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ASSESSMENT AND OPTIMAL COMBINED UTILIZATION OF RENEWABLE ENERGY SOURCES IN THE REMOTE INHABITED LOCATIONS

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Abstract- Currently, in many countries there are regions which due to remoteness and geographic conditions do not have access to the central power system. The power systems in these cases are performed in form of local isolated systems with their own energy sources. These sources are power plants operating on the base of local renewable resources - wind, solar, small rivers hydro-potential. The energy potential of local renewable resources depends on the climatic conditions in the area. The paper provides an assessment of the renewable resources potential for the terrain in the mountainous regions of Azerbaijan. Based on long-term observations of solar radiation levels, ambient temperature, wind speed and other parameters, the calculated theoretical and technically possible values of electricity generation have been determined. The structure of considered distributed generation system includes the direct current sources (PV-systems) which are distributed among individual consumers. Sources of alternating current - wind generators operate according to the scheme of centralized power generation and its distribution among individual consumers. An estimated model of total consumption for the selected remote area has been compiled. The goal of the optimal planning problem is to determine the optimal composition of renewable energy sources (PV systems and wind turbines) turbines), which power generation would fully cover the maximum total annual consumption. To achieve this goal, the method of probabilistic combination of the number of individual PV systems and wind turbines is used. The estimates of the RES potential for specific geographically remote areas, the RES optimal placement and power generation to cover the local power demand are presented in the paper. The technical feasibility study for each available type of RES using and the share of their participation in covering load schedules for a typical rural settlement in remote area are included on to this paper as well.

Keywords: Stand Alone System, Renewable Energy Sources, Distributed Generation System, Energy System Optimization, Solar power generation modeling, Wind Turbine Unit Modeling, Demand Maximum Optimal Covering, Remote Regions Electric Power Supply.

1. INTRODUCTION

Recent years the systems with individual power sources and main Power Grid connection for the reliability of consumers power supply have been widely used in remote areas. A large number of studies have been devoted to the design, optimization and operation modes for such systems [1-5]. The use of DG and RES is considered one of the basic trends for the power systems development in future. Over the past 20 years, a lot of research has been carried out to support the growth and integration of RES into power systems. During this time, investments in the new technical means introduction for the DG systems with RES effective management have been significantly increased [6, 7].

Among the important problems arising during the transition to the DG technology are the use of RES in DG systems, their integration on to the power system, the involvement of DG sources in the operational control processes [4], 5]. Based on the accumulated experience, each country has developed the Rules governing the procedure for connecting the DG to the power system, determined the volumes of the sources installed capacity, and especially RES. Unlike DG systems integrated with the power system, DG systems in remote areas often form and function as completely isolated microsystems. The microsystem considered in this work for remote areas is formed in accordance with the specific geographic conditions of Azerbaijan, and its main sources are RES: solar and wind power plants with an appropriate infrastructure of reserve sources - batteries of sufficient power and diesel generators.

The purpose of the article is to determine the energy potential of each type of RES as part of DG, the optimal use of the estimated resources to cover the time schedule of a given load, as well as a comparative assessment of various options for the generation structure in a geographically remote area. At present, when designing hybrid DG systems, the problems of choosing and optimal combination of various RES with corresponding reserve energy storage devices, as well as managing the modes of energy production and consumption, are considered and solved in many cases in isolation [8, 9].

At the same time, instantaneous and unpredictable fluctuations in energy consumption occur simultaneously in the DG system, which, along with the discontinuity and variability of energy production from RES, leads to an imbalance between generation and consumption. Smoothing the effect of this imbalance, and, consequently, improving the efficiency of the system is achieved by optimal control of the sources and backup energy storage integrated into the system, as well as regulation of the load schedule in form of consumption limitation (demand control), if necessary [10-12].

Unlike Grid connected DG systems, the DG system for remote regions is formed and functions as a completely isolated microsystem. In this article, this microsystem is formed in accordance with the geographical location and natural conditions of one of the southern regions of Azerbaijan - Lankaran, and in its composition the main sources of energy are RES - solar and wind power, as the most typical for this area. The aim of the work is to determine the energy potential of each type of RES, the optimal use of these resources to cover the time schedule of a given load and a comparative economic assessment for various options for the generation structure when covering the load. During the DG system formation with a mix of RES the optimal choice of the unit capacity for each source and their locations is essential [13-17]. Ignoring or incorrectly solving this problem will lead to ineffective use of the RES potential and large losses in the DG system.

2. INTEGRAL STRUCTURE OF AN AUTONOMOUS DG MICROSYSTEM WITH RES

Recent years, the share of electric power generation by sources in autonomous power systems that have no connection with the central Grid has significantly increased. Such isolated systems are usually designed and installed in geographically distant locations as microsystems. If earlier conventional technology power sources were used in such systems (mainly diesel generators), now DG systems with RES are widely used [18-21]. The choice of a DG with different kinds of RES in its structure for each remote area requires the study of the following problems [22-25]:

- What types of ERS and in what combination are the best in terms of technical and economic indicators;
- What is the share of the capacity for each type of RES.

The difference between RES by the type of primary renewable resource (solar radiation, wind, etc.) as well as the degree of the greatest usefulness of the certain types of RES use complicates the above optimization problems solution. Currently, a number of approaches are proposed to solve the problem of choosing the optimal Microgrid structure, the value of the installed capacity of each type of RES. This paper presents the results of studies to determine the optimal structure of renewable generation and other components of the AC/DS Microgrid for the climatic conditions of remote areas, typical for the south of Azerbaijan.

The most common types of RES for the localities of this region are solar radiation, wind energy, thermal waters, hydro resources of small rivers, etc. Let us assess the potential for each individual type of RES using the example of a rural area remote from the center of Lankaran. In this settlement, the main consumers of electricity are 15 individual residential buildings, the administrative building of the municipality, a store and 2 production facilities (dairy products), equipped with the necessary equipment (pumps, small production and refrigeration equipment), street and industrial lighting systems, communications, computer systems and security systems.

For the settlement power supply a hybrid AC/DC microsystem is proposed, which also includes generating capacities - RES (solar and wind) and a backup energy storage system (batteries and a diesel generator). The system has a possibility (in the future) of connecting electric vehicles - both DC loads when charging their own batteries, and as DC sources for operating on the DC network, if necessary. A hybrid AC / DC microsystem [17] is proposed to supply power to the selected settlement as Figure 1.

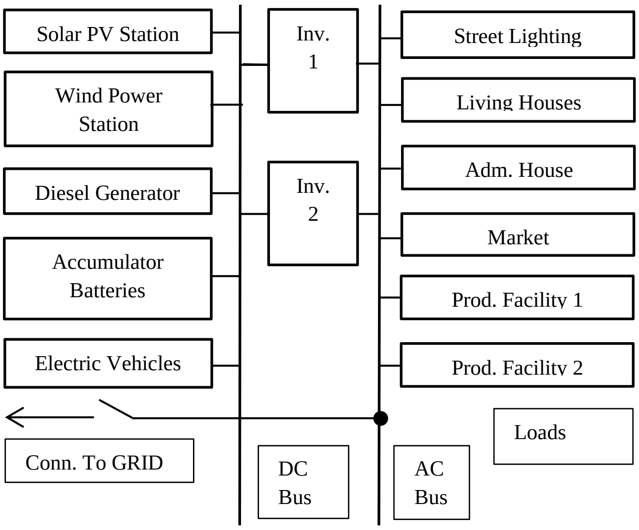

Figure 1. A hybrid AC/DC microsystem [17]

In this Microsystem, wind generators, a diesel generator and a load operating from an alternating current network are connected to the AC subsystem. Solar power station PV panels, electric energy storage system, and a load operating on direct current are connected to the DC (direct current) subsystem. The diesel generator in the AC subsystem is included for operation during periods of insufficient power producing from wind turbines (during low wind speeds - less than the nominal value).

Each solar PV array (power 1.5-2.0 kW for each PV panel) can be oriented in a given direction. In order to assess the integral structure of RES, the numerical values of these sources power generation, an analysis of the power consumption by loads during the year, as well as solar radiation, temperature and wind speeds in the selected region under study (according to meteorological data collected over a period of more than 20 years) was carried out.

3. SOLAR RADIATION AND WIND SPEED PARAMETERS IN LANKARAN REGION

To obtain the characteristics of solar radiation and wind speeds in the Lankaran region and other regions of the south of Azerbaijan, we used measurement data based on meteorological data collected over a period of more than 20 years [14, 20]. These data were summarized and presented in the form of monthly average daily values of parameters as Figures 2 and 3. As you can see, the highest values of solar radiation fall on July, and wind speeds - in December.

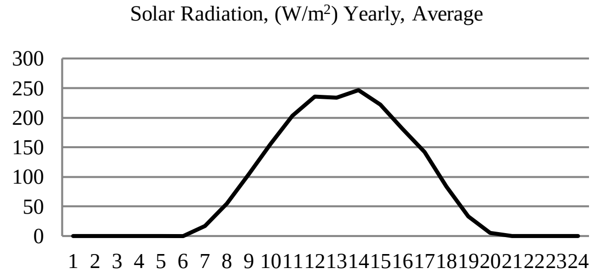

Figure 2. Solar radiation yearly, average [14, 20]

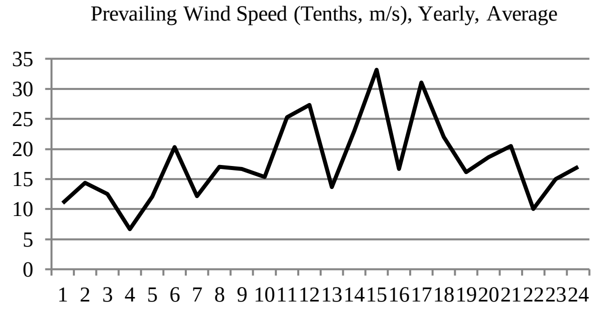

Figure 3. Wind speed, yearly, average [14, 20]

4. ACCUMULATOR BATTERIES - RESERVE ENERGY STORAGE DEVICES

Battery system (BS) - backup energy storage systems are used in an autonomous Microgrid power system to accumulate surplus energy generated by RES (wind turbines and solar panels) in order to spend the accumulated energy during the period of its deficit to cover the load connected to the AC and DC subsystems. The state of the BS charge depends on its previous state and the load flows distribution in the DG system. The state of BS charge can be estimated for each subsequent time interval from the balance equation between the absorbed and generated power in a given interval.

5. ELECTRIC POWER CONSUMPTION CHARACTERISTICS

To determine the total electrical energy demand in the study settlement, calculations of the electrical load were carried out in accordance with the conditions in the rural areas of Azerbaijan. These data can be used to determine the RES power production (average daily, average monthly and average annual) to cover the load schedule of the settlement.

To construct the average daily load graph of the settlement, the corresponding load graphs were used for individual components - 15 individual residential buildings, the administrative building of the rural municipality, a shop and 2 industrials. The results of load calculations are shown below as Figure 4 and 5.

The total parameters of the average daily load schedule for the entire settlement are presented on the curve as Figures 6-10.

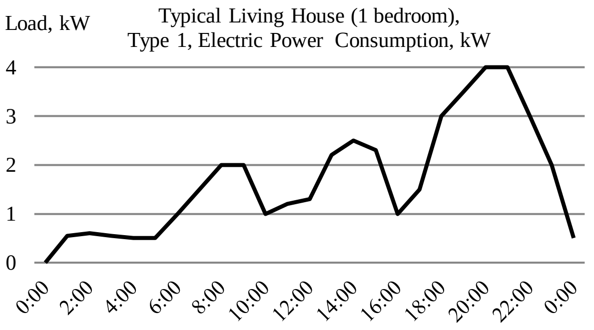

Figure 4. Living House Type 1 Power consumption [10, 14, 20]

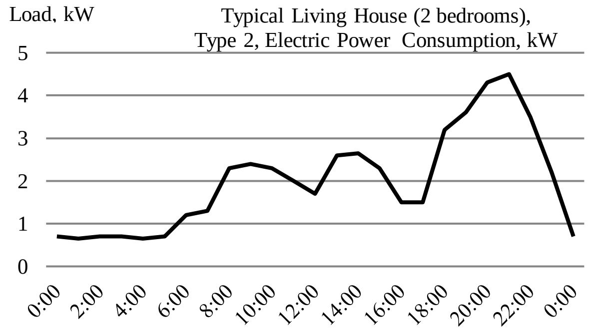

Figure 5. Living House Type 2 Power consumption [10, 14, 20]

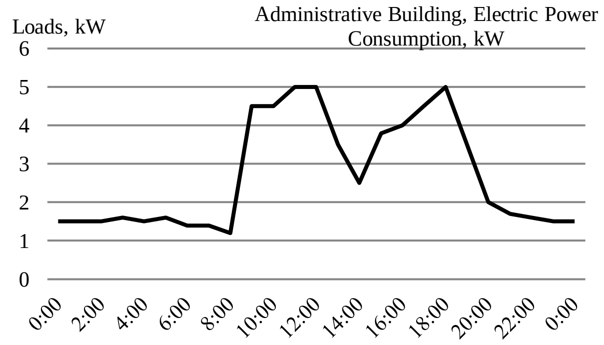

Figure 6. Administrative building's power consumption [10, 14, 20]

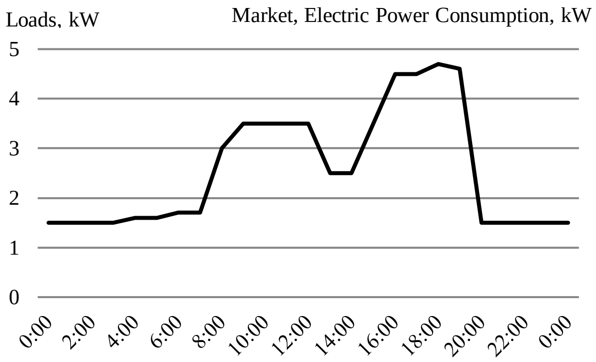

Figure 7. Market's power consumption [10, 14, 20]

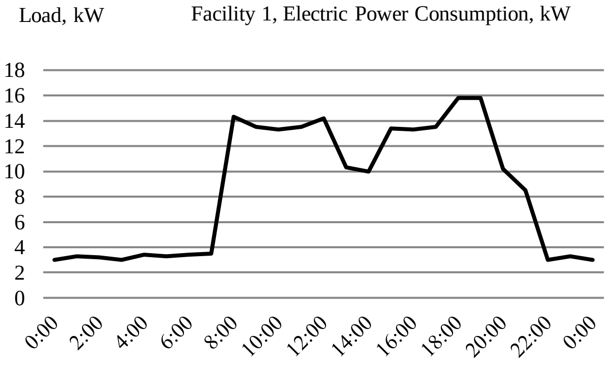

Figure 8. Facility 1 power consumption [10, 14, 20]

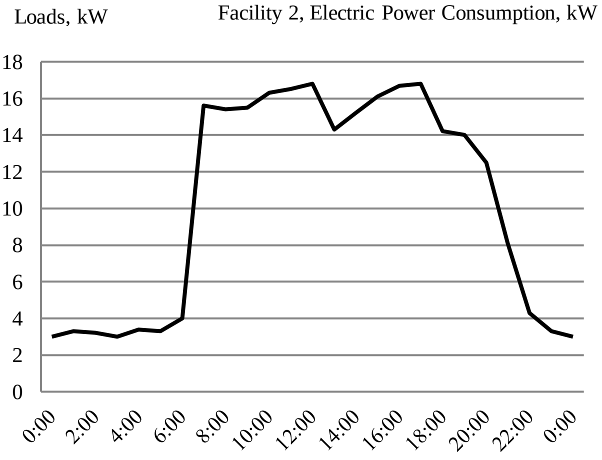

Figure 9. Facility 2 power consumption [10, 14, 20]

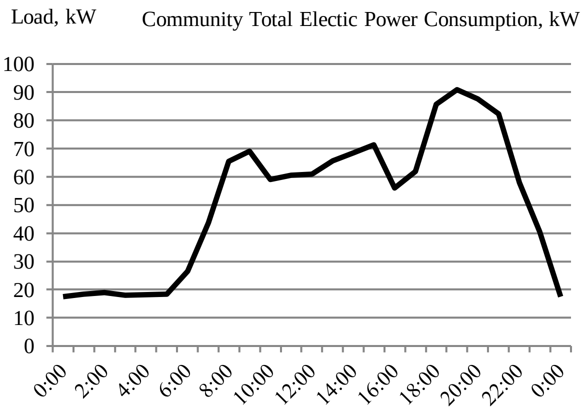

Figure 10. Community's total electric power consumption [10, 14, 20]

6. SOLUTION OF PROBLEM OF CHOOSING OPTIMAL STRUCTURE OF AN AUTONOMOUS DG SYSTEM WITH RES

In this paper, the problem of the autonomous DG system structure optimizing is solved based on the data set of input variables - the solar radiation parameters, wind speeds, ambient temperature, changes in the power of the daily load schedule, the BS state of charge and other objects of the microsystem.

At the same time, the optimal volumes of wind turbines power generation connected to the AC subsystem and the share of power generation from a diesel generator in low wind speeds are determined. In addition, the optimal generation from solar panels connected to the DC subsystem and the corresponding share of energy from batteries - storage is estimated. As a result, a set of the following parameters is determined:

- the number of solar PV panels;
- the number of wind turbines;
- the standby diesel generator power production;
- the total power supplied by storage batteries;

The main goal of the RES power generation control in this system is to obtain the maximum coverage of the loads power consumption in each short time interval (in operation, every current hour of the daily schedule is taken as this interval). In the observation interval in which the values of solar radiation and wind speeds have variability relative to their nominal values and the total power generation from RES covers consumption in this interval. With an excess of power generation from RES in the system, storage devices receive and store this energy.

7. METHODOLOGY FOR CHOOSING OPTIMAL COMPOSITION OF RES AND PLACEMENT

Planning the selection and placement of RES in the DG system, mainly operating in an autonomous mode plays an important role for the efficient and reliable functioning of the system [26-31]. To include the AC subsystem power generation with a wind farm and DC subsystem power generation with a solar station in the hybrid DG system optimal resource planning model, the probability distribution functions of these power flows are divided into a sequence of periods, each of which determines the intervals of changes in wind speed and solar radiation. From the total number of states, states with the Rayleigh Beta distribution are determined, each of which characterizes a probabilistic model of variability - a smaller number of states affects accuracy, while a large number of states affects the complexity of the optimal placement problem. The step size of the state variability, determined by the distribution function, was chosen for solar radiation 0.1 kW/m^2 and 1 m/s for the variability of the wind speed. The probability of random variability of solar radiation and random variability of wind [10, 14] during periods of selected states at given hours is determined as:

$$P_s\left(G_r\right)=\int_{S_{r1}}^{S_{r2}} f_b\left(S\right)dS \tag{1}$$

$$P_w\left(G_w\right)=\int_{V_{w1}}^{V_{w2}} f_b\left(V\right)dV \tag{2}$$

8. MODELS OF AC SUBSYSTEM'S SOURCES

The power production determines by the wind speed and turbine's technical parameters. Depends of the wind speed the power production in different time intervals can be determined in accordance with [10, 14]:

$$P_{w,\omega}\left(V_{a,\omega}\right)=\left\langle P_{nom}\frac{V_{a\omega}-V_{ci}}{V_{a\omega}-V_r}\right\rangle \tag{3}$$

$$0\le V_{a\omega}-V_{ci} \tag{4}$$

$$V_r\le V_{a\omega}\le V_{c0} \tag{5}$$

9. DC SUBSYSTEM'S SOURCES MODELS

Power generation by one solar station module (PV - panel) depends on the intensity of solar radiation, ambient temperature and technical parameters of the module. Taking into account these factors, as well as the presence of the beta radiation probability distribution function [10, 14] for a given area, the following equations are used to calculate:

$$T_{sr}=T_{sa}+S_{ar}\frac{(N_{0t}-20)}{0.8} \tag{6}$$

$$I_r=S_{ar}+S_{ar}\left[I_{sc}+K_t(T_r-25)\right] \tag{7}$$

$$V_r=V_{0c}+K_vT_{cr} \tag{8}$$

$$P_{sr}=(S_{ar})=N.FF.V_r.I_r \tag{9}$$

$$FF=\frac{V_{mpp}I_{mpp}}{V_{oc}I_{sc}} \tag{10}$$

10. SELECTION OF A SOURCES COMBINATION IN AC/DC SUBSYSTEMS OF DG

The choice of RES locations is based on the efficiency factor of solar station modules and wind turbines using on the site. The factor is the ratio of the average power output to the rated nominal power. The average output per hour is the sum of the power produced in all possible states for a given hour multiplied by the corresponding probability of that state.

The average production value is determined for each time interval, typical for each season. The probabilistic model [10, 14] of a set of RES can be described by a random variable:

$$\xi(t)=\left\{V_w(t),R_s(t)\right\} \tag{11}$$

The probability distribution function of a quantity can be expressed using the theorem for multiplying the probabilities of independent events - random sequences of wind and solar radiation parameters [10, 14] in the following form:

$$F\left\{V_w(t),R_s(t)\right\}=\xi\left\{(V_w(t)\right\}.\xi\left\{(R_s(t)\right\} \tag{12}$$

or

$$F\left\{G_w(V_w),G_s(R_s)\right\}=P\left\{(G_w(V_w)\right\}.P\left\{G_s(R_s)\right\} \tag{13}$$

The probability of a possible combination of RES in the DG system [10, 14] can be represented as:

$$P\left\{G_g\right\}=\left\{G_w,P(G_w)\right\};\left\{G_s,P(G_s)\right\} \tag{14}$$

In accordance with the set goal of maximizing the coverage of demand in the remote system at the expense of preliminary estimated RES, it is necessary that with each change in the generation state, the system fulfills the equality condition:

$$P_w+P_s+P_{ess}+P_{diesel}=P_{load} \tag{15}$$

The difference:

$$\left(P_w+P_s\right)-P_{load}=P_{ess}+P_{diesel}=\Delta P \tag{16}$$

In case of under-coverage of RES loads, i.e. if $\Delta P<0$, then for the duration of this situation, additional power comes from the ESS and the diesel generator.

Otherwise, if $\Delta P>0$, if necessary, depending on the state of charge - according to these data, the generation of RES power (daily average, monthly average and annual average) can be determined to cover the settlement load schedule, the excess generation from RES is used to charge the ESS, or a shutdown occurs one of the types of renewable energy sources - mainly - with an insufficient energy resource.

11. CALCULATIONS AND MODELING IN DG MICROSYSTEM WITH RES.

The described methodology for DG with RES functioning was used when for modeling the processes in the system. Simulation results in the form of tables and diagrams are presented below.

A combination of the probabilities of joint operation of RES and backup sources (storage batteries and a diesel generator) can be presented as Table 1 [10, 14].

Table 1. A combination of the probabilities of joint operation of RES and backup sources

Status options	Generation from wind turbine, % of rated power	Generation from a wind generator, % of rated power	Reserve sources (batteries + diesel generator), % of rated power	Load, in% of maximum load
1	0	0	1	0.75
2	0	0.5	1	0.75
3	0	1	1	0.75
4	0.5	0	1	0.75
5	0.5	0.5	1	0.75
6	0.5	1.0	1	0.75
7	1.0	0	1	0.75
8	1.0	0.5	1	0.75
9	1.0	1.0	1	0.75

12. MODELING RESULTS.

Below presented the simulation results performed according to the accepted scheme of the DG with RES. We will consider the processes occurring in the DG Microgrid scheme [17, 20] of a remote consumer (settlement) as part of the Lankaran Region Distribution Zone of Azerenerji Grid in an island mode. The circuit is powered by two AC bus systems (bus 133) and DC (bus 120) current as shown on Figure 11.

The connection of this consumer with the regional power grid is carried out through the T5 400 kVA transformer, line 187 and the T5 2.5 MVA transformer.

The AC bus is powered through a T14 transformer by a renewable energy source - a wind farm, consisting of 3 wind generators with a unit capacity of 70 kW. In the absence of electricity on the AC bus, a 200 kW diesel generator (Gen2) is provided, connected to the AC bus.

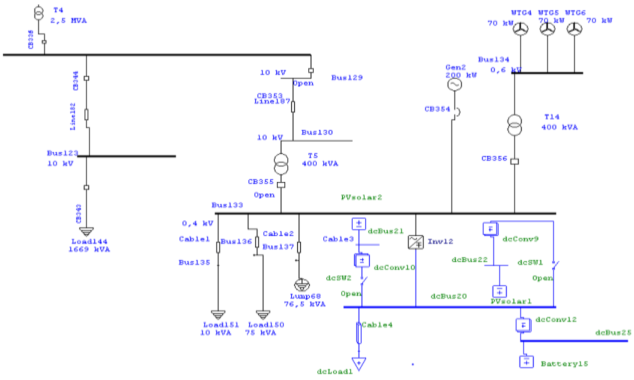

Figure 11. Power supply diagram of a remote consumer (consolidated scheme of 2 similar communities with equivalent summarized generation and corresponding loads) [17, 20]

The DC bus 129 is powered by 2 solar panel systems (PVsolar1 and PVsolar2 each with a capacity of 150kW) and converters (dcConv9 and dcConv10). Both busbar systems are interconnected by a bi-directional inverter (Inv12). AC bus 133 is connected to an AC load (Load 150, 151 and Lump 68), and dcLoad1 is connected to the DC bus. In the absence of wind generation and solar energy or in case of its deficiency, the system provides power from a battery pack (Battery15) connected to the DC bus through a DC-DC converter (dcConv12).

The algorithm of operation of the considered scheme of a remote consumer is to maximize the use of the energy potential of RES - wind power plants and solar power units. Under normal conditions, the AC bus is powered with a voltage of 0.4 kV from the secondary winding of the step-down transformer T14 and, if necessary, receives electricity from solar power units through the Inv12 inverter. When there is a shortage of energy from renewable energy sources, the system is powered by a battery pack through appropriate converters and continues to supply consumers for some time, depending on the capacity of the batteries, and then, when the batteries are depleted, a diesel generator connected to the AC bus is started.

Let us consider a number of cases that may occur when the system operates with a remote consumer as they are shown in Table 1.

Let's consider all 9 cases. There is no wind, PV solar installations do not work (evening and night time); in this case, one of the options is to supply the mains with a Gen2 diesel generator.

From the consideration of the scheme, it follows that the required power for powering residential buildings and an industrial complex (10+73+77 kW) is covered by a diesel generator (160kW). It can be seen that the load on the DC bus is supplied by the battery system, although the control scheme also provides for the possibility of using in this case the energy from the diesel generator through the Inv12 inverter.

Case 2, in Table 1, when there is no electricity generation from wind generators (wind speed is less than 3 m/s for the selected wind turbine models), but the remote microsystem consumer is powered by one of the PV solar units.

It can be seen from the consideration of the circuit that the wind generator does not provide power, and the power supply of 160 kW consumers is carried out from PV-solar units PVsolar2 through its DC-DC converters and Inv12 inverter.

Case 3, in Table 1, when there is no power generation from wind generators (wind speed is less than 3m / s for the selected wind turbine models), but the remote microsystem consumer is powered by PV solar units.

It can be seen from the consideration of the circuit that the wind generator does not provide power, and the power supply of 160 kW consumers is carried out from PV-solar units PVsolar2 through its DC-DC converters and Inv12 inverter. It should be noted that 160 kW passes through the inverter Inv12, i.e. each of the operating solar power units contributes equally to power flow of 160 kW.

Case 4, in Table 1, when there is no electricity supply from solar units, and the remote consumer is powered from a wind generator, which at a wind speed of 10 m/s produces about half of the rated power.

At the same time, as can be seen from the analysis of the flow distribution results, the wind generator delivers 86 kW of power to the AC bus of a remote consumer, and the missing 74 kW is fed to this bus from the batteries through the Inv12 inverter.

In case 5, according to Table 1, the wind turbines still produce 86 kW at a wind speed of 10 m/s, and one unit is used from solar units. At the same time, as can be seen from the calculation scheme of modeling and the results of flux distribution from the wind farm to consumers, 86 kW is supplied, and the rest of the required power (74 kW) comes from one of the solar power units, in this case from PVsolar2.

In case 6 according to Table 1, the wind turbines still produce 86 kW at a wind speed of 10 m/s, and both units are used from solar units. At the same time, as can be seen from the calculation scheme of modeling and the results of flow distribution from the wind farm to the consumers, 86 kW is supplied, and the rest of required power (74 kW) comes from both solar power units.

In case 7, according to Table 1, the wind turbines produce a full 189 kW at a wind speed of 12 m/s, and the solar units do not work (for example, at night). At the same time, as can be seen from the calculation scheme of modeling and the results of flow distribution from the wind farm to consumers, 188 kW is supplied, while 160 kW feed the loads on the AC bus, and 28 kW through the Inv 12 inverter are fed to consumers on the DC bus and charge of accumulator batteries.

In case 8, according to Table 1, the wind turbines generate a full 189 kW at a wind speed of 12 m/s, and the solar units are used at 50% of their capabilities, i.e. for example, one of the two PV power units is in operation. At the same time, as can be seen from the calculation scheme of modeling and the results of the flow distribution from the wind farm to consumers, 189 kW is supplied, while 160 kW feed the loads on the AC bus, and 28 kW through the Inv 12 inverter are fed to the consumers on the DC bus and charge. It should be noted here that the control scheme in this case preferred the use of solar energy to wind energy, although another option can be provided in the control and management unit.

For case 9, 100% power generation is provided by wind and solar units.

The analysis of the results obtained for all variants of the remote consumer's network operation given in Table 1 allowed us to obtain the results summarized in Table 2.

Results of optimal coverage of loads (demand) from RES in the DG system [17] as Table 2.

Table 2. Optimal coverage of loads (demand) from RES in the DG system

Status	Wind turbine's gen., kW	Solar station generation, kW		Power from the Standby energy sources (batt. + diesel), kW		Pres-Pconv, kW	Pload AC, kW	Pload DC, kW
		1	2	Diesel	Batt.			
1	0	0	0	160	0	-160	150	10
2	0	160	0	0	10	150	150	10
3	0	80	80	0	10	150	150	10
4	86	0	0	0	84	2	150	10
5	86	74	0	0	10	150	150	10
6	86	37	37	0	10	150	150	10
7	189	0	0	0	0	189	160	-28
8	189	0	0	0	0	189	160	-28
9	189	0	0	0	0	189	160	-28

13. CONCLUSION

The paper proposes an approach for the types of RES optimal choice and their placement in the DG system - autonomous power supply to consumers of geographically remote regions, with the help of which the maximum coverage of electricity demand for a typical rural settlement with local agricultural production is provided. Based on the data of long-term measurements of solar radiation, wind speeds, ambient temperature and other parameters characterizing the geographical area, the probability distribution functions of these parameters were constructed, and models of wind turbines, solar PV units power generation in the study area were compiled. A probabilistic combination of the joint participation of different types of RES in covering the annual maximum load has been compiled. Based on the linear programming method algorithm, the calculations of the optimal values of the wind farm and PV system installed capacities providing the maximum demand with high accuracy were carried out.

NOMENCLATURES

1. Acronyms

DG	Distributed Generation
RES	Renewable Energy Sources
AC	Alternating Current
DC	Direct Current
PV	Photovoltaic

2. Symbols / Parameters

$P_s\left(G_r\right)$: The probability of solar radiation in the *R* state;

$P_w\left(G_w\right)$: The probability of wind speed in the *W* state W;

S_{r1}; S_{r2}: Limits of the solar radiation variations in the *R* state;

V_{w1}; V_{w2}: Limits of the wind speed variations in the *W* state.

$P_{w,\omega}$: Wind turbine's power production in the state interval;

$V_{a,\omega}$: Average wind speed in the state;

V_{ci}, V_r, V_{c0}: Wind turbine starting wind speed, the nominal wind speed, wind turbine's stopping wind speed.

T_{sr}: PV section temperature in the state *R* interval;

T_{sa}: Ambient temperature, °C;

K_v: Voltage factor divided on temperature (*U*/°C);

K_t: current factor divided on temperature (*I*/°C);

N: Section temperature during parallel working, °C;

FF: Fill factor;

$G_w(V_w)$, $G_s(R_s)$: Discrete random sequences of power generation for every day during the year by renewable energy sources - for a wind farm and a solar station, respectively;

$P\{(G_w(V_w)\}$, $P\{G_s(R_s)\}$: Sequence probability distribution $G_w(V_w)$, $G_s(R_s)$;

P_{ess}: The capacity of the storage system.

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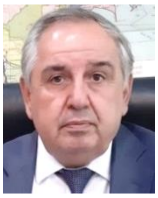
BIOGRAPHIES



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