

Optimal Sizing of Hybrid AC/DC Distributed Generation Systems with On-Site Renewables for Off-Grid Power Supply to Remote Areas

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Abstract — This study proposes a self-contained hybrid power system with DC and AC voltage buses connected to renewable and conventional energy sources to supply power to remote areas. The conventional sources are meant to serve as a backup for renewables to meet the demand during power shortages in the system. This research focuses on integrating an optimal structure of an off-grid system consisting of PV and WT generators with a battery energy storage system (BESS) and a diesel generator set (DGS) to ensure high reliability of power supply to a remote area. We contribute a machine learning algorithm (TLBO) for optimal sizing of the installed capacity of the PV-WT-BESS-DGS hybrid system components. The algorithm relies on the original multi-objective function to determine the most advantageous values of unit capacities for PV and WT plants, as well as the number of batteries and diesel generators, to meet the demand in the hybrid system under different scenarios of PV and WT power shortage.

The optimization problem is solved considering the variability of meteorological conditions as manifested in the random and uncertain intermittency of PV and WT generation as well as in the stochastic nature of the electricity consumption process. To enhance the

efficiency of its solution, this study seeks to cluster these processes and identify common scenarios for the data set of hourly measurements of PV and WT generation and loads during the year. We use k-means clustering to determine the number of clusters for PV, WT, and loads for representative geographical areas. The study reports the results of the analysis of optimal configurations for a hybrid AC/DC system made up of PV, WT, BESS, and DPS in these areas.

Index Terms — Distributed generation, microgrids, hybrid systems, PV generators, wind turbines, battery energy storage, teaching learning-based optimization (TLBO), common scenarios of wind speed, solar radiation and electrical loads, AC/DC systems.

I. INTRODUCTION

The great bulk of the research on the transformation of electric power systems deals with the development of distributed generation (DG).

In the last decade, DG has become an increasingly more attractive option because of the widespread use of renewable sources. DG configurations that integrate renewable sources such as PV and WT generators can fully serve the demand while operating off-grid. At the same time, due to the intermittency and uncertainty of PV and WT power generation in DG systems, power supply stability may be disturbed, and in case of excessive power generation, it may lead to power shedding [1–3]. Hybrid DG configurations with WT and PV generators, an integrated BESS, and a diesel generating set are considered reliable off-grid power supply systems for rural and remote areas [4, 5].

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A critical challenge for hybrid systems incorporating distributed generation and on-site renewables is optimal sizing of individual components, such as wind turbines, solar generators, and battery energy storage system. This sizing is essential to achieve optimal technical performance, ensuring compliance with reliability standards, and economic performance through minimization of total costs of power supply to consumers in a given area.

The unreliability of renewables can be overcome by increasing the size of the components (PV and WT generators), but this also increases the cost of the system. On the other hand, under-sizing of components can lead to power outages when the renewable power generation is less than the loads. Therefore, it is critical to optimally size renewable sources, thereby determining the exact number of their components [6]. A hybrid PV-WT-BESS-DGS microgrid has been designed and successfully utilized to supply electricity to three remote hamlets [7]. Studies [6, 7] and several other works related to optimal sizing of hybrid systems with renewable sources rely on the HOMER software for solving the problem. The software has some practical limitations, as it is mainly intended for economic valuation of hybrid system component selection and does not consider the impact of meteorological changes on system reliability. In recent years, various metaheuristics-based algorithms have been developed for multi-objective optimization, including genetic algorithms, which have been widely adopted [8, 9].

This paper solves the problem of optimal sizing of components of an off-grid PV-WT-BESS system with the aid of the improved TLBO algorithm (JAYA). Unlike existing algorithms designed to determine the optimal parameters of the hybrid system, the TLBO algorithm used in this paper allows considering variability of meteorological conditions. To capture the stochastic variability of wind speed, solar radiation, and electricity consumption, we performed their spatial and temporal analysis and identified common scenarios for optimal sizing of renewable sources in the proposed microgrid setup. The scenarios generated by our model approximate the original scenarios and reduce the number of data for efficient combination of hybrid system components.

The proposed optimization approach was applied to a case study of representative geographical areas in Azerbaijan.

II. THE STATEMENT OF THE PROBLEM OF OPTIMAL SIZING OF THE HYBRID AC/DC (PV-WT-BESS-DGS) SYSTEM TO ENSURE SYSTEM RELIABILITY FROM THE TECHNICAL STANDPOINT

1. Configuration of the hybrid AC/DC distributed generation system "PV – WT – BESS – DGS"

This paper presents a standardized hybrid dual-bus AC/DC distributed generation system with on-site renewables. The following are connected to the AC subsystem: wind turbines, loads consisting of AC and DC consumers, and a DGS that serves as an emergency source. The DC subsystem has a wind turbine, a battery energy storage, and DC and AC loads connected to it.

The AC and DC subsystems are interconnected by a bi-directional inverter. Depending on power generation from sources in the AC and DC subsystems, there can be various load conditions in each of the subsystems and in the entire hybrid system: balanced, surplus, and shortage. Under the balanced conditions, the total power generated from PV in the DC subsystem and WT in the AC subsystem equals the total power of consumers in these subsystems. When the total power output in the DC and AC subsystems exceeds the total consumption and total power in the battery storage system, the excess power is discarded. In the event of a power generation shortage in the AC and DC subsystems, when the overall load exceeds the available supply and the battery capacity is insufficient to compensate for this shortage, the corresponding part of the load is shed.

2. Reliability criteria for off-grid AC/DC systems

Maintaining the reliability of off-grid AC/DC systems is essential when selecting the performance specifications as this directly impacts the continuous power supply dependent on renewable energy generation. These specifications are formalized by the following indices [10]:

1. Probability of power outage:

$$\tilde{\Delta P}_{load} = \frac{\sum_{t=1}^T \Delta P_{load}(t)}{\sum_{t=1}^T (P_{loadDC}(t) + P_{loadAC}(t))}, \quad (1)$$

where $\Delta P_{load}(t)$ – the amount of the disconnected power of the total load in the AC/DC system; t – the duration of the shortage $T = 8760$ h.

2. Proportion of generation shed $P_{gen}(t)$: when the sum of the generation from AC and DC subsystems exceeds the total load, and the BESS reaches its maximum storage

capacity, the excess generation must be disconnected:

$$\Delta P_{gen}^{\sim} = \frac{\sum_{t=1}^T \Delta P_{gen}(t)}{\sum_{t=1}^T (P_{DC}(t) + P_{AC}(t))}. \quad (2)$$

We have designed a flowchart of calculation of optimal values of reliability indices (1) and (2) for off-grid hybrid AC/DS systems.

III. THE USE OF K-MEANS CLUSTERING FOR GENERATING COMMON SCENARIOS OF RANDOM VARIATIONS IN SOLAR RADIATION, WIND SPEED, AND ELECTRICITY CONSUMPTION FOR REPRESENTATIVE GEOGRAPHICAL AREAS OF AZERBAIJAN

The intermittent nature of power generation from solar PV and wind turbines makes their integration into the electric power system challenging. There are different approaches to decompose a data set of random variable changes into a combination of multiple recurrent changes. This study uses *k*-means clustering to generate common scenarios of solar radiation, wind speed, and loads. The resulting common clusters significantly reduce the number

of investigated scenarios that would otherwise have to be generated from a large set of input data. *K*-means clustering is performed as follows:

1. Input an array of time series data for solar radiation (W/m²), wind speed (m/s), and loads (W) for 1 year.
2. Perform individual clustering of stochastic processes of loads, solar radiation, and wind speed on the basis of hourly measurements for the entire year; the basic unit of clustering is one day (24 hours).
3. Based on the known relationship (spatial correlation) between loads and solar radiation, perform their joint clustering.
4. Identify common solar radiation/load scenarios according to the centroids of the solar radiation/load clusters (based on the joint load/solar radiation data set).
5. Use each type of solar radiation/load scenarios and common scenarios for wind data (based on the centroids of wind speed clusters) to establish relationships between solar radiation/load and wind speed.

Aided by the computer implementation of the above steps, we determined the optimal number of clusters for

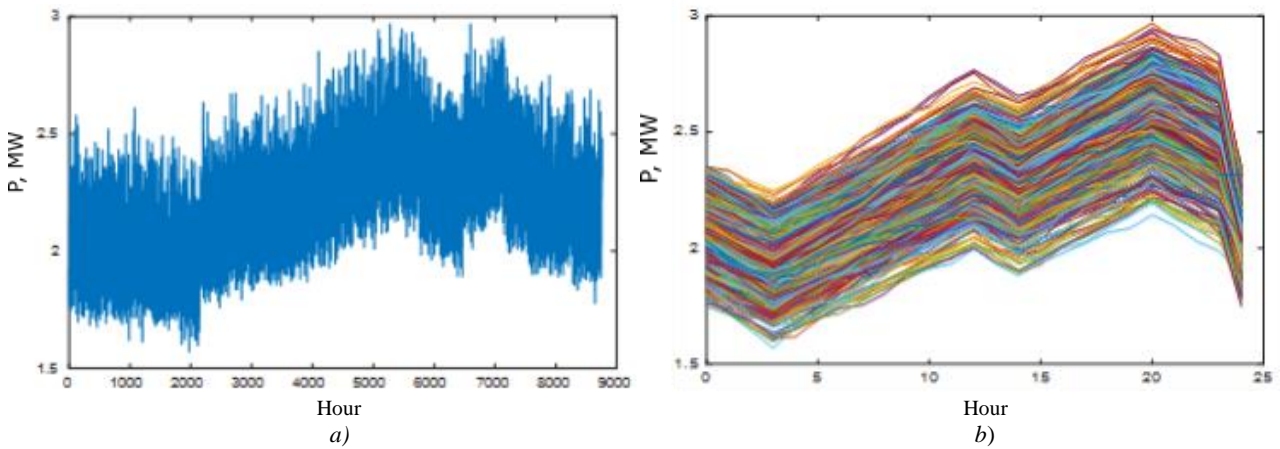


Fig. 1. Profile of load changes by hour throughout the year (a) and day (b).

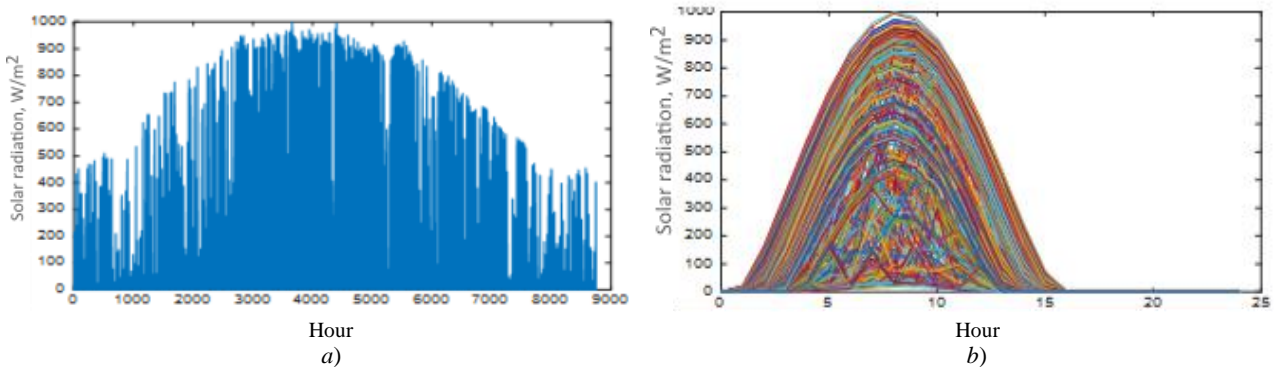


Fig. 2. Profile of solar radiation changes by hour throughout the year (a) and day (b).

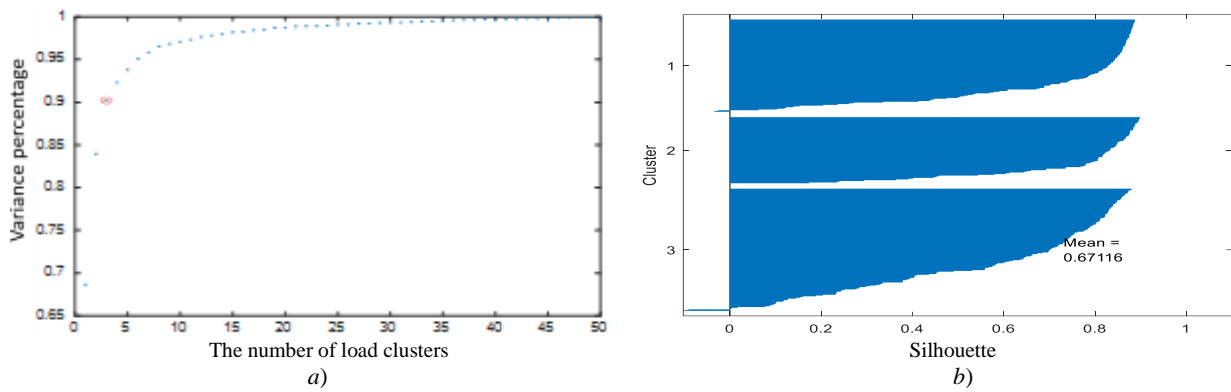


Fig. 3. Optimal numbers of clusters for annual load variability (a) and corresponding silhouettes (b).

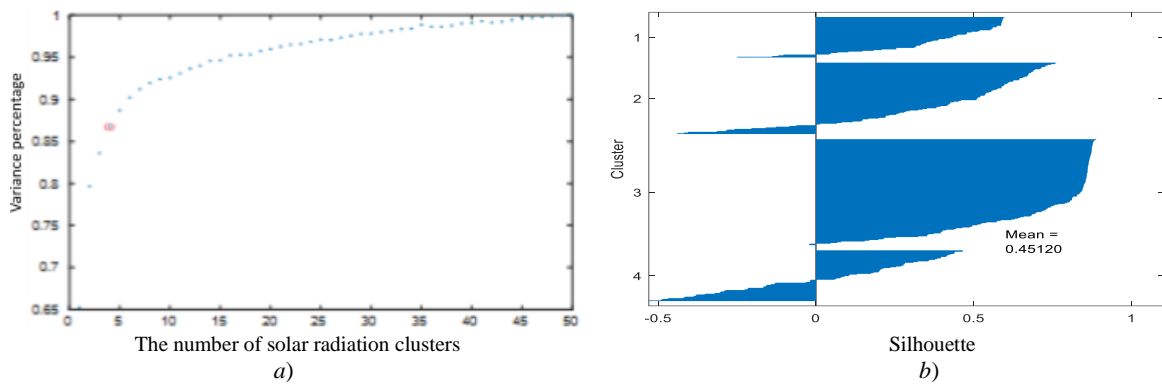


Fig. 4. Optimal number of clusters for annual solar radiation variability (a) and corresponding silhouettes (b).

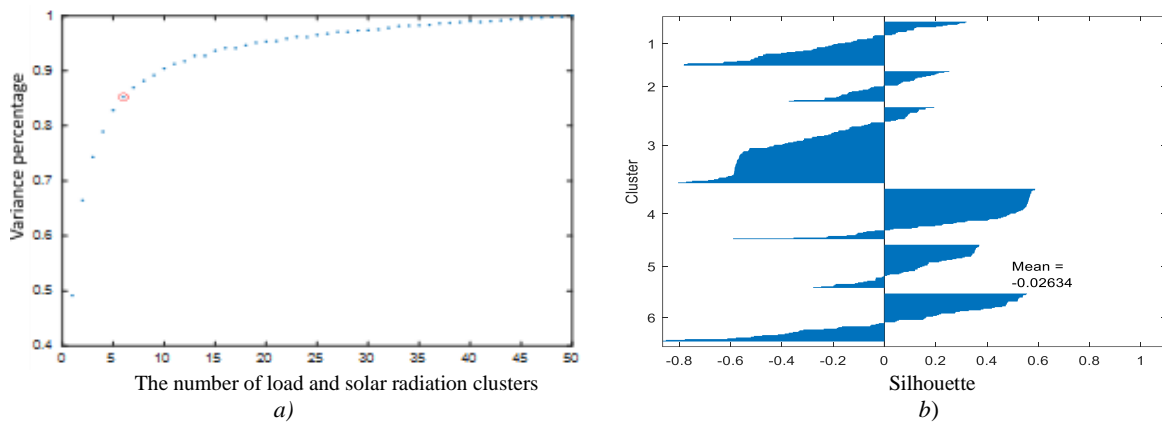
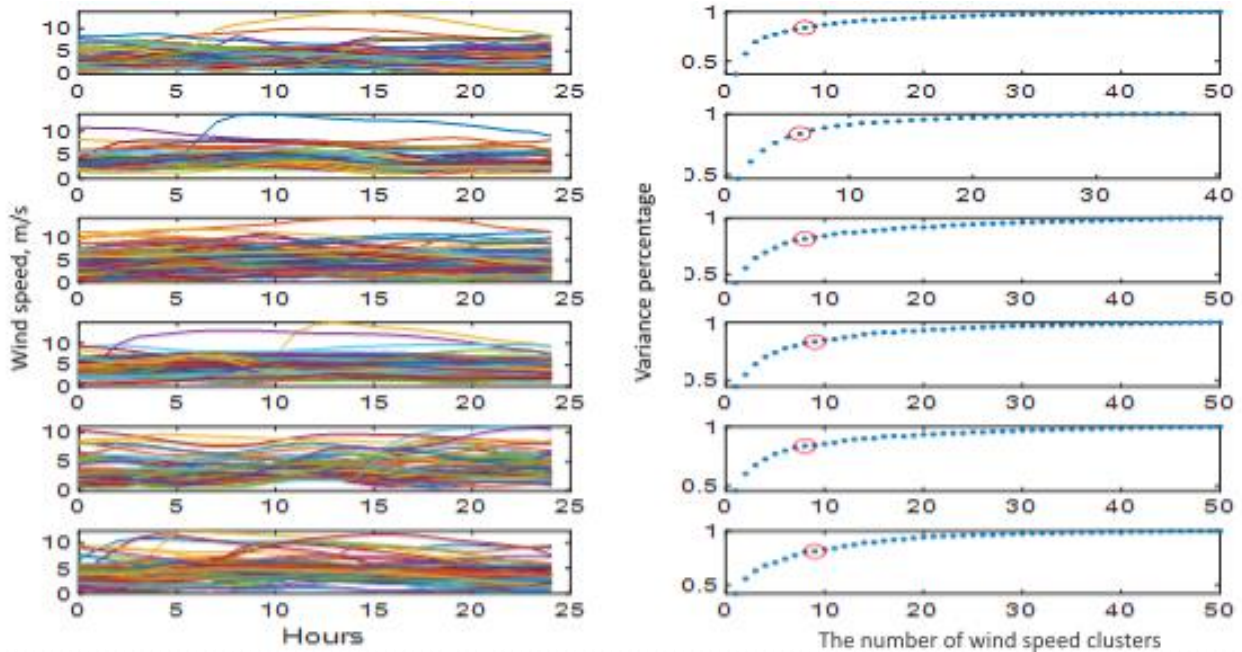


Fig. 5. Optimal number of clusters for a set of solar radiation/load variability data (a) and their silhouettes (b) throughout the year.



a) Changes in wind speed in accordance with solar radiation/load

b) The number of clusters in accordance with daily changes in wind speed

Fig. 6. Optimal number of solar radiation/load variability clusters according to wind speed variability.

radiation/electrical load and wind speed for mountainous areas of Azerbaijan.

IV. CLUSTERING ANALYSIS OF VARIABILITY IN SOLAR RADIATION, LOADS, AND WIND SPEED FOR METEOROLOGICAL CONDITIONS OF MOUNTAINOUS AREAS IN AZERBAIJAN

The clustering analysis and identification of representative clusters relied on hourly measurements of solar radiation, loads, and wind speed obtained for a remote area of the Kalbajar district of the East Zangezur economic region of Azerbaijan. The measurements covered a time span of one year. Figures 1(a, b), 2(a, b), and 3(a, b) show images of these processes for one-year and one-day time spans, respectively.

The comparative analysis of solar radiation and load dynamics for both the one-year and one-day time spans has revealed that they exhibit a more recurrent pattern compared to the speed fluctuations. Based on these considerations, we also analyzed the clusters of the joint dynamics of loads and solar radiation to find common scenarios.

The optimal numbers of clusters for load, solar radiation, and wind speed data for a period of 1 year for the Kalbajar

district were determined with the aid of the algorithm reported in [10]. Figures 4 to 6 illustrate the trend in the percentage ratio of the variance in clustering results related to the dynamics of loads and solar radiation, along with the corresponding silhouettes of the clusters.

Thus, as seen in Fig. 1–6, the optimal number of scenarios for the load data is 3, for solar radiation data – 4, together for solar radiation and load data – 6. There are 6 scenarios for combined load, solar radiation, and wind speed data, consisting of the following number of clusters: 6, 7, 8, 9, 8, and 9. In total, 282 scenarios were obtained. The identified numbers of scenarios serve as the initial base for the mix of RES connected to the AC and DS subsystems of the hybrid system.

Optimal control of power generation in AC and DC subsystems depends on the spatial and temporal operating conditions of the hybrid system, which is treated as a multi-objective problem.

V. THE MULTI-CRITERIA FUNCTION OF OPTIMAL SIZING OF AN OFF-GRID HYBRID AC/DC SYSTEM WITH INTEGRATED PV AND WT GENERATORS

An essential part of configuring an off-grid hybrid system with on-site renewables is to ensure the reliability of its operation under uncertain and changing

meteorological data on solar radiation and wind speed, as well as the random process of power consumption by electrical loads [11]. The power output in the AC subsystem is expected to cover in full the load P_{AC}^e connected to the subsystem and transmit up to 30% of the output, in the event of its excess, to the DC subsystem.

The output of PV generators in the DC subsystem is assumed to be sufficient to meet its connected load and, in the case of its excess, to transmit the surplus power to the AC subsystem. In the event of excess generation $P^W(t)$ over period t , reliability in the system can technically be maintained by pursuing the objective:

$$F_1(N^W, N^{PV}, N^{bat}, N^{DG}) = \sum [P^W(t) - P_{DC-AC}^{PV}(t) - P_{AC}^L(t)] \Rightarrow \min,$$

where $N^W, N^{PV}, N^{bat}, N^{DG}$ – the number of wind turbines, solar cells, battery storage units, and diesel generators, respectively; $P_{DC-AC}^{PV}(t), P_{AC}^L(t), P^W(t)$ – power flows between AC and DC buses, loads connected to the AC bus and wind turbine generation power at time t , respectively.

Accordingly, when wind power is insufficient, the objective of optimal power management in the hybrid AC/DC system is described by the function:

$$F_2(N^W, N^{PV}, N^{bat}, N^{DG}) = \sum [P^W(t) + P_{DC-AC}^{PV}(t) + P^{DG}(t) + P_{AC}^L(t)] \Rightarrow \min.$$

The optimization of power management in the event of excess or shortage of the power generated from PV (DC subsystem) can be expressed through the following objectives.

Power excess:

$$F_3(N^W, N^{PV}, N^{bat}, N^{DG}) = \sum [P^W(t) - P_{DC-AC}^{PV}(t) - P^{bat}(t) - P_{DC}^L(t)] \Rightarrow \min.$$

Power shortage:

$$F_4(N^W, N^{PV}, N^{bat}, N^{DG}) = \sum [P^{PV}(t) + P_{DC-AC}^W(t) + P^{bat}(t) - P_{DC}^L(t)] \Rightarrow \min.$$

Inverter output power:

$$P_{inv}(t) = \frac{P^L(t)}{\eta_{inv}},$$

where η_{inv} – the inverter efficiency factor.

Possible scenarios of hybrid system operation (PV + WT):

1) $\sum P_G$ exceeds the power required to serve the load (inverter input power). In this case, the excess energy is stored in the battery storage, and the power remaining after the battery is charged to full capacity is not used, i.e., is shed.

2) $\sum P_G$ is less than the power required to serve the load. The power shortage is compensated by the storage unit.

3) In the case the equality $\sum P_G = P_{inv}$ holds, the power (capacity) P_{bat} remains unchanged.

Table 1 shows the results of the calculations that assume that the amount of the disconnected load ($F = \min DL$) at $100 < N^{bat} < 20\,000$, $100 < N^{PV} < 60\,000$, $100 < N^W < 5\,000$, $C_{bat} = 40\,000\,Wh$, $P^{PV} = 125\,W$, and $P^W = 5\,000\,W$ is the objective function.

The optimal solution is presented in the first row of Table 1. Other options were also considered.

VI. CONCLUSION

1. The present paper proposes a technique for optimally sizing an off-grid power system with a dual-bus AC/DC configuration and intermittent renewable sources to improve the reliability and efficiency of its operation. The optimal architecture of the hybrid power system is derived based on the analyzed scenarios of the system's performance over a year, given the random variability of solar radiation, wind speed, and stochastic load variability

TABLE 1. Calculation Results

N	N^{bat}, N^{PV}, N^W	DL	Utilized capacity	$F(...)$
1	15.621; 6.893; 3.328	0	0.2256	0
2	7.038; 27.790; 2.436	0	0.3732	0
3	9.384; 12.836; 3.171	0	0.3866	0
4	12.076; 199; 4.069	0	0.4159	0
5	12.433; 33.398; 4.241	0	0.4875	0
6	2.068; 51.802; 4.291	0	0.7508	0
7	9.220; 8.200; 4.361	0	0.5338	0
8	14.504; 55.473; 3.022	0	0.3311	0
9	6.096; 35.392; 4.867	0	0.6783	0
10	1.939; 28.149; 2.969	0	0.6308	0

in the investigated remote area.

2. This study has introduced a machine-learning algorithm designed to identify the optimal values for available wind and solar generation capacity across all scenarios. The suggested approach for generating scenarios and the algorithm for identifying optimal parameters of the hybrid system were tested in the power supply systems planned for construction in representative geographical areas in Azerbaijan.

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