Abstract--The paper analyses specific features of a system for power supply to isolated territories and populated settlements in Russia. The problems of development of isolated power supply systems are formulated in terms of current trends, technologies and software tools. The optimization problem of different generation units mix is presented. Test system study is discussed.

Index Terms--Small isolated territories, Technical and economic features, microgrid concept, Development optimization procedures

I. INTRODUCTION

In Russia there are many small isolated settlements. They are supplied with electricity from diesel power plants using expensive fuel delivered at large distances. However, in many cases it is possible to supply electricity to consumers on the basis of renewable energy sources, such as wind turbines, small hydropower plants, power plants based on biomass, in particular by converting it into gaseous or liquid fuel. The studies show that in the majority of cases the use of renewable energy sources is economically sound. However, because of variable power generation by wind turbines and small hydropower plants the diesel power plants can serve as standby sources. Besides, for this purpose it is also advisable to consider energy storage systems. Electricity demand management and enhancement of consumers’ role in the process are topical as well.

The power supply system to be formed in such a way is a microgrid of specific structure. Because of unsteady character of power generation, availability of energy storage systems, electricity demand management and also stricter requirements of consumers to power quality and power supply reliability (as a result of extensive use of the up-to-date domestic appliances) development optimization of such power, is not an easy problem that calls for further research.

The paper analyzes specific features of microgrid operation in different seasons of the year and at different hours of the day, formulates a set of problems on optimal development of power supply system.

II. ISOLATED POWER SUPPLY SYSTEMS

About 60% of Russia’s territories, mostly in the North, are not connected to centralized electricity supply due to their geographical position.

Fig.1 [1] presents the zone of centralized electricity supply from interconnected power systems and local power systems in the northern regions. On the remaining territory there are a great number of isolated consumers that are supplied with electricity from low capacity autonomous power sources.

Many studies are devoted to technical and economic assessment of electricity supply to isolated consumers. The feasibility of connecting them to centralized power source or using local small power sources is shown in [1-3]. Also the areas of efficient centralized and decentralized power supply are presented depending on electricity tariffs and diesel fuel cost.

This approach makes it possible to identify at the regional level the zones which require further detailed estimation of applicability of one power supply option or another in terms of their technological feasibility and cost efficiency. The approach also suggests determination of specific options of electricity supply to each consumer, order of power source
commissioning, mix of equipment and required investments. Results of the studies for different regions allow one to make recommendations concerning prospective directions of technological progress in the area of small-scale energy, estimate feasible scales of implementation and market of equipment for economically attractive projects [3,4].

Construction, expansion and operation of power facilities in decentralized areas are very much affected by the following specific features of the territory [5]:

- poor development of the territory, prevalence of small and medium-size settlements;
- hugeness of the territory that causes higher costs of electricity transportation which in combination with low density of electrical loads results in higher costs of centralized power supply;
- use of liquid fuel from distant sellers as a basis for remote power generation systems; complexity, labor intensity and seasonal character of fuel delivery (by air, river or trucks), which increases specific weight of fuel constituent in operation costs of electricity generation;
- remoteness and hard accessibility to the territories which is exacerbated by severe natural climatic conditions.

The above specific features of the territories determine conditions for power supply to decentralized areas, which are characterized by the following [5]:

- low demand for electricity which makes construction of large-scale power supply systems cost-inefficient;
- high transportation constituent in fuel cost due to the need of long-distant fuel deliveries, many stages of transportation and its seasonally limited time frames;
- low technical level of power facilities demonstrating high degree of moral and physical depreciation of equipment;
- low economic characteristics of autonomous power sources (excessive specific fuel consumption for energy generation, overpricing of generated electricity);
- low level of electricity supply reliability.

A large number of scattered consumers which can be supplied with electricity only from autonomous power sources and the problems in the existing decentralized power supply system require urgent development and optimization of power supply to isolated consumers. An obvious way to enhance energy efficiency of such areas is maximal use of alternative and local energy resources which may only become real through a comprehensive analysis of alternative energy development options and assessment of their technical and economic efficiency.

The use of renewable energy sources as an alternative to traditional energy sources has become a priority in the energy policy of economically developed countries. Russia’s energy strategy till 2030 envisages substitution of 20 mln t.c.e. of conventional energy carriers for renewable energy sources. This goal can only be attained through a comprehensive consideration of scientific, economic and technological aspects of putting into operation renewable energy facilities. Introduction of renewable energy technologies along with rational management may foster power supply to the areas with insufficient fuel supply and poorly developed transport infrastructure; resolve the problem of efficient use of resources and involvement of unused energy sources and resources in the regional energy balance; improve environmental situation in the areas of heat and electricity generation, thus contributing to acceleration of economic development in the regions and improvement of social and living conditions of the population. The concept of virtual power plant intended to control operation of power supply systems with distributed generation generally implies integration of distributed generation sources, load-controlled consumers and energy storage systems into a single object in terms of control. This concept can be successfully applied to power supply systems operating autonomously as well as to those connected to the main grid [6].

The problems of power supply to isolated territories are actively studied in different countries. Description of different types of distributed generation capacities that can be installed in the isolated power systems is presented in [7] along with the technical data on energy units and available methods for forecasting electricity generation. Consideration is also given to the issues of power quality and involvement of renewable sources in electricity generation. In small-scale isolated systems various disturbances can cause large frequency deviations. In [8] the model is presented to calculate the maximum frequency deviation.

The models created for isolated microgrid also include those intended to optimize the systems for control of distributed generation, including, in particular renewable energy sources [9-13]. Models of the kind make it possible to optimize network operation by different parameters.

The paper [14] presents design and planning methods for the development of renewable energy microgrids in remote systems using the sustainability philosophy as a guiding framework. The development of microgrids brings a new paradigm in energy consumption of end-users, thus it is required to build a strong social agreement among the microgrid stakeholders. A multi-objective evolutionary optimization algorithm is proposed to balance the diverse and often conflicting technical, economical, environmental and social goals related to energy sustainability.

There are also some publications which deal with economic potential and technological capabilities of microgrids [15,16].

III. PROBLEM OF GENERATION MIX OPTIMIZATION

According to the characteristic of isolated electricity supply systems in Russia optimization of their expansion requires consideration of generation units that use fuel resources for electricity and heat production (diesel, gas turbine, steam turbine, microturbine and other plants) and renewable energy sources (wind and solar units, biomass-fired plants, small-scale hydro power plants and others) [17]. Due to variability of consumer load curves and uneven electricity generation from renewable energy resources account is taken of energy storage devices of different types (super flywheels, battery energy storage systems and others).

A time period during a day is considered for a long term. The representation of isolated electricity supply system relies on balances between generation and load that are specified
with certain discretization of a day. Taking into account a relatively small number of some types of generation units, their mix is considered to be discrete.

Technical and economic characteristics of generation units and energy storage devices in the form of relationships between discounted costs and power generated by the unit are generally nonlinear. When optimized they are approximated by piecewise-linear functions. For wind units, solar units and mini HPPs characteristic daily power generation curves are specified for certain conditions, for example, for the period of winter load peak which determines the maximum requirements for the total power generated.

Based on the above said the optimization problem of the isolated electricity supply system expansion is represented as the following mixed-integer linear programming problem for each time instant of a day taking into account the level of discretization detail of daily power generation and consumption curves:

$$\min \sum_{i=1}^{n} C_i(u_i, P_{gi})$$

subject to constraints

$$\sum_{i=1}^{n} P_{gi} = P_{e2j};$$

$$u_{im} P_{gm}^{\min} \leq P_{gm} \leq u_{im} P_{gm}^{\max};$$

$$c_i(u_i, P_{gi}) = a_{km} + b_{km} P_{gi}^{gm}, \ k \in K;$$

$$i = 1, n; \ m \in M$$

where \(n\) – the number of time instants during a day at discretization of daily power generation and consumption curves;

\(u\) – binary variable that takes a value of 0 or 1 to take into account presence (1) or absence (0) of generation by the units of certain type \(m\);

\(K\) – the number of intervals in which the cost characteristic of power generation by the units of power plants is linearized;

\(m \in M\) - index of generation unit of a certain type;

\(P_{e2}\) - total load of a system;

\(P_{gi}\) - power generated by the unit of type \(m\).

In this case, energy storage devices are also considered in the mix of generation units. They are taken into account with the sign “plus” at power generation and with the sign “minus” at power storage (consumption).

By solving the formulated problem we:

1. Minimize the costs of electricity production during the considered day.
2. Determine optimal values of capacity of energy storage devices as its highest value at a certain time instant of discretized daily load and generation curves.

The considered problem can be solved for several given characteristic calculation days during a year for a long term. In this case the energy storage capacity assumed is the largest value obtained on the basis of several considered characteristic daily curves.

IV. CASE STUDY

The model presented in Chapter III was used to consider 3 scenarios of the isolated electricity supply system expansion. The daily load curve in Fig. 2 shows that the maximum electric load is 12 MW. Discretization of the load curve was performed at 15 min intervals.

![Fig. 2 Power demand](image)

Table 1 presents installed capacities for fuel-fired power plants of four types: cogeneration plants on gas turbine, diesel unit, micro-gas turbine and steam turbine [18].

**Table 1.** Installed capacities for fuel-fired power plants

<table>
<thead>
<tr>
<th>Generator Type</th>
<th>Power [kW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHP Gas Turbine</td>
<td>4,000</td>
</tr>
<tr>
<td>CHP Diesel</td>
<td>3,000</td>
</tr>
<tr>
<td>Micro Gas Turbine</td>
<td>3,000</td>
</tr>
<tr>
<td>CHP Steam Turbine</td>
<td>4,000</td>
</tr>
</tbody>
</table>

**Scenario 1.** The structure of generation units including only fuel-fired power plants, whose characteristics are given in Table 1 is studied. As a result of optimizing the mix of generation units the value of discounted costs makes up 249.47 euro.

**Scenario 2.** The structure of generation units that includes in addition to Scenario1 wind turbines with the total capacity of 30 MW and solar plants with the total capacity of 0.2 MW is studied. As a result of optimizing the mix of generation units the value of discounted costs equals 234.62 euro. Reduction in the value of discounted costs as compared to Scenario 1 is explained by decrease in the current fuel costs for fuel-fired power plants that exceeds the share of additional costs for equipment of wind and solar power plants.

**Scenario 3.** The same structure of generation units as in Scenario 1 with addition of an energy storage device with the discounted costs \(c(P_s) = 0.35 + 0.1P_s\) and the capacity of 0.187 MW is considered. As a result of optimizing the mix of generation units for this Scenario the value of discounted costs equals 234.71 euro, which is somewhat higher than for Scenario 2, since the costs for installation of energy storage device are somewhat higher than the saving of costs owing to optimization. The optimal energy storage capacity was determined to amount to 1.19 MWh (see Fig. 3).
V. CONCLUSIONS

Specific characteristics of isolated electricity supply systems in the remote territories of Russia in terms of high fuel cost for traditional small power plants determine the economic soundness of using renewable energy sources. Non-uniform power generation by power units on renewable energy resources makes it necessary to consider energy storage devices in the structure of generation sources. A combination of traditional units and power plants on renewable energy resources, energy storage devices and consumers with a non-uniform load curve allows the creation of such isolated electricity supply systems to be considered based on the principles of a virtual power plant.

The problem of optimizing the mix of generation units for the isolated electricity supply system that is addressed in the paper and formulated as a problem of mixed-integer linear programming makes it possible to validate expansion of these electricity supply systems. The illustrative example indicates efficiency of the suggested approach.

VI. REFERENCES


VII. BIOGRAPHIES

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