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Designing a Distributed Renewable Energy Generation System for Use in Challenging Climatic and Landscape Conditions

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This paper presents a concept for distributed renewable energy generation systems designed for use in challenging climate and landscape conditions. The proposed configuration is a hybrid system utilizing solar, wind, and small hydroelectric power plants, selected for their adaptability to remote and infrastructure-constrained areas. Particular attention is paid to the system's operational sustainability, modular scalability, and energy autonomy, considering environmental constraints, resource availability, and operational efficiency. A systems approach is employed to determine the optimal configuration of generating units, energy storage units, and control subsystems. As a result, a basic distributed energy system configuration is proposed that can serve as the foundation for decentralized energy supply in hard-to-reach areas. A test example of the system consisting of a 100 W solar module and a 200 W wind turbine is considered for the study, but the characteristics of these devices can be easily changed by the user according to their requests and needs. The study highlights the potential of renewable energy sources as a sustainable foundation for reliable off-grid energy solutions.

Keywords: Hybrid energy systems, renewable energy, distributed energy generation.

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Research Article

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Introduction

The development of renewable energy sources (RES) has become one of the most important areas of global energy policy in recent decades [*Song et al.*, 2022], driven by the need to increase the sustainability of energy supplies, reduce dependence on fossil fuels, and minimize environmental impacts [*Lerman et al.*, 2021]. In this context, the concept of distributed energy, based on localized, autonomous, or semi-autonomous generation systems capable of operating independently of centralized power grids, is particularly important.

For the Russian Federation, with its vast territory and high natural and climatic variability, issues of reliable and efficient energy supply to remote and hard-to-reach areas remain particularly pressing [*Buchatskaya et al.*, 2025]. The territories of Krasnodar Krai and the Republic of Adygea – regions with heterogeneous geography, high-mountain and rugged landscapes, limited infrastructure in some municipalities, and a high percentage of generated energy deficits – demonstrate a high demand for autonomous energy solutions. At the same time, the region possesses significant potential for the use of renewable energy sources: high insolation, the presence of wind corridors, and water resources for small-scale hydropower [*Buchatskiy et al.*, 2024]. Figure 1 shows a map of renewable energy resources for the territory of Krasnodar Krai and the Republic of Adygea.

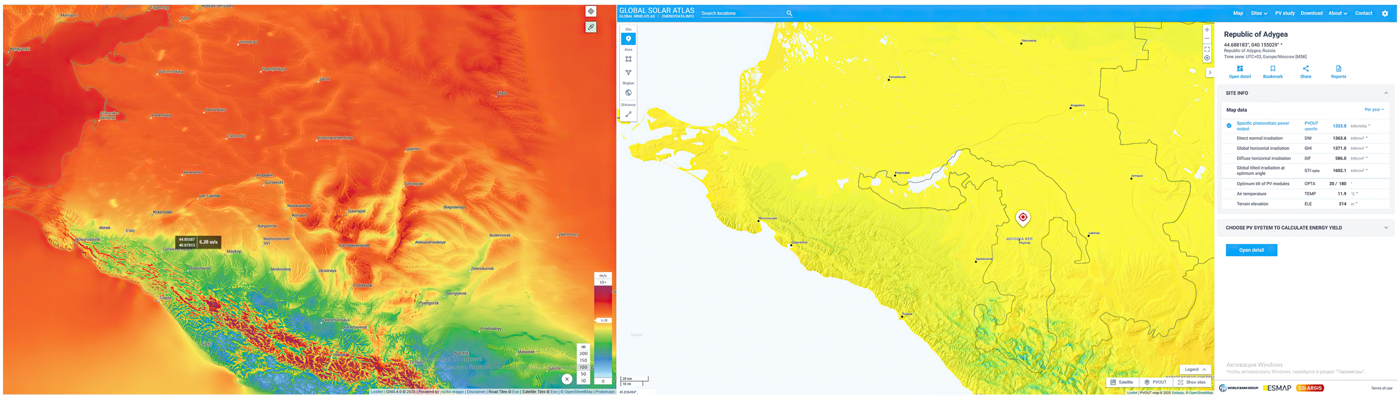

Figure 1. Distribution of renewable energy resources potential in the Krasnodar Territory and the Republic of Adygea (wind and solar energy).

The use of distributed energy generation systems based on solar, wind, and hydroelectric power not only ensures energy independence and improves the quality of life in isolated communities, but also contributes to the achievement of sustainable development goals, economic decarbonization, and energy balance diversification [*Nadeem et al.*, 2023]. Given this, the development of locally adapted distributed energy solutions using renewable energy sources is a pressing scientific and applied challenge. This paper examines the basic configuration of a distributed energy generation system designed for operation in challenging climatic and landscape conditions, with an emphasis on utilizing the region's natural resources as the basis for the development of a flexible and sustainable energy infrastructure.

Materials and Methods

Distributed renewable energy generation and utilization systems are currently receiving extensive coverage in the literature, given their role in the development of smart grids [*Putrus and Bentley*, 2016] and the leading role of renewable energy sources as a tool for achieving global decarbonization goals. In this context, an important category is represented by small-scale systems (up to 5 kW) that provide electricity to local users, primarily from renewable energy sources. As a result, these systems are most often considered autonomous energy systems, which include an electrical energy storage system (battery) and a connection to the national grid to transfer excess/deficit energy from the energy flow [*Vlad et al.*, 2016].

Such energy systems play a special role in remote regions where the use of energy from other sources is extremely difficult or simply impossible, including the mountainous regions of our country. Mountainous regions, which occupy approximately 30% of Russia's area and are home to more than 10 million people, are characterized by extreme terrain and challenging climatic conditions: up to 70% of populated areas are located in areas inaccessible to centralized power grids, while a wide temperature range, high humidity, and frequent precipitation place additional demands on the designed energy systems [*Mori et al.*, 2021]. Such conditions make it impossible to create an autonomous energy system based on the use of a specific renewable energy source [*Delille et al.*, 2012], necessitating the use of a combination of energy resources, energy storage systems, and other energy sources (available grid or diesel generators) to ensure a stable supply to the consumer. Such systems are classified as distributed generation systems, the concept of which involves the implementation of small-scale integrated power supply systems based on renewable energy sources or clean fossil fuels as an energy source, isolated or connected only to the distribution network, which can be scaled as technologies develop and improve [*Cheng et al.*, 2025]. Figure 2 presents a comparison of the concepts of traditional (centralized) and distributed generation.

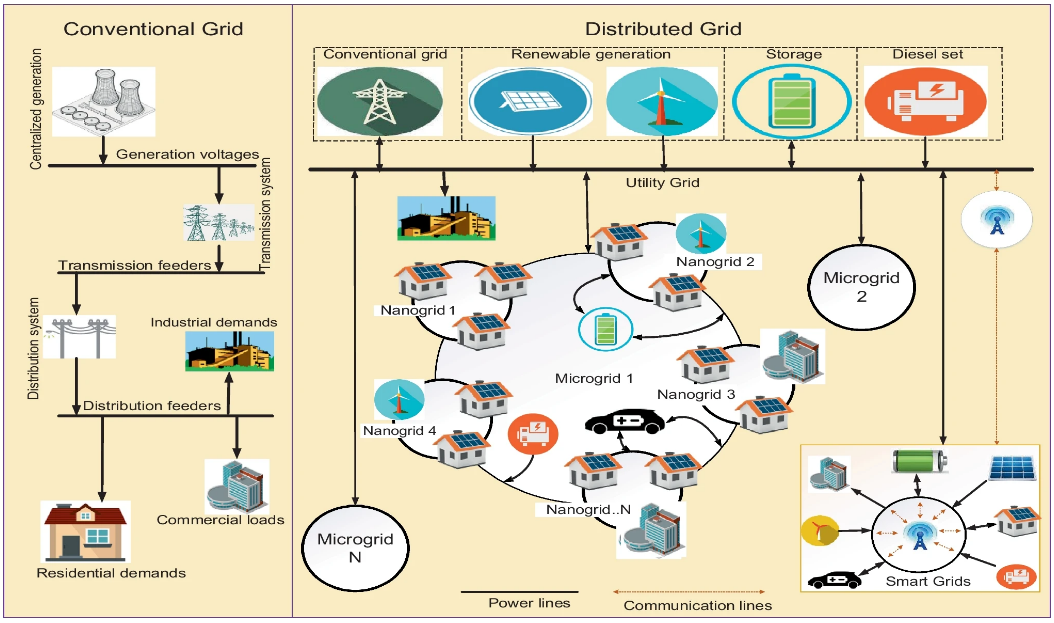

Figure 2. Structural differences between traditional grids and distributed generation.

One definition of distributed generation [*Iweh et al.*, 2021] implies the use of dispersed, small- or medium-sized, integrated power generation units that are not centrally controlled by the main grid and are primarily connected close to load centers to improve power supply, resulting in their energy management strategy typically being independent of the central grid. This definition focuses on pinpoint power dispatch and demand/load management, as opposed to centralized control of power flows, which carries a high risk of large-scale power outages. Figure 3 presents the main sources and technologies used in organizing distributed energy generation systems.

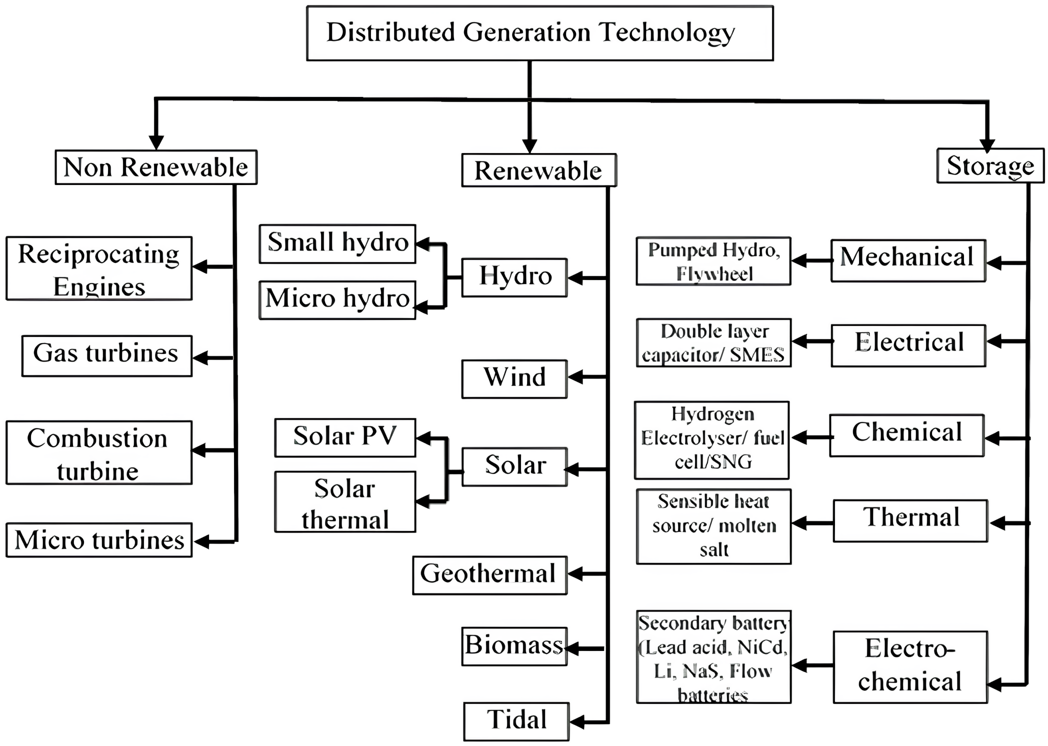

Figure 3. Distributed generation technologies.

The main difficulty in planning distributed systems is determining the most suitable configuration of the energy system, for which it is necessary to carry out a planning procedure [*Hao et al.*, 2022], the algorithm of which is presented in Figure 4.

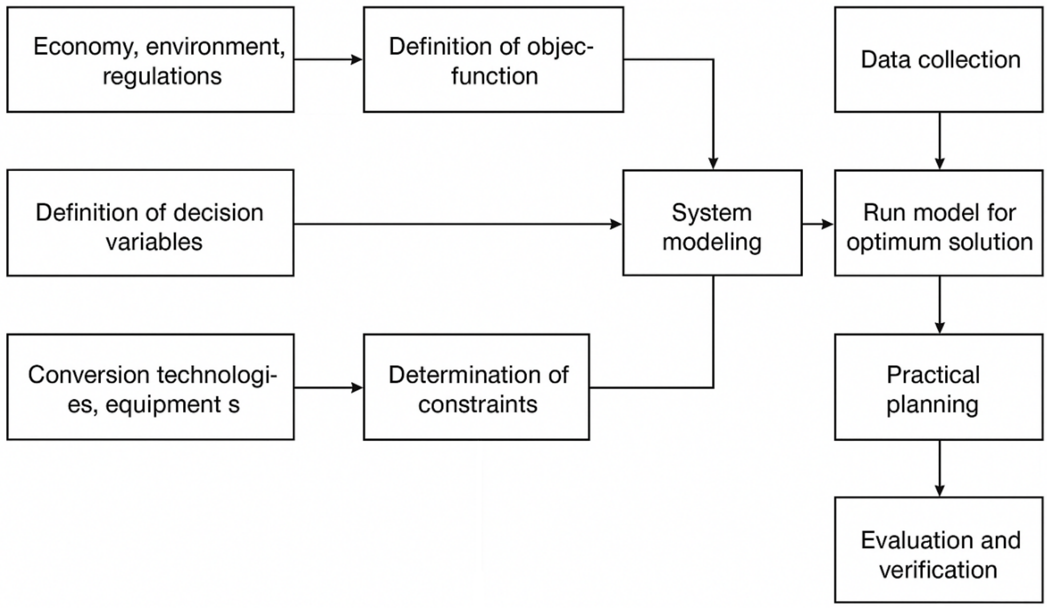

Figure 4. Flowchart of the distributed energy systems planning method.

However, when creating a distributed energy system for operation in remote areas, such as mountainous regions, the majority of energy must be generated through the integration of renewable energy (in some cases, up to 100% in the absence of a common energy grid). This complicates the task, as the process of integrating renewable energy resources is complex and multi-stage.

For the Krasnodar Krai and the Republic of Adygea, the most common resources are solar, wind, and hydroelectric power [*Bedanokov et al.*, 2025; *Simankov et al.*, 2023b], the use of which should form the core of the distributed energy system. An integral part is an energy storage system [*Simankov et al.*, 2024], allowing for the use of energy during periods of low generation, and an energy grid, which is not necessarily a branch of the centralized energy infrastructure, but can serve as a link between several remote generation sources, to which end consumers connect. Figure 5 shows a diagram of such a distributed energy system based on the use of renewable energy resources.

Using the proposed design, a power system model was implemented in a dynamic simulation environment, incorporating three main generation sources: solar and wind energy, as well as energy from small rivers and streams. To simulate energy production, the following prototypes of real devices were selected, the parameters of which can be modified in accordance with changes in the scale of the operating power system:

- YSM-100 100 W solar panel;
- wind generator ROSVETRO SS-200 200 W;
- hydroelectric generator with a pipe width of 10 cm (a model of an overhead water wheel for small streams and mountain rivers).

The first step in assessing the theoretical potential of renewable energy sources for mountainous areas is to model the generation of electricity from photovoltaic plants.

The efficiency of photovoltaic panels is determined by their final temperature and varies for different panel types. The dependence of solar panel surface temperature on ambient temperature can be calculated using the following equation:

$$T_{\text{pi}} = T_{\text{impact}} + \frac{E_i}{800} * \left(T_{n.\text{temp}} - 20\,^{\circ}\text{C}\right),$$

where T_{pi} – solar panel surface temperature, °C; E_i – arrival of solar radiation; T_{impact} – ambient temperature at the design point, °C; $T_{\text{n.temp}}$ – normal operating temperature of a solar panel, °C.

The normal operating temperature of the solar panel used was taken from the device documentation and is 45 °C. The methodology for assessing the power generation of a solar power plant, taking into account efficiency and temperature, is as follows:

$$P = I_{\text{gtc}} * F * \eta * \left(1 - k_t * \left(T_{\text{pi}} - 25\right)\right) * k_{\text{cloud}},$$

where P – solar power plant capacity, W; I_{gtc} – total solar radiation, W/m²; F – solar panel area, m²; η – efficiency of photovoltaic converters; k_t – temperature coefficient of change in efficiency of photovoltaic panels; T_{pi} – solar panel surface temperature, °C, k_{cloud} – cloudiness coefficient.

Similar results were obtained in [*Badran et al.*, 2009; *Jansen and Smulders*, 1977]. The authors analyzed the effect of solar module heating temperature on electricity generation in their local conditions, considered several methods for calculating the power of solar modules, and selected a suitable result. The cloud accounting method was taken from [*Simankov et al.*, 2023a]. Thus, the formula will take the form:

$$P = I_{\text{gtc}} * 0.509234 * 0.1964 * \left(1 - 0.0045 * \left(T_{\text{pi}} - 25\right)\right) * k_{\text{cloud}}.$$

Currently, solar radiation and temperature data were taken from the PVGIS website for the mountainous area, and cloud cover data from the http://rp5.ru/ website for the city of Maykop. These data are fed to the model using the “Reading lines from file” block. The next step is to model wind turbine power generation.

A wind turbine captures energy from moving air and converts it into electricity. The energy captured is affected by factors such as air density, blade coverage, air velocity, and power factor, as shown in the following equation.

$$P = \frac{\rho * V^3 * A}{2} * k,$$

where P – wind power plant capacity, W; ρ – air density, kg/m³; V – wind speed, m/s; A – area covered by the rotor blades, m²; k – efficiency of a wind turbine.

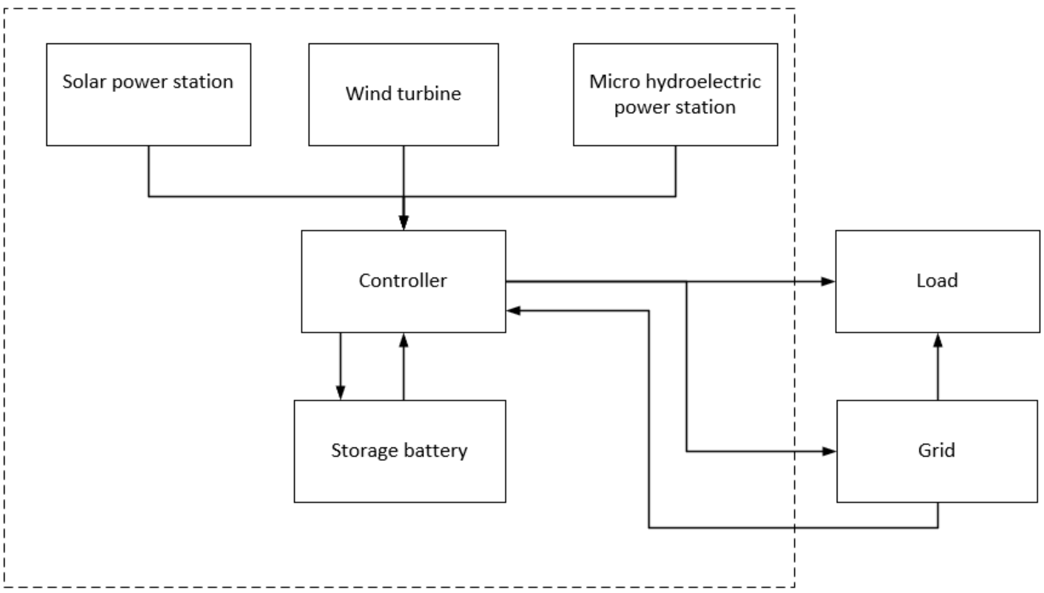

Figure 5. Functional diagram of a distributed energy system based on renewable energy sources.

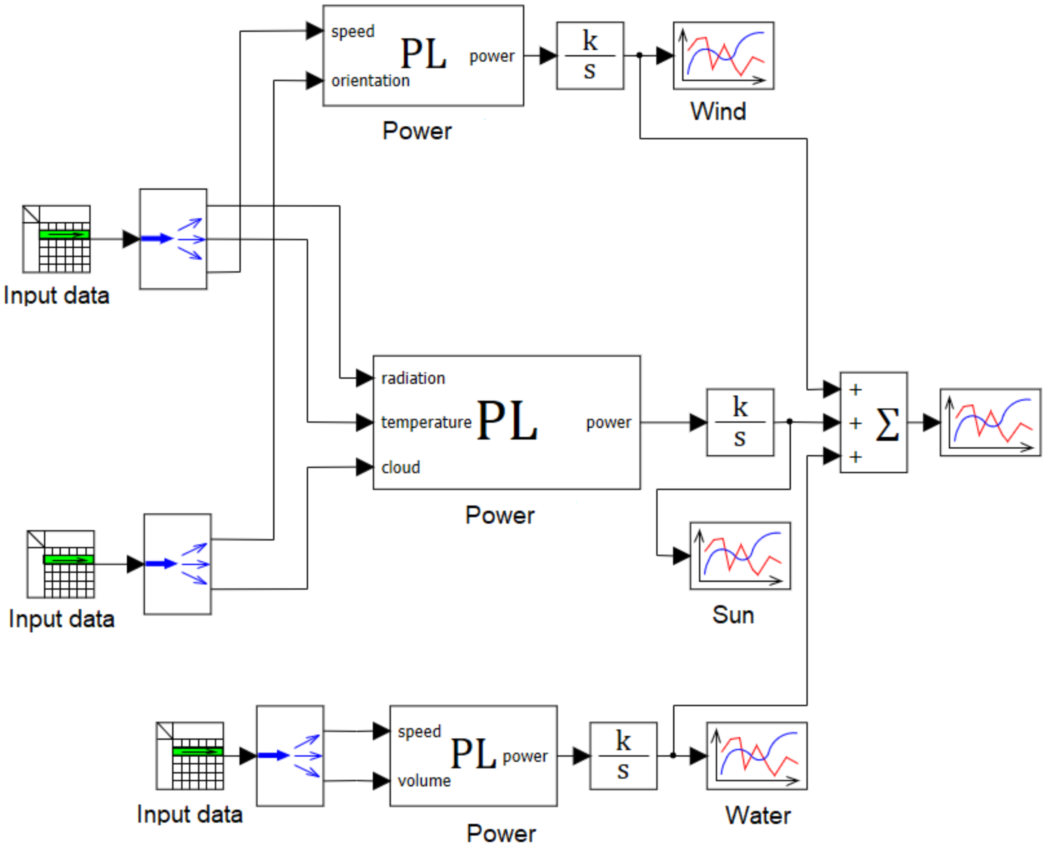

Figure 6. Simulation model of a distributed energy system based on the assessment of the theoretical potential of renewable energy sources.

For our operating conditions, the air density is 1.225 kg/m^3, the area covered by the rotor blades is $\approx$1.0568 m^2 , and the efficiency is about 40%. Taking these requirements into account, the formula will take the following form:

$$P = \frac{1.225 * V^3 * 1.0568}{2} * 0.4.$$

Wind speed data for the mountainous area was taken from the PVGIS website and is also fed to the model from a file. For the wind turbine used, there is no need to consider wind direction, as the current model is automatically oriented to the wind and does not require a wind direction dataset.

The final step in developing a model for assessing theoretical potential is simulating the power generation from a mini hydroelectric power plant. The factors influencing the amount of energy generated by a hydroelectric power plant are given in the following equation:

$$P = \rho * Q * g * h * k,$$

where P – hydroelectric power station capacity, W; Q – water flow in the pipe, m^3/s; g – acceleration of gravity, 9.81 m/s^2; h – height difference, m; k – efficiency of mini hydroelectric power plants.

For our mountainous conditions, the difference in height between the inlet and outlet of the water flow in the pipe is 1.2 m, the water density is 1000 kg/m^3, and the efficiency is over 70%. Taking this into account, the formula takes the following form:

$$P = 1000 * Q * 9.81 * 1.2 * 0.7.$$

As a result, a model for assessing the theoretical potential for energy generation from renewable energy sources was developed, presented in the Figure 6.

As a result, theoretical values for the maximum electricity generation from three sources per year were obtained: a wind turbine, a solar panel, and a turbine hydro generator (Figure 7).

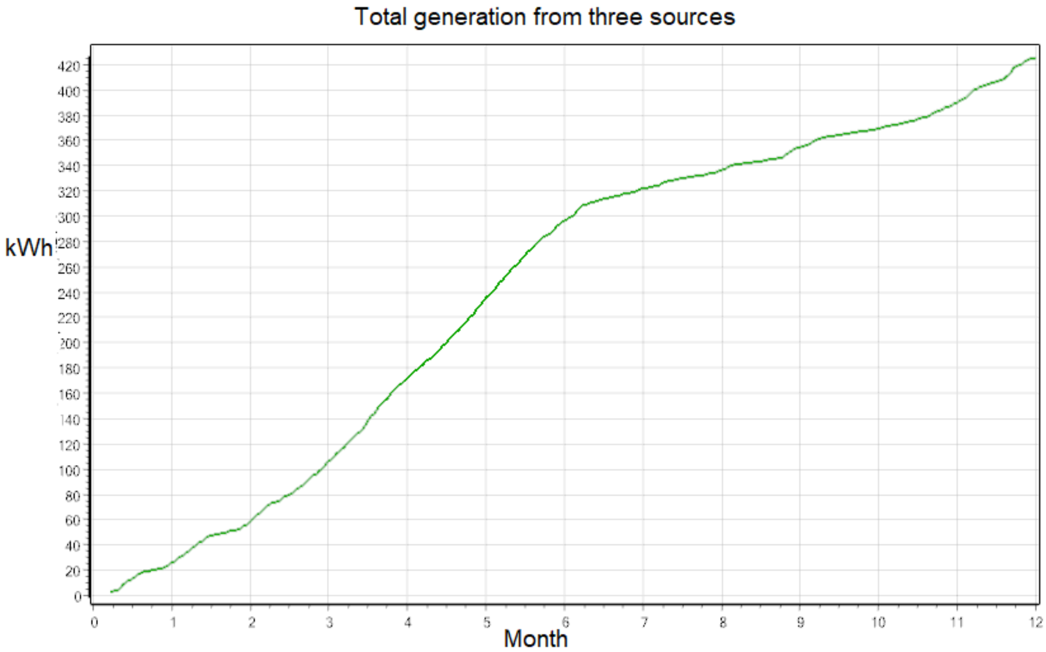

Figure 7. Generation volumes using three sources of green energy.

Conclusion

This paper examines the basic configuration of a distributed energy system based on renewable energy sources – solar, wind, and small hydropower – designed for operation in conditions with limited infrastructure, challenging terrain, and climatic conditions, which is particularly relevant for regions such as Krasnodar Krai and the Republic of Adygea. The proposed system can be used in both stationary and mobile energy complexes, providing power to remote communities, socially significant facilities, and industrial infrastructure. The constructed functional diagram reflects the main components and interaction principles of distributed generation elements, and the implemented simulation model allows for estimating the total theoretical electricity output from three generator types over various time periods, enabling an initial assessment of the feasibility of using such a system within specific geographic coordinates. The paper presents a test configuration of the energy system, but at the user's request, it can be easily changed to the required one by replacing the main parameters, which makes its use flexible and applicable for various generation capacities and provides the opportunity to assess the energy potential in various areas.

The results demonstrate that an integrated approach to designing distributed energy systems using multiple renewable energy sources enables increased energy autonomy, reduced dependence on external grids, adaptability to seasonal and weather fluctuations, and stable operation even in challenging terrain and climate conditions. Thus, the proposed system can be considered a promising solution for ensuring reliable and environmentally friendly energy supply in remote and hard-to-reach regions.

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