The application of autonomous systems based on renewable energy sources in rural settlements of different regions of Russian Federation

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Abstract. The aim of the research is to analyze and determine the most perspective renewable energy source (RES) for autonomous off-grid electrification in small settlements (less than 500 people) of Russia. Three climate zones were investigated in the research – South region, Far East region, Central region where average summer insolation is 5,76 kWh/m²; 5,88 kWh/m²; 5,35 kWh/m² and average winter insolation is 1,93 kWh/m²; 0,75 kWh/m²; 1,03 kWh/m², respectively. Output power values were similar in all investigated regions, however the main economic impact comes from social-economic factors – regional fuel price, transporting costs, assumed to be 75$US/month and size of photovoltaic system – higher solar activity needs fewer PV cells to satisfy required load. Using simulating software, hybrid photovoltaic-diesel systems demonstrated various costs of energy (LCOE): 0.257$/kWh in Krasnodar region, 0,378$/kWh in Orenburg region and 0,4$/kWh in Irkutsk region. Higher solar activity during winter season in Krasnodar region that allows to reduce fuel consumption as well as LCOE. Increased solar activity also allows to reduce the number of panels required to satisfy the demand. These results was compared to diesel only generators. Krasnodar region generators LCOE was 1,19$US/kWh, Orenburg region generators LCOE was 1,13$US/kWh, Irkutsk region generators LCOE was 1,31$US/kWh. The investigation also shows the influence of the ecological factor on the utilization of renewable energy sources – decrease in fuel consumption from 6000 liters per year to about 250 liters per year as well as reducing the carbon dioxide emissions.

1 Introduction

According to the latest All-Russian Population Census total number of rural settlements in Russian Federation exceeds 150 thousands. In most regions of Russian Federation, bigger part of rural population are living in small villages (population under 1000 persons). Vast territories of the country and centralized energy policy are limiting the possibilities of electrification of small rural settlements. Almost 60% of Russia’s territory are not connected to the centralized electricity supply grid. Especially northern regions [1] due to geographical

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location. In this case people in regions had to create decentralized energy grids. The problem of decentralized electrification in northern and far west regions are investigated in many studies. [2-4] But the problem of remote locations is present not only in northern regions. The Southern Federal District has about 2% of the reserves of Russian oil, 7% of gas, and 3.5% of coal resources [5] are concentrated in its territory, for which reason the energy shortfall here is mainly covered by the use of coal from the Siberian Federal District and natural gas from the Ural Federal District [6]. By importing energy and fuel resources from other districts significantly increase the price of energy for remote settlements.

Other important reason of population decline and reducing number of villages is migration to the bigger settlements. The closure of educational institutions, healthcare centers and hospitals, is primarily due to difficulties with the supply of energy to remote regions. [7] In the situation of disconnection from the main energy supply grid, remote settlements are forced to use diesel generators to create living conditions in their homes. Renewable energy in Russia is represented by solar, wind and geothermal energy, as well as several small power plants based on biogas and biofuels. In the works of [8-10] annual solar radiation in Russia varies from less than 2.8 kWh/m² per day to 6 kWh/m² per day in Southern regions. Wind and solar energy potentials surpass the natural gas-based (currently the main energy source in Russia) power generation several times to order of magnitude (depending on the region of Russia) [8] Photovoltaic systems are one of the best solutions for countries with high solar potential such as Egypt [8], Algeria [12] and India [10]. The main idea of the research is to investigate the possibility of creating electrification system based on the renewable energy sources for small rural settlements. According to RIARating 2018 data, more than half of Russia's regions are in a deficit in energy efficiency [1]. The small population and the long distance to the nearest center make such settlements economically unprofitable for energy suppliers to create full-fledged energy supply lines.

2 Methods

2.1 Population analysis

To select the most promising regions for the implementation of autonomous renewable energy systems, we analyzed the groupings of rural settlements by population in the constituent entities of the Russian Federation, presented in the results of the All-Russian Population Census [12] We investigated the regions with the most varied climate conditions. Krasnodar region, located in sub-tropical climate zone, Irkutsk regions, located in the extreme-continental climate zone and Orenburg region, located in the moderate climate were chosen for the research. In this research we investigated 3 villages in the chosen regions – Bzhid, Krasnodar region (44.352737, 38.666694), Angasolka, Irkustk region (51.746832, 103.756700), Shkunovka, Orenburg region (50.775991, 55.367155)

2.2 Evaluating of renewable potential

Evaluating the renewable potential of Russian Federation for rural settlements three most prospective options were considered – solar photovoltaic (Solar PV) systems, wind turbine systems and hydropower generation. Hydroelectricity producing is the most developed renewable energy source in Russia – the share of hydropower among all renewable energy sources is around 16.5% [13, 14]. Due to geographical location restrictions of the hydropower station, it is not economically viable for most of the rural settlement to rely on hydropower electrification. At wind speed started from 12 m/s at the 100m height, wind turbine can produce almost 3kWh [7]. But these parameters can be achieved only using large wind
turbine, which are non-transportable, extremely expensive and requires large installation space. Solar irradiation per day can reach up to 5,4 kWh/m² making PV solar arrays much more convenient.

2.3 Load demand specification

According to the research [15] in the total energy consumption of a rural settlement, the main share of energy is consumed by the residential sector, including private household plots (approximately 80-85%), peasant (farm) households, approximately 5-7%.

Table 1. Number of rural settlements of Russian Federation with different population sizes [13]

| Region            | Total number of rural settlements | Number of rural settlements with different population |
|-------------------|-----------------------------------|------------------------------------------------------|
|                   | Under 500 person s                | 500-1000 person s | 1000-2000 person s | 2000-3000 person s | 3000-5000 person s | 5000-7000 person s | 7000-10000 person s | 10000-20000 person s | Over 20000 person s |
| Orenburg region   | 559                               | 94             | 240             | 154             | 25             | 19             | 10             | 12             | 5             | 0             |
| Irkutsk region    | 365                               | 68             | 105             | 142             | 32             | 8              | 7              | 1              | 2              | 0             |
| Krasnodar region  | 352                               | 10             | 29              | 63              | 66             | 69             | 70             | 25             | 36             | 14            |

Table 2. Grouping of rural settlements by population size of Federal Region of Russian Federation [16]

| Region            | Total population of rural settlements | Total population size of the rural settlements |
|-------------------|--------------------------------------|-----------------------------------------------|
|                   | Under 500 person s | 500-1000 person s | 1000-2000 person s | 2000-3000 person s | 3000-5000 person s | 5000-7000 person s | 7000-10000 person s | 10000-20000 person s | Over 20000 person s |
| Krasnodar region  | 2028394               | 100             | 6102            | 99698           | 15917          | 26780          | 41208          | 20476           | 46372          | 41503         |
| Orenburg region   | 6102                  | 21360           | 26780           | 41208          | 20476          | 46372          | 41503         |
| Irkutsk region    | 99698                 | 15917           | 26780           | 41208          | 20476          | 46372          | 41503         |

The share of the communal and household sector of the village is about 8-15%. In this work we assumed the load profile of small settlement which consist of 8 small (180-240 m²) living houses with basic electronic devices, school building, administrative building, hospital building and a canteen. Additionally, the load from farm with 3 to 5 cows, 3 to 5 calf, 8 to 10 pigs (Table 3). All energy consumption figures are obtained for the climatic conditions of the Central Region. The peaks of the load demand are in the morning, around the noon and in the evening. It can be explained by simultaneous turning on the electronic equipment at the start of the day, food preparation for lunch and dinner. Average daily consumption of estimated village is about 11.3 kWh per day.

Table 3. Power consumption structure for community infrastructure and facilities.

| Model                          | Installed capacity (kWh) | Model                          | Installed capacity (kWh) |
|-------------------------------|--------------------------|-------------------------------|--------------------------|
| Living house                  | Hospital building        | Lighting, electrical appliances| 2.0                      | 0.45                   |
| Thermal processes (heating, cooking) | 1.0                      | Heating                       | 1.0                      |
| School building               | Canteen                  | Lighting, electrical appliances| 0.8                      | 0.37                   |
| Heating                       | Thermal processes (heating, cooking) | 2.85                           |
| Administrative building       | Farm                     | Heating                       | 1.0                      |
| Lighting, electrical appliances| 0.6                      | Food preparation              | 0.3                      |
| Heating                       | 0.8                      | Microclimate (heating, ventilation) | 1.0                           |
|                              |                          | Water supply                  | 0.4                      |
3 Results and discussion

We used the HOMER Pro software to simulate the operating conditions with the climate parameters of the different regions and analyze how different climate conditions can affect the energy production. On the Fig 1-3 it can be seen that in every region there is deficit of solar radiation in winter months. Overall, energy production via PV cells pretty similar in all three investigated regions. During the winter there was not enough solar activity, this is why decision of supporting diesel generator as additional source of energy was made. Analysis of the energy generation in various regions, demonstrated similar results in all investigated areas. This means that main differences in the performance outcome of the systems comes from socio-economic features of the region. Lower fuel consumption and regional fuel prices directly affect the cost of energy in each region.

Fig. 1. Average monthly electric production in Bzhid, Krasnodarskiy region.

Fig. 2. Average monthly electric production in Shkunovka, Orenburg region.

Fig. 3. Average monthly electric production in Angasolka, Irkustk region.

Geographical location of the village is connected to the transporting costs of fuel, as well as regional fuel prices. At the moment of the investigation the price of diesel fuel in Krasnodar was 0,62 $/l, in Orenburg price was 0,64 $/l and the highest price of diesel fuel was in Irkutsk region at 0,69 $/l. Additionally 75$US based on the average tariffs for the transportation of petroleum products on distances less than 50 km.

In this research we simulated our model based on the following components of the hybrid system – 6kW power PV array, 15 12V with 1kWh of energy storage lead-acid batteries as storage system and additional 1kW diesel generator as supportive source of energy. The cost of diesel generator, cost of installation were taken as 600$/kW, and 10% of initial cost of the generator. The operating & maintenance cost (OMC) was considered $0.03/h. The operating lifetime was taken as 15,000 h. Up to date diesel fuel cost in Russia is $0.5/L. Additionally, we added extra $0.15/L for transporting costs, because a lot of distant regions has limited access to fuel and there is need to deliver it to the consumer. The initial cost and total NPC...
of the hybrid PV + Diesel system were found to be $5748 and $12402 respectively. Higher solar activity in the region which leads to the need for fewer solar cells. Lowest Cost of Energy (LCOE) at 0.257 $/kWh was achieved in the condition of Bzhid village, using only power of 4kW PV array (standard LCOE is 0.318$US/kWh). LCOE for hybrid system in Shkunovka village was 0.378 $US/kWh. And lastly, LCOE for hybrid system in Angasolka village was 0.406 $US/kWh. Comparing these results to standalone 2kW diesel generator, cost of energy while using only diesel generator in Krasnodar was 1.19$US/kWh. Cost of energy in Orenburg region was 1.13$US/kWh and in Irkutsk region the cost of energy was 1.31$US/kWh (Figure 4).

Table 4. - Results of the simulation in HOMER Pro for investigated regions.

| Source of energy | Annual production, kWh/year | Tot. production % | Annual consumption | Excess energy, kW | % | Fuel consumption, liters |
|------------------|-----------------------------|-------------------|-------------------|------------------|---|-------------------------|
| PV array         | 6995                        | 90.6              | 3805              | 3428             | 44.3 | 0                       |
| Diesel Generator | 601                         | 9.43              |                   |                  |     |                         |

Shkunovka, Orenburg region

| PV array         | 7338                        | 89.3              | 4109              | 3728             | 43.3 | 0                       |
| Diesel Generator | 625                         | 10.7              |                   |                  |     |                         |

Angasolka, Irkutsk region

| PV array         | 6304                        | 85.3              | 4109              | 2136             | 30.6 | 0                       |
| Diesel Generator | 785                         | 14.7              |                   |                  |     |                         |

Other important aspect of the comparison is overall fuel consumption. Using load profile assumption and chosen locations of the villages we simulated the off-grid electrification station in the HOMER Pro software to see how environmental conditions of the different regions and climate zones affect the performance of the system.

Table 5. – Social-economic and environmental conditions of investigated regions.

|                      | Shkunovka, Orenburg region | Angasolka, Irkustk region | Bzhid, Krasnodar region |
|----------------------|---------------------------|---------------------------|------------------------|
| Population           | 23                        | 28                        | 30                     |
| Climate              | Moderate                  | Extreme-continental      | Sub-tropical           |
| Average value of summer insolation, kWh/m² | 5,35                      | 5,88                      | 5,76                   |
| Average value of winter insolation, kWh/m² | 1,03                      | 0,75                      | 1,93                   |
| Average summer temperature, °K | 290,5                     | 303,65                    | 306,85                 |
| Average winter temperature, °K | 260,45                    | 241,05                    | 272,85                 |
| Fuel price, $US     | 0,64                      | 0,69                      | 0,62                   |
| Distance to the nearest city, km | 5,6                       | 26                        | 14                     |
4 Conclusions

This paper investigated the use of renewable energy source based systems for electrification of rural settlements in distant regions of Russian Federation.

1. Different region with various climate conditions and were investigated to research the performance of the systems. Federal regions were analyzed by the density of population and the number of rural settlements.

2. The most promising solution for electrification was found to be hybrid PV system with supporting diesel generator and battery storage. Initial Cost of the Hybrid PV-diesel system was 5748 $US and Present cost of the system was 12402 $US.

3. Comparing Hybrid PV-diesel system with diesel only system the lowest cost of energy as main economic factor was 0,257 $US/kWh in Bzhid, Krasnodar region for hybrid system and 1,19 $US/kWh for diesel only generator. In Shkunovka village of Orenburg region hybrid system cost of energy was 0,378 $US/kWh compared to diesel 1,13 $US/kWh and hybrid cost of energy in Angasolka village of Irkutsk region was 0,406 $US/kWh compared to diesel 1,31 $US/kWh.

4. Main pricing factor of RES systems was found to be transporting costs, regional fuel prices, size of storage system and size of PV array. The last parameters, in the condition of high solar activity, can be adjusted to satisfy the required load demand by fewer components. For example, Krasnodar region, reducing LCOE from 0,318 $US/kWh to 0,257 $US/kWh by decreasing power of PV array from 6kW to 4kW.

5. Switching from diesel generators to hybrid systems allows to reduce fuel consumption as well as carbon dioxide emissions. It is possible to decrease fuel consumption from 6000 liters per year to about 250 liters per year.

Fig. 4. – Levelized cost of energy in the investigated regions.

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