

METHODOLOGY FOR DETERMINING TYPICAL SCENARIOS OF TOTAL ELECTRICITY GENERATION BY GREEN SOURCES REDUCING THE RISK OF DISRUPTION OF BALANCE RELIABILITY

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Abstract

The article proposes a methodology for identifying scenarios for aggregate electricity generation by renewable sources, such as wind and solar power plants, located in geographically diverse regions of the area with different climatic and weather conditions. To cover the demand of electric power systems, it is rational to use these green sources with complementarity from generation when planning load modes, as well as to reduce the risk of balance reliability of power systems. To determine the scenarios of aggregate generation of the used green sources, a cluster analysis is used based on the clustering of medoids using real-time measurements of wind speed, solar radiation and ambient temperature performed for all regions of the considered area where all green sources of electricity in the form of wind and solar power plants are installed. Clusters of these sources and loads are established separately and jointly. For each scenario of generation and planned growth in demand of the power system, the volume of additional capacity of green sources is estimated. The proposed methodology was tested on the example of the power system of Azerbaijan. The study found that, in order to reduce the risk of disruption to the system's balance reliability, scenarios of combined generation from wind farms located in the northern regions adjacent to the Caspian Sea with electricity generation from solar farms located in the southwestern regions of the country provide a more reliable way to increase the share of wind and solar generation in covering the planned demand growth compared to scenarios based on the separate use of these green energy sources.

Keywords: renewable energy sources, wind (WPP) and solar power plants (SPP), power generation by variable renewable sources (VRES), stochasticity of green energy generation, cluster analysis, scenarios of the process of generating green sources, the risk of violation of balance reliability

I. Introduction

One of the important factors determining the process of transformation of the electric power industry is the significant growth of the share of renewable energy sources. Over the past 40 years, the total electricity generation in the world has grown by more than 25%, including the global installed capacity of power plants operating on renewable energy sources (RES), which reached 3870 GW by 2023 [1]. Currently, RES accounts for 90% of new energy capacity with an increase in capacity of about 473 GW.

Among the renewable energy sources integrated into the energy systems of countries around the world, wind and solar power plants produce the largest share of renewable energy with corresponding installed capacity values for 2024 – 1900 GW (the capacity of photovoltaic power plants, which exceeds the capacity of nuclear power plants by 5 times [2]; the capacity of wind power plants is more than 1000 GW [3].

Unlike traditional sources of electric energy, wind and solar power plants are usually located in regions with “critical” meteorological conditions, in which wind and solar radiation have long periods of time, which ensures the presence of renewable energy potential in these regions. The generation of electric power at wind and solar power plants has a randomly uncertain nature and depends on the meteorological conditions of the region of their location. In order to compensate for random changes in the power system from the generation of variable renewable energy sources (RES), an additional energy source is installed in the system. At present, traditional power plants or a system of electric energy batteries are used as sources supporting the power system with backup generation during periods of reduced RES power generation. The choice of the type of additional source depends on a number of technical and economic capabilities of the system, as well as on the meteorological conditions of the regions [4-6].

Sustainable and efficient operation of a power system with integrated wind and solar power plants requires a deep analysis of the variability of power generation by these stations, modeling their forecasting for current periods of time and taking into account meteorological data [7, 8]. Research shows that with the growth of the share of power generation, the problem of cooperation of the power of these stations in order to cover the demand in the energy system during planning and operational management becomes increasingly urgent.

The works [9-14] present the results of a study of scenario analysis of the complementarity of wind and solar power plants, and their application to cover demand in parts of the energy system with deficiencies in renewable generation.

In [15,16] the studies of spatial and temporal changes of climatic variables were conducted, which show that demand coverage in the energy system with wind and solar power plants can be improved by additional generation from the complementarity of these plants located in regions with different geographic and climatic conditions. In [17, 18] based on the analysis of correlation dependencies between regions with wind and solar power plants it was established that in a region with a predominant share of wind generation in relation to other regions with the lowest share of renewable generation, compensation for the variability of which provides an additional opportunity to cover demand load due to the introduction of solar generation.

Identifying patterns of generation deviations between renewable stations in individual regions would improve the quality of planning and operational dispatch control when covering the demand of the power system [19-21].

The paper proposes a methodology for identifying scenarios for cooperative generation of variable renewable sources located in regions with different geographic and weather conditions. Based on hourly changes in wind speed, solar radiation, air temperature and other parameters related to weather conditions, a cluster analysis of scenarios for regions with integrated wind and

solar power plants was performed, and scenarios for aggregated generation between regions were identified. The following scenarios for the development of the energy balance in regions involving variable renewable energy sources are considered and compared: only wind energy sources; only solar photovoltaic sources; additions of wind and solar energy. For each scenario, the characteristics of additional capacity, typical daily profiles, extreme values, as well as excess / deficit of RES energy are estimated.

II. Method for Identifying Green Co-Generation Scenarios

The problem of assessing the risk of violation of balance reliability and determining the “additional” generated capacity from green sources located in a region with a current excess of capacity to the capacity generated by a renewable source located in another region of the power system with a capacity deficit for the same period of time is considered. The proposed method is based on cluster analysis using k -medoid clustering. In accordance with the medoid clustering method, the possible capacity of primary wind and solar resources and the demand for electricity are determined when planning the development of the power system (from the point of view of planning the generation of renewable energy sources to cover future demand). For each scenario of power system development, the characteristics of additional capacity for a typical daily load schedule, extreme values and energy deficit are estimated.

2.1. Cluster Analysis of Changes in Generation from Green Sources Taking into Account Meteorological Conditions of the Regions of their Integration into the Energy System

The essence of the identification of aggregated generation is to use cluster analysis to identify clusters with identical parameters that satisfy certain accepted criteria from stochastic processes of variability generated by wind and solar power plants.

Building dependencies of wind and solar power plants connected to the power system diagram in its different regions allows us to determine the main features of the models describing these dependencies. Using this approach, it is possible to filter out the effects of individual locations with an integrated renewable power plant and group locations of the power system electrical network diagram with similar behavior of electricity production [22].

Identification of scenarios of aggregated power generation by renewable power plants is a key step to determine the possibilities of their expansion of installed wind and solar power plants in the energy system for the planned period. The use of cluster analysis is effective in terms of accuracy and detail of display of data describing the processes of variability of renewable energy potential and weather conditions in the regions [23-25,8,11].

Cluster analysis is a classical methodology for analyzing process state observation data based on their representation as a set of clusters in such a way that the elements of a cluster are always similar (in some sense) to each other than to the elements of other groups [24]. This step can be used to discover statistical patterns in the data, which can often be associated with different physical processes.

In this paper, the patterns of power generation by wind and solar power plants installed in the power system can be identified using the k -medoid clustering method. The k -medoid clustering model can be described as [24]:

$$D = \operatorname{argmin} \left\{ \sum_{k=1}^k \sum_{n=1}^k \left(\|x_n - C_k\|^2 \right) \right\} \quad (1)$$

$$x_n = \begin{pmatrix} w_{1,1}w_{1,2}, \dots, w_{1,i} \\ w_{2,1}w_{2,2}, \dots, w_{2,i} \\ w_{n,1}w_{n,2}, \dots, w_{n,i} \end{pmatrix} \quad (2)$$

where D – distance between current hourly change values and the medoid of each cluster; C_k – cluster medoid of k –th cluster; n –the number of measured parameters (the values of power generation from renewable energy plants, the power load of the power plant, wind speed, solar radiation, ambient temperatures, etc.) that should be grouped into k – clusters ($k < n$); i – number of renewable stations.

The clustering algorithm is applied separately for each renewable power plant and the region as a whole with installed wind and solar power plants. Despite the subjectivity in the exact definition of cluster centers, this methodology provides a consistent classification for most data. The k –medoid clustering method is a non-hierarchical clustering algorithm and is designed to group data into k –clusters, where is " k " predetermined. The optimal value of the number of clusters can be determined by the criterion proposed in [25-27]. This criterion allows determining the appropriate number of clusters by calculating the Euclidean distance between clusters and comparing the internal sum of squared errors of each cluster. Further, the samples of power generation by renewable power plants obtained using this method are designated for wind power plants (WPP) and, respectively, for solar power plants (SPP).

2.2. Algorithm for Selecting Scenarios for the Most Profitable Expansion of Green Power Plants to Cover the Planned Growth in Demand and Reduce Risk in the Energy System

The paper examines the problem of planning the expansion of the installed capacity of renewable sources for the next 10 years (until 2035) using the Azerbaijan energy system as an example. The total installed capacity of the energy system is 7.5 GW, including the total generation from all types of renewable sources of 1.2 GW.

To assess possible scenarios for expanding the installed capacity of wind and solar power plants by 2024, an optimization method using linear objective functions was used [25]. The implementation of the algorithm based on this method is particularly useful due to its simplicity compared to other algorithms based on the principles of heuristic search. The function describing the process of demand variability is considered as a "net" load N_{net} (specified as the difference between the total demand minus the total generation by all renewable power plants). The subsequent period of N_{net} growth by ΔN_{net} assumes the development of wind and solar power plants over the same period in such a combination that the demand coverage for ΔN_{net} is optimal.

To determine the expansion scenarios for renewable power plants installed in the power system, the following target functions are adopted:

Minimum standard deviation of the random variable of the annual change in net load
 (NS_{demand}):

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

Minimum standard deviation of net load by hours during the year:

$$SO(z) = \sqrt{\frac{\sum_{t=1}^T (z(t) - \bar{z})^2}{T-1}}, \quad \forall t \quad (4)$$

where $Z(t) = N_{net}(t_{hour})$ – net load changes by hour over one year; $T = 8760$ u; \bar{Z} – average hourly change in load over one year.

Minimization of functions (3) and (4) have the following solutions:

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

and

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

Solutions (5) and (6) satisfy the constraints on annual capacity generation from renewable sources up to 30% of demand (as an example, the conditions of planned demand coverage in the energy system of Azerbaijan by expanding generation at wind and solar power plants by 30% by 2030 are taken).

$$30 \left\{ \sum_t \frac{(W + Sol)(t)}{N_{net}(t_h)} \right\} \leq N_{net \max} \quad (7)$$

Subject to the following conditions being met

$$N_{net}(t) = P_{load}(t) - (P_{wind}(t) + P_{PV}(t)), \quad \forall t \quad (8)$$

$$P_{wind}(t) + P_{PV}(t) + \sum_R \sum_{it} N_{wind}(it, r_W) \cdot P_{wind}(t, r_W) + \sum_{r_S} \sum_{it} N_{SPP}(it, r_S) \cdot P_{PV}(t, r_S), \quad (9)$$

$$\forall t, \forall it, \forall r_W, \forall r_S$$

$$VRE_{surplus}(t) = \begin{cases} VRE(t) - S_{demand}(t), & \text{if } VRE(t) > S_{demand}(t) \\ 0, & \text{if } VRE(t) \leq S_{demand}(t) \end{cases} \quad (10)$$

$$z, NL, VRE, VRE_{surplus}, N_W, N_S \in NR \quad (11)$$

where $t \in [t_1, t_2, \dots, t_{8760}]$ – indices for hourly output values of renewable energy sources over time; $it \in [it_1, it_2, \dots, it_m]$ – number of single renewable installations at power plants; $r_S \in [r_{s1}, r_{s2}, \dots, r_{sM}]$, $r_W \in [r_{w1}, r_{w2}, \dots, r_{wN}]$ – number of regions where renewable power plants are located. $VRE_{surplus}$ – excess generation from renewable power plants; $P_{wind}(t)$ и $P_{PV}(t)$ – denote the existing hourly generation of wind and solar PV stations.

In equations (7)–(11), N_W and N_S represent the number of wind and solar power plants determined by the optimization algorithm for wind and solar power generation models.

III. Analysis of Scenarios for Aggregation of Green Generation Sources in Planning to Cover the Demand of Energy Systems

Research on testing the proposed methodology for determining scenarios of complementarity between regions of the energy system containing wind and solar power plants. Over the past 10 years, several renewable power plants have been commissioned in the country based on the use of the potential of wind, solar and hydroelectric resources, which were installed in the period 2015-2024. Currently, projects have been developed for the construction of a number of wind and solar power plants, the commissioning of which will allow the transport of "green energy" to Europe. A preliminary assessment of the transmission of green energy shows that its capacity will be at least 2 GW.

3.1. Data Characterizing Meteorological Conditions and Electricity Generation by Green Sources in the Regions

The installed capacity of the Azerenergy system is about 7.5 GW, a significant part of which is thermal power plants using gas turbine technology - about 5.6 GW, hydroelectric power plants - 1.4 GW, wind, solar and small hydroelectric power plants instead of taking - 0.5 GW. In 2024, renewable power plants produced 850 million kWh, including 6% by wind power plants, 67% by solar power plants and 27% by small power plants. Significant potential of wind and solar energy falls on two large geographical and economic regions of the country - Absheron, including the coastal zones of the Caspian Sea and the East Zangezur region, including the Karabakh regions. Therefore, the first wind and solar power plants were introduced in these regions. Figure 1 shows the general structure of the location of wind and solar power plants in two geographical regions - the Absheron region and the Karabakh region. In the Absheron region, two wind power plants are in operation as of 2023: the Khizi-Absheron wind power plant with a capacity of 240 MW and the Yeni Yashma wind power plant with a capacity of 50 MW. In the Karabakh region, the Jabrayil solar power plant with a capacity of 240 MW and the Kelbajar wind power plant with a capacity of 100 MW are included in the energy system. A significant consumption of the generated power falls on the Absheron region. Table 1 shows the technical parameters of renewable power plants installed in the regions.

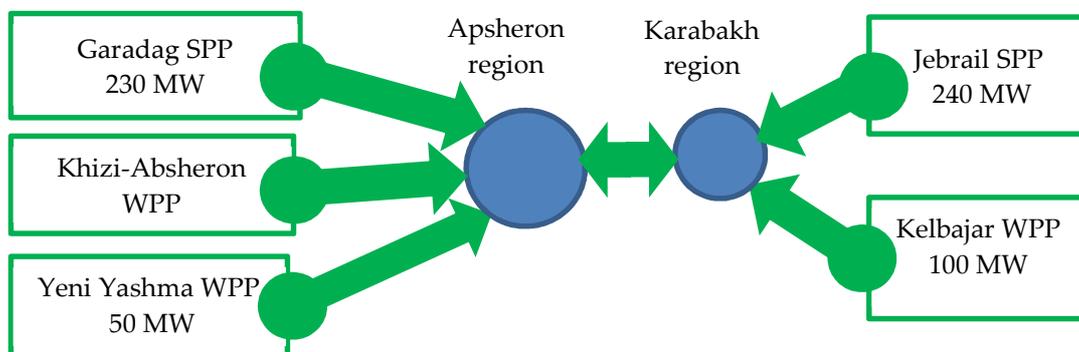


Figure 1: General structure of the location of active variable renewable Sources located in two regions of Azerbaijan

Table 1: Statistical indicators of annual electricity production at power plants

Power Plant	P, MW	Min MWh	Min (no zero) MWh	Max MWh	Average	Median	Dispersion	Standard deviation
Apsheron region								
Garadag SPP	230	0	0.213	209.3	35.91	0	$3.17 \cdot 10^{15}$	$5.63 \cdot 10^7$
Khizi-Absheron WPP	240	0	0.135	248.0	55.82	48.66	$2.17 \cdot 10^{15}$	$4.66 \cdot 10^7$
Yeni Yashma WPP	50	0	0.035	50.0	14.46	12.83	$1.42 \cdot 10^{14}$	$1.19 \cdot 10^7$
Total	520	0	0.171	442.5	106.18	93.60	$6.81 \cdot 10^{14}$	$8.25 \cdot 10^7$
Karabakh region								
Jebrazil SPP	240	0	0.22	223.5	36.61	0	$3.41 \cdot 10^{15}$	$5.84 \cdot 10^7$
Kelbajar WPP	100	0	0.071	100.0	28.28	23.22	$0.58 \cdot 10^{15}$	$2.42 \cdot 10^7$
Total	340	0	0.071	291.5	64.89	43.93	$3.98 \cdot 10^{15}$	$6.31 \cdot 10^7$
Karabakh and Absheron regions								
Total	860	0	0.0712	678.9	171.08	138.5	$1.68 \cdot 10^{16}$	$1.29 \cdot 10^8$

Figure 2 and Figure 3 show the power generation profiles of wind and solar power plants in the regions of Absheron and Karabakh, respectively. As can be seen from these figures, the process of generating power from renewable energy sources in the Absheron region has a relatively uniform intensity compared to the profile of renewable energy sources in Karabakh. The profile of Karabakh has a clear similarity with the power generation profile of the solar power plant installed in this region.

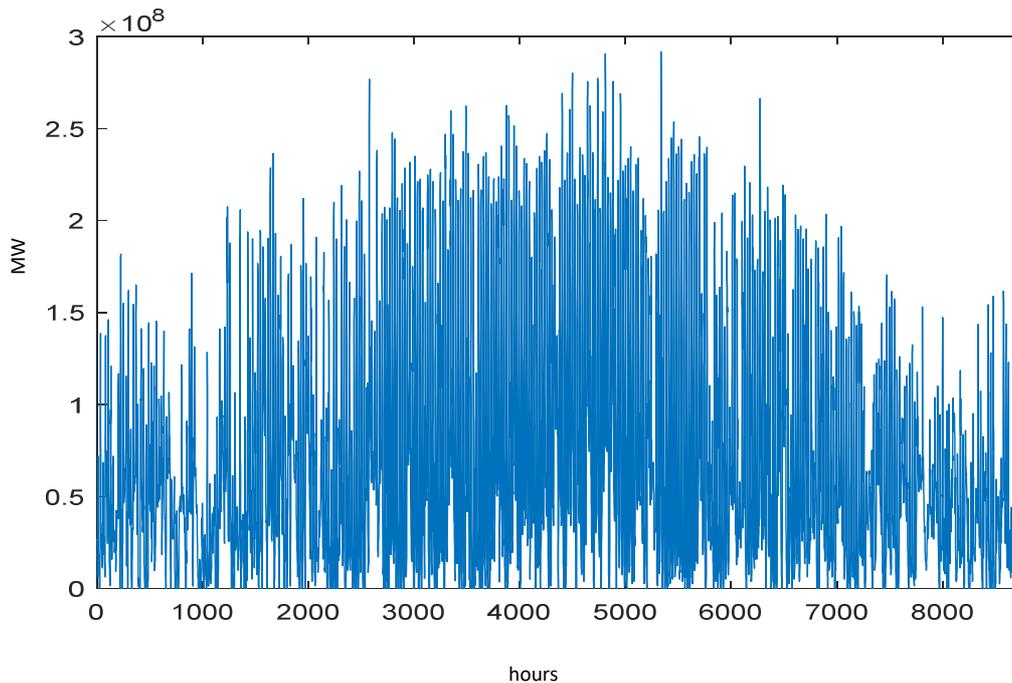


Figure 2: Profile of hourly power generation in the Karabakh region (total installed capacity 340 MW)

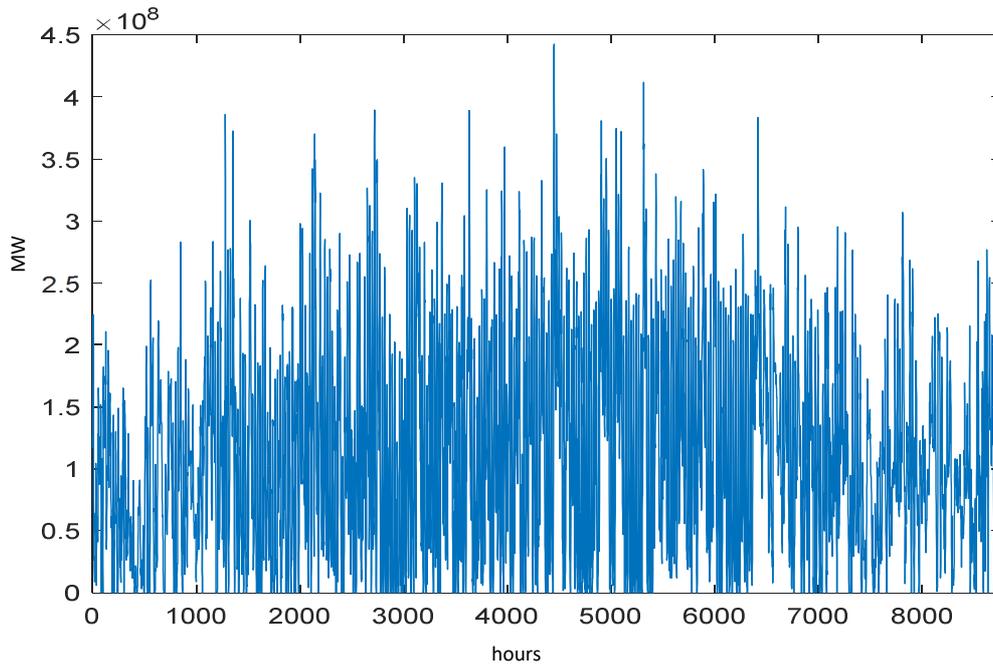


Figure 3: Profile of hourly power generation by renewable power plants in the Absheron region (total installed capacity 520 MW)

3.2. Clustering of Renewable Power Generation in Regions Taking into Account Meteorological Conditions

Figure 4a and Figure 4b show the probability distribution curves of hourly changes in power generation by renewable sources in the regions of Absheron, with one installed solar power station Garadag with a capacity of 240 MW and two wind power plants Khizi-Absheron - 230 MW and Yeni Yashma - 50 MW and one solar power station Jebrazil 240 MW in the Karabakh region. As can be seen from the comparison of these figures, during the average values of power generation in the Absheron region with a high probability exceed the average value of power generation in the Karabakh region by more than 30%.

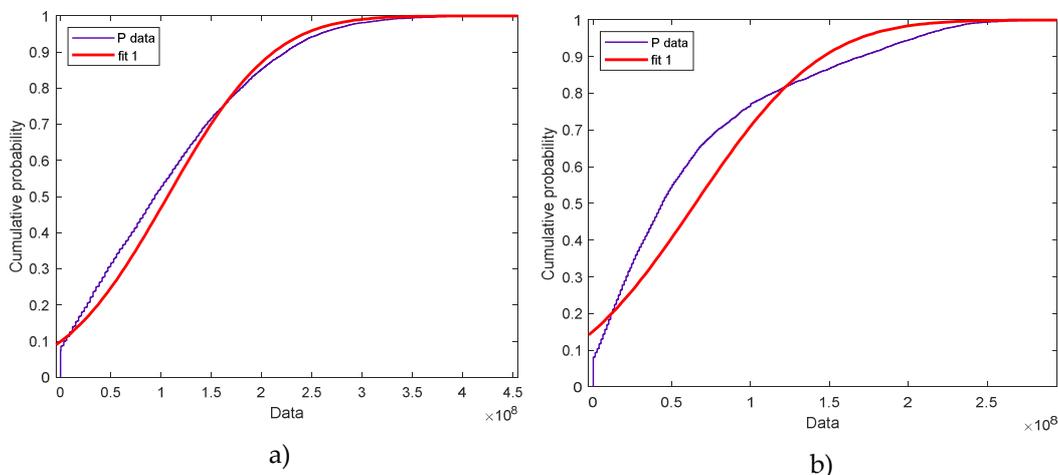


Figure 4: Probability of distribution of annual electricity generation
 a – for SPP-WPP of the Apsheron region; b – for SPP-WP of the Karabakh region

Figure 5 and Figure 6 show clusters of daily changes in the power system load and solar radiation in the regions. The intensity of solar radiation in the regions allows solar power plants to generate electricity over a significant period of time during the day.

Figure 7 shows clusters of daily changes in wind speeds in the regions during the year in accordance with clusters of changes in solar radiation and daily consumption. The silhouettes shown in Figure 8 reflect the number of significant clusters of wind and solar energy with the corresponding clusters of the system load.

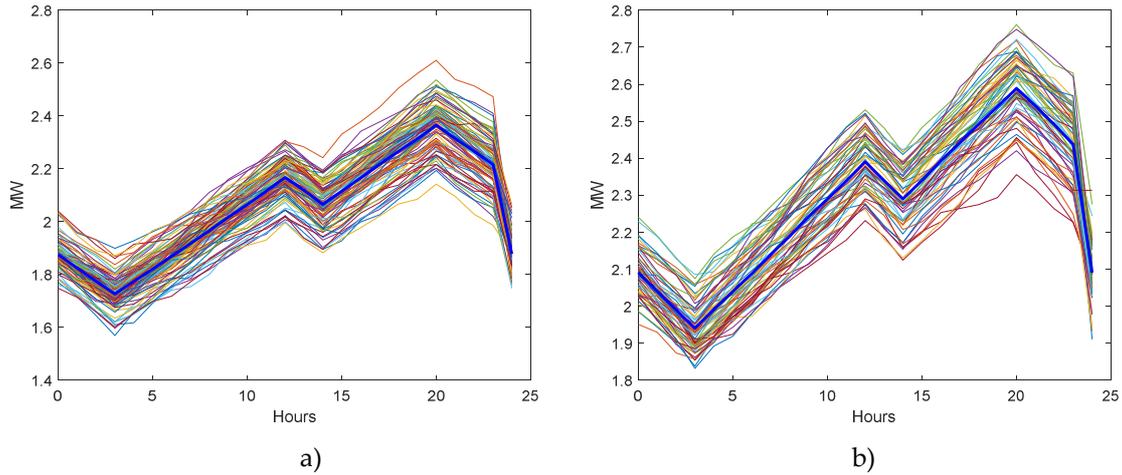


Figure 5: Clusters of daily load changes in the power system
a - 3st cluster; b - 4nd cluster

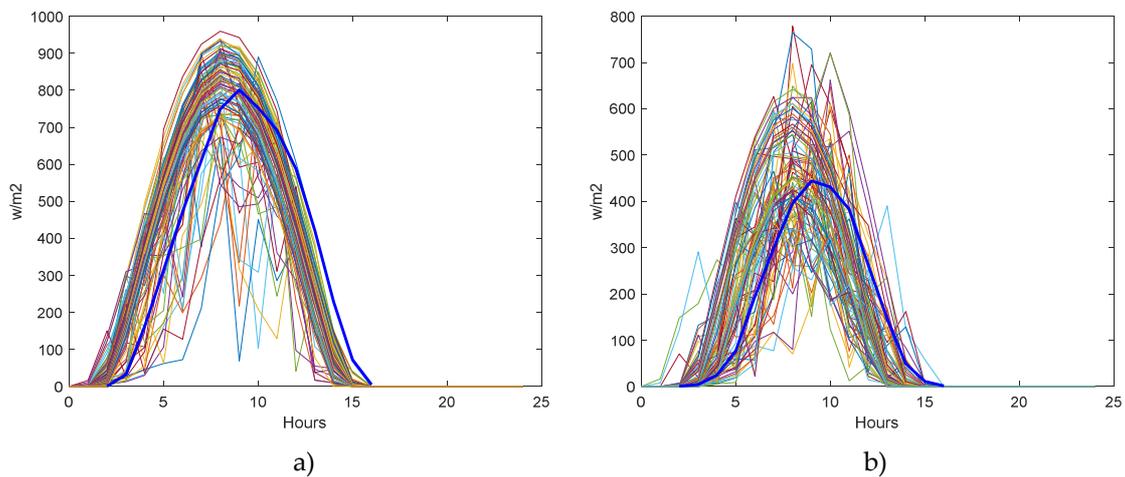


Figure 6: Solar radiation clusters in regions
a - Absheron; b - Karabakh

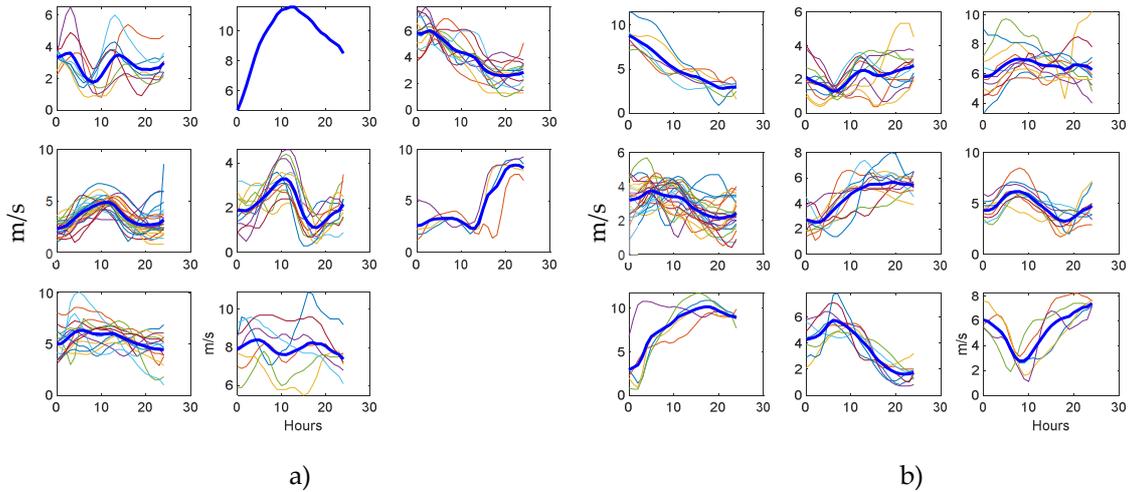


Figure 7: Wind clusters corresponding to the 3st cluster of radiation and load
 a -Absheron; b - Karabakh;

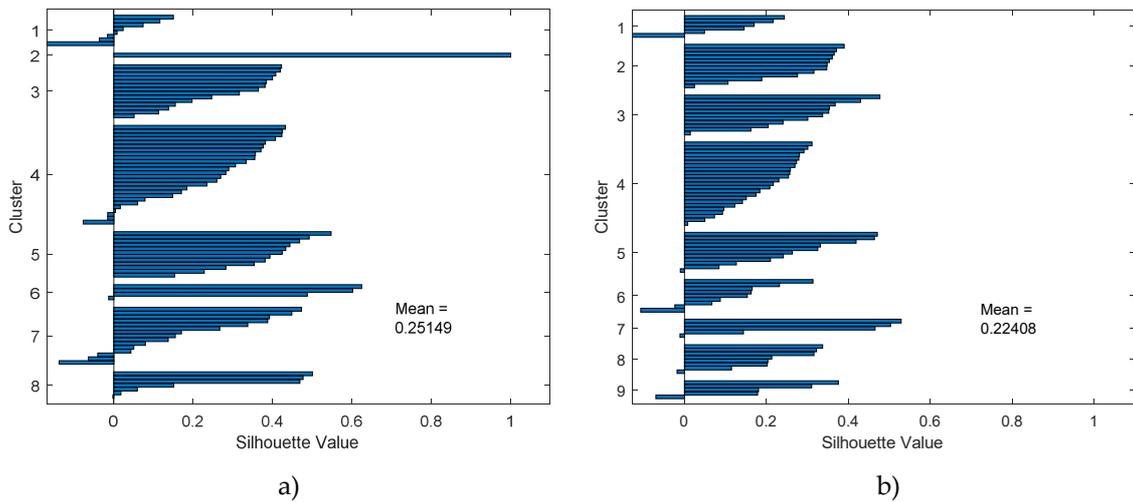


Figure 8: Silhouettes of optimal numbers of wind speed clusters
 for 3st cluster of radiation and load
 a -Absheron; b - Karabakh;

IV. Results of the Analysis of Scenarios for the Aggregation of Electricity Generation from Green Sources Located in Regions of the Country with Different Climatic Conditions

Based on hourly measurements of demand in the power system and meteorological data - wind speed, solar radiation, air temperature, obtained with a resolution of 1 hour during the year in two regions (Figure 1), with installed wind and solar power plants, a cluster analysis was carried out and typical scenarios for power generation by plants in each region and their interactions between regions were identified.

The studied variants of scenarios and optimization of load coverage due to power generation by renewable power plants are given in Table 2.

Table 2: Scenario and optimization options

Scenarios	Functions of the goal of optimal development	The means used
Wind _{so}	Minimize the objective function (1) by adding generation from renewable power plants	Wind
PV _{so}		Solar PV
PV+Wind _{so}		PV+Wind
Wind _{soh}	Minimizing the standard deviation of hourly change in N_{net} by adding generation from renewable power plants	Wind
PV _{soh}		Solar PV
PV+Wind _{soh}		PV+Wind

Statistical data characterizing the output of wind and solar power plants installed in the regions of Absheron and Karabakh for 2024 are given in the table. As can be seen from the table, all indicators of the Absheron region, including SO, are higher than the corresponding indicators of renewable stations by 12% or more. This gives reason to believe that when optimizing the planned coverage of the net load of the power system, the output of solar power plants can complement the fully used output capacity of the Khizi-Absheron region.

Figure 9, Figure 10 and Figure 11 show respectively the generation of electricity and the probability of its distribution for 2024 by wind and solar power plants located in the regions of Absheron, Karabakh and SPP-WPP of the Karabakh and Absheron regions together.

As with wind power generation, solar power generation exhibits seasonal behavior with high positive gradients from sunrise, reaching the earth's surface with minor gradients around midday 11-14 hours and high negative gradients until sunset.

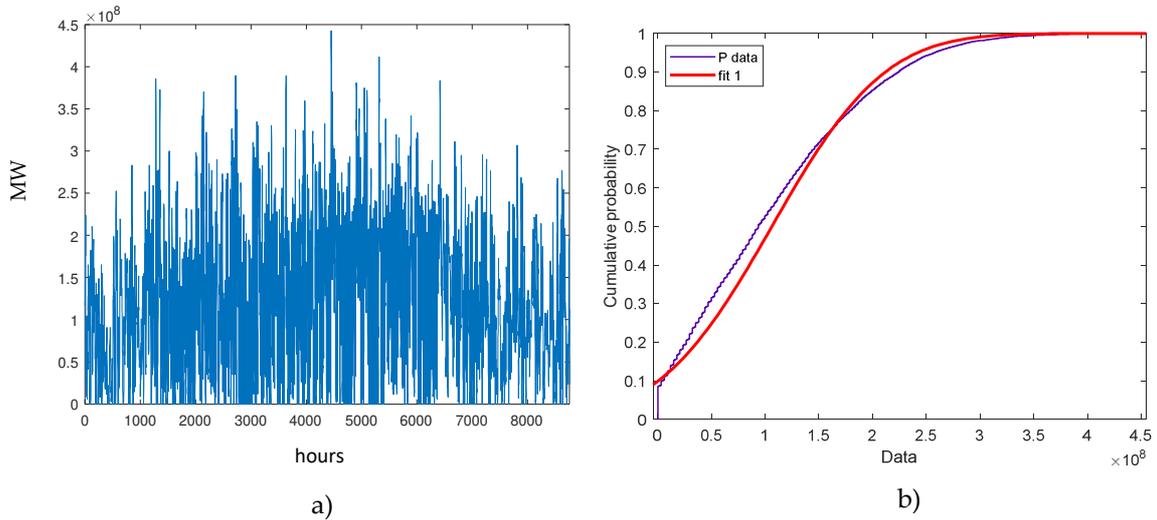


Figure 9: Annual electricity production of the SPP-WPP of the Apsheron region
 a - annual electricity production;
 b - probability of distribution of annual electricity generation;

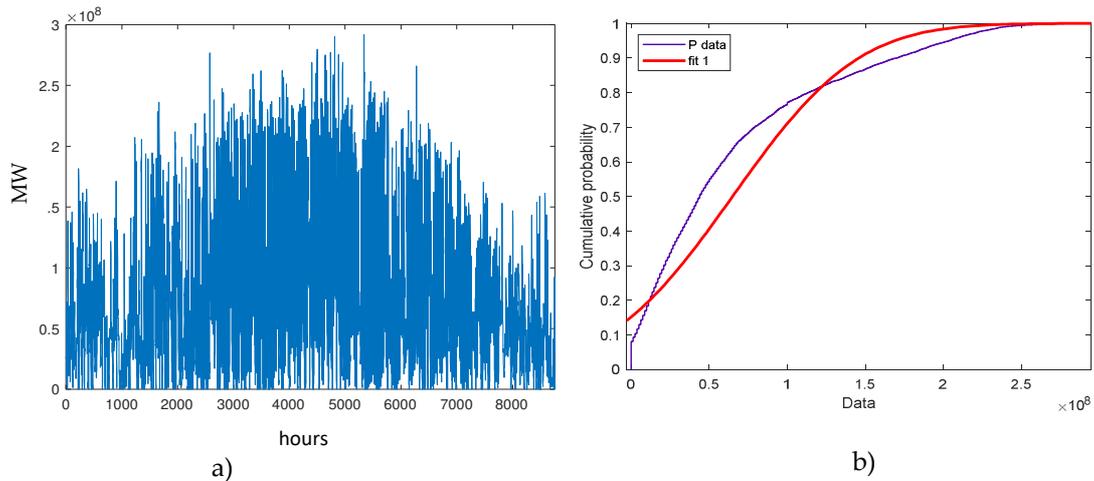


Figure 10: Annual electricity production of SPP-WPP of the Karabakh region
a - annual production of electricity;
b - probability of distribution of annual electricity generation;

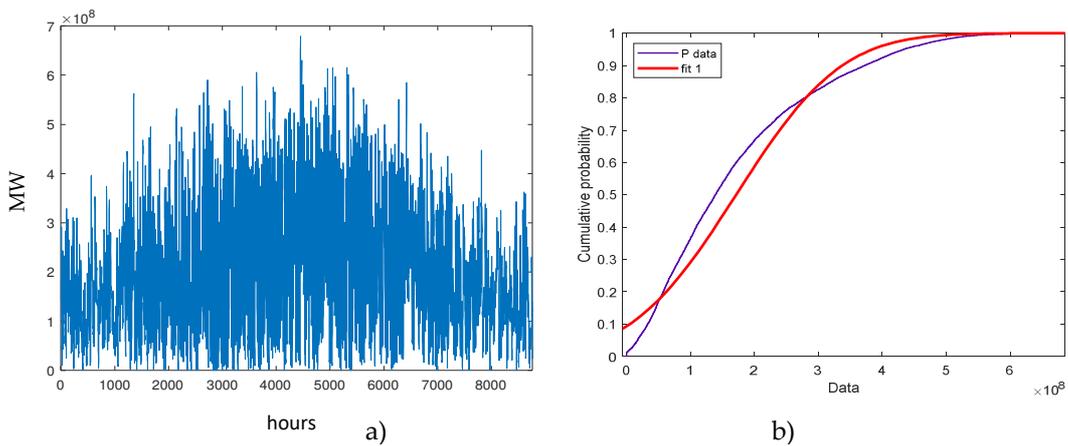


Figure 11: Annual electricity production of SPP and WPP in the Karabakh and Absheron regions:
a - annual production of electricity;
b - probability of distribution of annual electricity generation;

The standard deviation of the power generation by wind power plants is determined on the basis of the wind energy potential and, depending on the amount of power generation by wind power plants, the possibility of complementarity with wind power plants in the region is established.

V. CONCLUSION

1. Integration of renewable green energy sources with variable generation into the power system, along with significant advantages in solving problems of environmentally friendly production of electric energy, commissioning of power plants in a short time, leads to the need to solve a number of non-standard problems on planning and optimization of the mode in the power system, prompt coverage of demand in normal and post-emergency modes, as well as the risk of violation of the balance reliability of power systems in the conditions of green technologies. The solution of these problems requires the creation of new scientifically sound methods, development of algorithms and programs for identifying scenarios for generating capacities by green sources

located in various climatic conditions, determining the ratio of generation of these sources and choosing scenarios of their complementarity for various periods of expansion of green generation.

2. An algorithm for identifying scenarios of electricity generation processes by green sources, such as wind power plants and solar photovoltaic stations located in the power system in places with different climatic conditions, is proposed based on cluster analysis using the medoids method. An algorithm for identifying patterns between scenarios of electricity generation by renewable power plants located in different regions is proposed.

3. Using the proposed method, a cluster analysis of high-resolution data was performed and spatial and temporal variability of wind and solar energy generation in Azerbaijan was revealed. Two regions with different characteristics of wind and solar energy profiles were identified. Based on these profiles, different scenarios for adding green generation to the current energy balance were considered to reduce the risk of disruption to operational reliability: 1 – only wind energy; 2 – only solar energy; 3 – adding wind and solar energy.

4. It was found that the highest share of green energy penetration in annual consumption was achieved using the complementarity of wind and solar power plants. In the PV plant + wind plant scenario, a sustainable way to increase the penetration of renewable energy to 30%, taking into account the annual energy surplus in relation to consumption equal to (5-10) %, is possible by increasing the capacity of solar plants, which reduces the risk of disruption of balance or regime reliability.

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