The installed capacity of the Azerenergy system is about 7.5 GW, the largest share of which comes from gas turbine



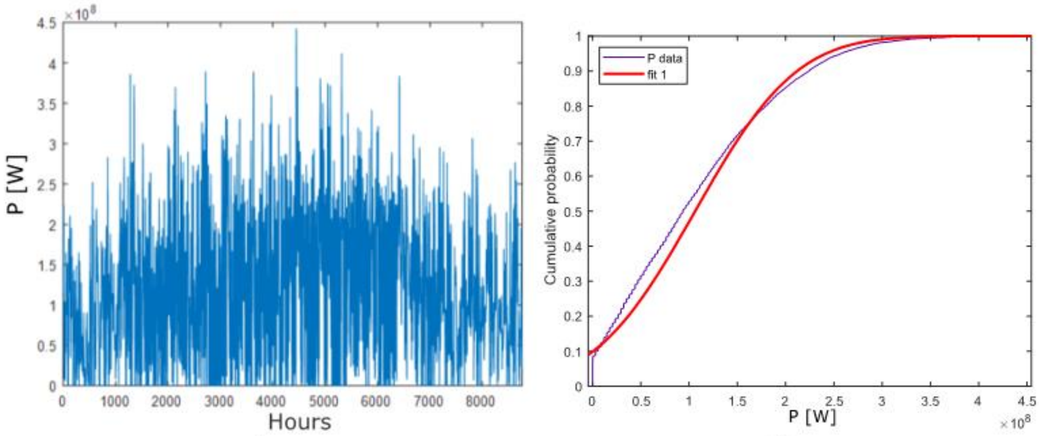
a) b)

Fig. 3. Silhouette values of optimal numbers for clusters of wind speeds: (a) for the 1st cluster of radiation and loads; (b) for the 2nd cluster of radiation and loads.



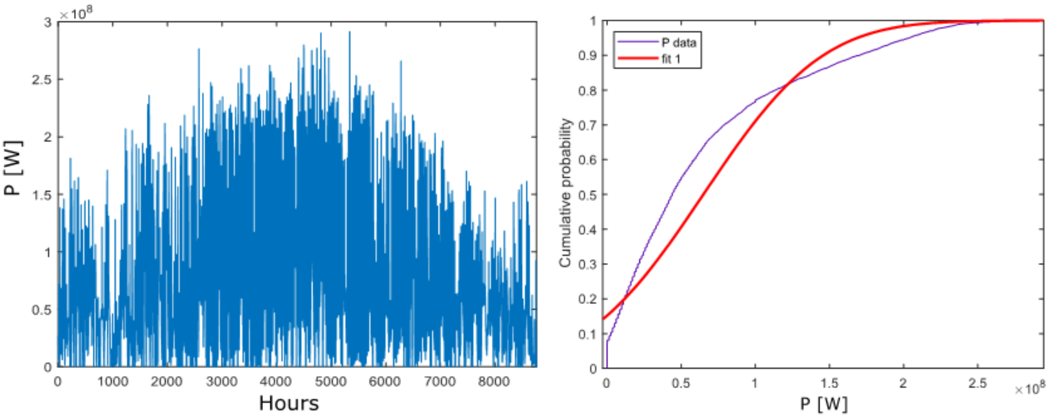
a) b)

Fig. 4. Clustering by the total annual water flow rate (a) and flow rates for individual sHPPs (b).



a) b)

Fig. 5. Annual power output of SPP-WF in the Absheron region (a) and probability of distribution of the annual power output (b).



a) b)

Fig. 6. Annual power output of SPP-WF-sHPP in the Karabakh region (a) and probability of annual power output (b).

thermal power plants (about 5.6 GW), followed by hydropower plants (1.4 GW). Wind farms, solar power plants, and small hydropower plants combined contribute 0.5 GW. In 2004, renewable power plants generated 850 mln kWh, of which 6% was generated by wind farms, 67% – by solar power plants, and 27% – by small hydropower plants. Wind and solar power potential is primarily concentrated in two major geographical and economic regions of the country: the Absheron region (including the coastal areas of the Caspian Sea) and the Eastern Zangezur region (including the Karabakh region). This is the reason for the placement of wind farms, solar power plants, and hydropower plants in those regions. Figure 1 shows the overall layout of wind farms and solar power plants in the regions of Absheron and Karabakh. As of 2023, there were two wind farms operating in the Absheron region, including the 240 MW Khizi-Absheron wind farm and the 50 MW Yeni-Yashma wind farm. The Karabakh renewable power plants connected to the power grid include the 240 MW Jabrayil SPP, 100 MW Kalbajar wind farm, and sHPPs with a total capacity of 170 MW.

B. Clustering of Power Output from Renewable Power Plants in the Region Given Meteorological Conditions

Figure 2 shows clusters of solar radiation in the regions. Solar irradiance in the regions makes it possible to generate electric power by solar power plants for most of the day.

The silhouettes in Fig. 3 and 4 show the number of significant clusters of wind and hydro power with the corresponding clusters of system loads.

IV. Results From the Analysis of Scenarios of Combined Power Output from Green Renewable Sources Located in the Areas with Distinct Meteorological and Climate Conditions

The cluster analysis was performed to identify common scenarios of power output in each region as well as cross-regional interactions. The analysis relied on hourly measurements of demand in the power grid and meteorological data. The meteorological data (wind speed, solar radiation, and ambient temperature) were collected hourly during a single year in two regions (see. Fig. 1) with installed renewables.

Figures 5 and 6 show, respectively, the power output and probability of its distribution among wind farms, solar power plants, and hydropower plants located in the Absheron and Karabakh regions in 2024.

The mean-square error of the power output of wind farms is derived from wind power potential. The wind farm output is a key factor to decide on the feasibility of complementarity of wind farms in the region.

V. Conclusion

1. This study proposes a clustering-based algorithm for identification of power output scenarios for wind farms, solar power plants, and hydropower plants that operate within the power system in the areas with distinct climate conditions. An algorithm designed to detect patterns in the power output scenarios of renewable power plants located in different regions of the country is presented.

2. The cluster analysis of data was performed to identify spatial and temporal variability in the power output of wind farms, solar power plants, and hydropower plants in the Azerbaijan power system. The analysis revealed two regions with different wind and solar power profiles as well as availability of hydropower resources. These profiles were utilized to investigate different scenarios of new capacity additions of renewable power plants for operation as part of the power system.

3. The findings suggest that the highest penetration of renewables (in terms of the annual consumption) is achieved when the outputs of wind farms and solar power plants complement each other. Under the WF+SPP scenario, a sustainable way to raise the penetration of renewables up to 30%, given the annual surplus output of 5 to 10% (relative to consumption), is to increase the capacity of solar power plants and small hydropower plants.

References

[1] Renewable Capacity Statistics 2024. IRENA (International Renewable Energy Agency). [Online]. Available: https://www.irena.org/Publications/2024/Mar/Renewable-Capacity-Statistics-2024. Accessed on: Oct. 3, 2025.

[2] Global Solar Power Generation. The Global Energy Association. Available: https://globalenergyprize.org. Accessed on: Oct. 3, 2025.

[3] WWEA Annual Report 2023: Record Year for Windpower. [Online]. Available: https://wwindea.org/AnnualReport2023. Accessed on: Oct. 3, 2025.

[4] P. V. Ilyushin, A. V. Pazderin, "Requirements for power stations islanding automation," in Proc. the 2018 International Conference on Industrial Engineering, Applications and Manufacturing (ICIEAM), 15–18 May 2018, Moscow, Russia, 2018.

[5] K. Guerra, P. Haro, R. E. Gutierrez, A. Gomez-Borea, "Facing the high share of variable renewable energy in the power system: Flexibility and stability requirements," Journal of Applied Energy, vol. 310, Art. no. 118561, 2022.

[6] H. Chandler, Harnessing variable renewables: A guide to the balancing challenge. Paris, France: International Energy Agency, 2011.

[7] P. V. Ilyushin, O. V. Shepovalova, S. P. Filippov, A. A. Nekrasov, "The effect of complex load on the reliable operation of solar photovoltaic and wind power stations integrated into energy systems and into off-grid energy areas," Energy Reports, vol. 8, pp. 1515–1529, 2022.

[8] A. M. Hashimov, N. R. Rahmanov, A. Z. Mahmudova, J. M. B. Morillo, "Assessment of Probability Distribution Sequence for Voltage Stability in a Power system with Large Share Integration of Variable Renewable Sources," International Journal on Technical and Physical Problems of Engineering (IJTPE), iss. 55, vol. 15, no. 2, pp. 291–296, 2023.

[9] V. A. Stennikov, V. G. Kurbatsky, N. R. Rahmanov, G. B. Guliyev, V. A. Shakirov, Regional Aspects of Wind Power. Irkutsk, Russia: Melentiev Energy Systems Institute SB RAS, 2020. (In Russian)

[10] N. Rahmanov, H. B. Guliyev, F. Sh. Ibrahimov, Z. A. Mammadov, "Determination of optimal dimensions of hybrid AC/DC distributed generation system with renewable sources for autonomous power supply of remote locations," in Proc. the Rudenko International Conference on Methodological Problems in Reliability Study of Large Energy Systems (RSES 2024), vol. 584, 2024.

[11] G. Niu, Y. Ji, Z. Zhang, W. Wang, J. Chen, P. Yu, "Clustering analysis of typical scenarios of island supply system by using cohesive hierarchical clustering-based K-Means clustering method," Energy Reports, vol. 7, suppl. 6, pp. 250–256, 2021.

[12] A. L. Kulikov, O. V. Shepovalova, P. V. Ilyushin, S. P. Filippov, S. V. Chirkov, "Control of electric power quality indicators in distribution networks comprising a high share of solar photovoltaic and wind power stations," Energy Reports, vol. 8. pp. 1501–1514, 2022.

[13] A. Buttler, F. Dinkel, S. Franz, H. Spliethoff, "Variability of wind and solar power – An assessment of the current situation in the European Union based on the year 2014," Energy, vol. 106, pp. 147–161, 2016.

[14] S. Han, L. Zhang, Y. Liu, H. Zhang, J. Yan, L. Li, X. Lei, X. Wang, "Quantitative evaluation method for the complementarity of wind-solar-hydro power and optimization of wind-solar ratio," Appl. Energy, vol. 236, pp. 973–984, 2019.

[15] K. Engeland, M. Borga, J.-D. Creutin, B. Francois, M.-H. Ramos, J.-P. Vidal, “Space–time variability of climate variables and intermittent renewably electricity production. A review,” Renew. Sustain. Energy Rev., vol. 79, pp. 600–617, 2017.

[16] G. Ren, J. Wan, D. Yu, “Spatial and temporal assessments of complementarity for renewable energy resources in China,” Energy, vol. 177, pp. 262–275, 2019.

[17] P. E. Bett, H. E. Thornton, “The climatological relationships between wind and solar energy supply in Britain,” Renew. Energy, vol. 87, pp. 96–110, 2016.

[18] J. Peter, “How does climate change affect electricity system planning and optimal allocation of variable renewable energy,” Appl. Energy, vol. 252, Art. no. 113397, 2019.

[19] N. R. Rakhmanov, V. G. Kurbatsky, H. B. Guliyev, N. V. Tomin, R. N. Rakhmanov, “Analysis and modeling of harmonic distortions in consumer's distribution networks, containing a powerful non-linear load,” E3S Web of Conf., vol. 58, Art. no. 03015, 2018.

[20] A. M. Hashimov, H. B. Guliyev, A. R. Babayeva, “Shunt reactors control algorithm using fuzzy sets theory,” International Journal on Technical and physical problems of engineering (IJTPE), iss. 38, vol. 11, no. 1, pp. 10–15, 2019.

[21] A. M. Hashimov, N. M. Rahmanov, N. M. Tabatabaei, H. B. Guliyev, F. Sh. Ibrahimov, “Probabilistic evaluation of voltage stability limit of power system under the conditions of accidental emergency outages of lines and generators,” International Journal on Technical and physical problems of engineering (IJTPE), iss. 43, vol. 12, no. 2, pp. 40–45, 2020.

[22] N. R. Rahmanov, V. G. Kurbatskiy, H. B. Guliyev, N. V. Tomin, Z. Mammadov, “Probabilistic assessment of power system mode with a varying degree of wind sources integration,” E3S Web of Conf., vol. 25, Art. no. 02003, 2017.

[23] A. Rylov, P. Ilyushin, A. Kulikov, K. Suslov, “Testing Photovoltaic Power Plants for Participation in General Primary Frequency Control under Various Topology and Operating Conditions,” Energies, vol. 14, no. 16, Art. no. 5179, 2021.

[24] P. V. Ilyushin, A. L. Kulikov, S. P. Filippov, “Adaptive algorithm for automated undervoltage protection of industrial power districts with distributed generation facilities,” in Proc. the 2019 International Russian Automation Conference, RusAutoCon, 08–14 Sep. 2019, Sochi, Russia, 2019.

Nariman R. Rahmanov, D. Sc. in Engineering, Professor, currently heads the Department of Modern Challenges in the Energy Sector and Artificial Intelligence at the Scientific-Research and Design-Prospecting Power Engineering Institute. He also holds the position of Chief Researcher at the Institute of Physics under the Ministry of Science and Education of the Republic of Azerbaijan. N. R. Rahmanov is a Deputy Editor-in-Chief of the Power Engineering Problems Journal. His research interests include long-term sustainable development of the power sector, operational management of power systems, hybrid systems with renewable energy sources, distributed power systems, microsystems, data analysis, and artificial intelligence. N. R. Rahmanov has authored 290 research papers.

Huseyngulu B. Guliyev, D. Sc. in Engineering, Professor at the Department of Mechatronics, currently serves as the Dean of the Department of Energy and Automation at Azerbaijan Technical University. His research interests include power system operation and control, distributed generation systems, artificial intelligence applications in power system control design, power system stability, renewable energy integration, power quality. H. B. Guliyev has authored 310 research papers and a monograph, while also holding 3 patents.

Famil Sh. Ibrahimov, B. Sc. and M.Sc. in Engineering, is currently a Junior Researcher at the Institute of Cyberphysical Systems and Cybersecurity of Azerbaijan Technical University. His research interests include analysis and control of steady states of electrical systems, modern relay protection systems of electrical networks, and fuzzy logic applications in power engineering. F. Sh. Ibrahimov holds 1 patent and is an author of 60 research papers.