Efficiency of Hybrid Renewable Energy Systems in Russia

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Abstract- The paper presents a research on the assessment of cost-effectiveness of a hybrid electric power system including photovoltaic modules, wind turbines, wood-fired biomass gasification power plants, batteries for electric energy storage, and diesel power plant. An optimal structure of the electric power system is determined for different climatic zones of Russia. The energy sources are ranked with respect to their efficiency, by imposing constraints on capacity of individual plants (ban on commissioning). The results obtained demonstrate that the use of photovoltaic modules in Russia is effective only in the southern regions of the country with the solar insolation on the horizontal surface of above 1200-1250 kWh/m^2/yr, the use of biomass gasification power plants and wind turbines is effective in all climatic zones. In the case of cheap fuel wood the biomass gasification power plants can play a major role in the power supply system. The study demonstrates a considerable economic effect of the renewable energy sources for many considered variants. However, the most preferable option is the combined use of different renewable energy sources: wind turbines, photovoltaics and a biomass gasification power plant.

Keywords renewable energy sources, wind turbines, photovoltaic modules, biomass gasification power plant, mathematical model, optimization, effectiveness.

1. Introduction

There has been a hot discussion on the impact of man's economic activity on the climate on Earth over the past decades. Reports of the Intergovernmental Panel on Climate Change (IPCC) in particular claim that there is a high probability that the predominant reason for warming observed since the middle of the 20-th century is an anthropogenic impact on the climatic system [1-3]. Warming is a consequence of a change in the energy balance of Earth due to an increasing concentration of greenhouse gases in the atmosphere, and, first of all, carbon dioxide (CO_2) from fossil fuel combustion.

Therefore, the importance of the development and adoption of renewable energy sources (RES) is increasing. Providing a noticeable environmental effect (reduction in the emissions of harmful substances to the environment), renewable energy sources in many cases can be cost – effective and competitive with fossil fuel power plants [4-9].

Russia at the official level recognizes the danger of the global climate change and expresses readiness to undertake measures to reduce greenhouse gas emissions. In particular, according to a Decree of the President of the Russian Federation in the time horizon until 2020 CO_2 emissions should be reduced by 25% compared to 1990 levels [10].

This goal can be achieved by implementing a program of the Government of the Russian Federation on RES development stimulation. The program sets a goal to put into service 3.6 GW of wind turbine (WT) capacity, 1.52 GW of photovoltaic (PV) capacity, and connect them to the power system by 2018 [11].

Originally, the RES development program suggested the use of Russian and imported assembly parts of the equipment with a gradual increase in the share of those domestically manufactured. However, depreciation of the ruble in 2014 made it unprofitable to buy the equipment abroad, and the economic crisis reduced the interest of investors in the implementation of the previously planned projects. Despite the difficulties faced by this program the first plants were put into service in 2015-2016. Therefore, the set goals can be accomplished, although later (2020-2025).

In Russia the most widely used renewable energy resource is hydro power. Along with its considerable potential, the involvement of wind and solar energy as well as wood biomass whose reserves are particularly great in the eastern and northern regions of the country (North-Western Federal District, Siberia and the Far East) [12]. The territories of potential application of the renewable energy sources within the autonomous power supply systems cover almost all regions of unreliable and off-grid power supply in the country, that make up 2/3 of the country's area [5].

The operation of renewable energy sources on the basis of wind and solar energy is stochastic. Therefore, it is sensible to include them into the hybrid (integrated) power systems that contain backup energy sources and electric batteries to provide continuous and reliable power supply. In Refs. [13-15] it is shown that photovoltaics, wind turbines and batteries in a low-power autonomous power system can meet no more than 80–85% of demand for electricity. Continuous and reliable power supply is provided first of all by backup energy sources, i.e. diesel power plants.

Hybrid renewable energy systems (HRES) have been the subject of many studies in recent years. In many publications the main attention is paid to the technical aspects of the HRES operation and simulation modeling of their operating conditions under different energy management strategies [16, 17]. Trazouei et al., in particular, use Imperialist Competitive Algorithm [18]. Okinda and Odero apply a parallel multidimensional implementation of genetic algorithm [19].

HRES are simulated with the models TRNSYS [20-22], HOGA (the model based on Genetic Algorithms) [23, 24] and other tools. The problem of cost-effectiveness assessment of hybrid renewable energy systems is often solved using the Hybrid Optimization Model for Electric Renewables (HOMER) [25-42]. This software models the operation of the systems in time, by enumerating different variants of their structure.

The researchers discuss various configurations of hybrid systems based on renewable energy resources for different locations. The most often considered configurations are PV/Diesel/Battery [14, 25, 26], Wind/Diesel/Battery [27, 28], PV/Wind/Battery [29, 30, 40, 41, 43-47], PV/Wind/Diesel [15, 31], PV/Wind/Diesel/Battery [32-35, 42, 48]. Whereas less attention is paid to the configurations based on biomass generators, such as PV/Gasifier/Diesel [36], PV/Wind/Biomass generator/Battery [37, 38], PV/Wind/Biomass generator/Diesel/Battery [39].

Arun specifies that the integration biomass gasifier in the hybrid system makes the system more sustainable as indicated by the significant reduction in the diesel fuel consumption and emissions [36]. Liu et al. show that under different climatic conditions of the seven selected locations in Australia a PV-wind-biomass-battery-converter system has the benefits of cost and emissions reduction [37]. Dursun et al. designed a wind/PV/biomass/battery hybrid power generating system which is environmentally friendly and consists of only renewable sources [38].

The hybrid systems studied by Sigarchian et al. consist of PV modules, a wind turbine, biogas engine, diesel engine and battery bank [39]. The feasibility of using locally produced biogas to drive a backup engine in comparison to using a diesel engine as backup was explored through a techno-economic analysis using HOMER. This hybrid system was also compared with a single diesel based power system. The result shows under which circumstances a system including a biogas engine generator set is economically a better choice than the one including a diesel engine generator set as backup.

Research in Ref. [6] is concerned with the analysis of cost-effectiveness of power plants using renewable energy resources according to the criterion of levelized cost of energy for different climatic zones of Russia. In the case of integrated systems this analysis should be expanded considering system effects that occur due to relations existing between energy sources of various types and energy storages. Such system effects are normally taken into account by applying special mathematical models.

The goal of the present research is to assess the effect of the joint use of renewable energy sources of different types within a low-power hybrid autonomous power system (up to 100 kW) in the zones of off-grid power supply in Russia. Special attention is paid to economic rather than technical aspects of hybrid energy system (wind turbines+PV modules+biomass gasifier power plant+diesel+batteries) operation.

The calculations are based on the mathematical model REM-2 (Renewable Energy Model) [49,50]. The model do not use in advance set energy management strategies. Unlike the known models [20-39] based on either enumeration of variants [7, 25-42] or dynamics simulation modeling [20-24,51], the model REM-2 makes it possible without use of in advance set energy management strategies to study power systems of various configurations with conversion of one energy form into another and storage of various energy forms, on the basis of GAMS (General Algebraic Modeling System) optimization algorithms.

2. Power Supply Scheme

The power supply system consists of wind turbines (WT), photovoltaic modules (PV), a biomass gasification power plant (BGPP) fuelled by wood, storage batteries (BAT), an inverter (INV) and a diesel power plant (DPP) (Fig. 1).

Energy sources with stochastic (random) generation (PV and WT) are connected to a DC line. After a corresponding transformation of voltage level they charge the storage battery. Diesel generator turns on at the time when generation from PV and WT is insufficient to cover the electrical load and storage batteries are discharged. The diesel power plant operates directly for load without additional transformation of voltage.

The power supply system includes the diesel power plant to provide continuous and reliable power supply [13]. The batteries can partially compensate for the non-uniform RES generation and provide additional energy and economic benefits owing to a reduction in the installed capacity of the diesel power plant and fuel consumption.

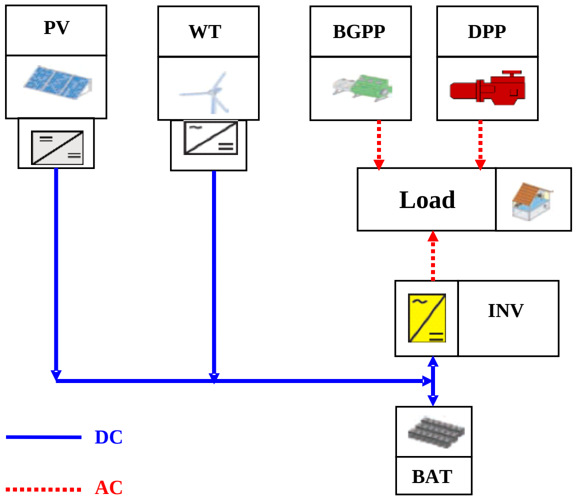

Fig. 1. Energy flows in the power supply system (PV – photovoltaic modules, WT – wind turbine, BGPP – biomass gasification power plant, DPP – diesel power plant, INV – inverter, BAT – battery).

3. Mathematical Model

The mathematical model applied for calculations does not require a preliminary setting of an algorithm to switch energy between energy sources, load and storage systems. Such an algorithm can be specified only for an energy system with relatively simple configuration. So the model allows studying energy systems of various structures with energy production, conversion and storage, including that considered in the present research (with RES and energy storage). A detailed characteristic is given in [49], below its main specific features are discussed.

For the considered energy system we specified the lists of primary energy resources J_1, secondary energy carriers J_2 and types of final energy J_3. The system includes energy plants (technologies) of two types: a) for energy conversion (transportation), and b) for energy (energy carrier) storage. In the conversion plants the primary and secondary energy is converted to final energy and/or to the secondary energy of another form. In the storage systems the secondary energy is stored to be used further. The model takes account of a random nature of incoming solar and wind energy.

The energy system operation is modeled with a time step Δt. Variables with index t = 0, 1, 2, …, T refer to the corresponding time instants.

At time instant t the capacity of the i-th energy conversion plant equals $N_{it} \le \overline{N_i}$ (where $\overline{N_i}$ is installed capacity). The following coefficients are specified for each energy conversion plant ($i \in I$): α_{ij} is specific (per unit) consumption of the j–th energy resource and β_{ik} is specific generation of the k–th energy type.

At time instant t the secondary energy reserve in the j-th storage is $Q_{jt} \le \overline{Q_j}$ (where $\overline{Q_j}$ is the storage capacity). For each energy storage technology ($j \in J_2$) we specify the efficiency η_j, which characterizes energy storage losses.

Moreover, for all the technologies ($i \in I \cup J_2$) the set parameters include: k_i is specific (per unit of installed capacity, for storage device – capacity) capital investment, μ_i is annual constant operating costs (share of capital investment) and ΔT_i *is* lifetime of the plant. In this research special attention is paid to economic rather than technical aspects of hybrid energy system. Therefore, all technologies are described identically as a "black box" with the input and output of the energy flows. The time series of solar insolation and wind speed were preliminarily constructed for PV and WT [5]. Power of photovoltaics varies proportionally to incoming solar radiation on their working surface. Power of wind turbine is proportional to the cube of the wind speed (on the segment of the power curve before the rated speed of wind turbine is achieved).

Mathematical statement of the problem is as follows: find the minimum of the objective function, i.e. the total discounted costs

$$Z = \sum_{i \in I} (F_i + \mu_i) k_i \overline{N_i} + \sum_{j \in J_2} (F_j + \mu_j) k_j \overline{Q_j} +$$

$$+ \frac{H}{T} \sum_{t=1}^{T} \sum_{j \in J_1} p_j \sum_{i \in I} N_{it} \alpha_{ij} \to \min$$

provided that some constraints on primary energy consumption, final energy production, secondary energy balances and constraints on the variables are met.

Here:

$F_i = \ln(1+d) / \left[1 - (1+d)^{-\Delta T_i} \right]$ is the capital recovery factor at an annual discount rate d; H = 8760 h/year; p_j – price of the primary energy resource.

The decision variables are installed $\overline{N_i}$ and current N_{it} capacities of energy conversion units, secondary energy reserves in storages Q_{jt} and their capacities $\overline{Q_j}$, as well as the flows of energy to be stored. Stochastic operating conditions of renewable energy sources are not optimized since they are determined by external natural conditions and are given for the model.

Objective function Z represents the total (annualized) discounted costs of the system construction and operation.

4. Initial Data

The main factors determining the cost-effectiveness of renewable energy sources are potential and reserves of a respective natural resource, technical and economic indices of power plants, and price of the replaced fossil fuel.

The resources of solar and wind energy are ubiquitous and differ only in the energy potential, whereas the resources of biomass energy are limited, i.e. some areas do not have biomass resources sufficient for industrial uses.

Energy generation from PV and WT depends considerably on climate conditions of the plant operation [5, 6]. Solar insolation of the Earth's surface and wind speed vary depending on weather conditions, and have a pronounced daily and seasonal dependences.

Annual insolation of the horizontal surface is determined first of all by the latitude of an area. Southern areas are the most favorable for the development of solar energy. Annual insolation varies across the territory of Russia within the range from 800–900 kWh/m^2 in the extreme North to 1000–1200 kWh/m^2 in the central zone and up to 1200–1400 kWh/m^2 in the southern regions of the country, respectively [6, 28, 29]. At the same time annual insolation of an inclined surface of a solar panel can reach 1500–1600 kWh/m^2 (in the south of Krasnodar and Primorye and in some other southern and high-mountain areas).

The long-term average wind speed measured at a standard height of 10 m is a key indicator for assessment of the efficiency of wind energy use. In Russia the highest wind speed is characteristic of the sea and ocean coasts (8–9 m/s), decreasing in continental regions up to 2–5 m/s [6, 52, 53]. As a rule, in the Center of Russia the long-term average wind speed does not exceed 2–4 m/s. The zones of average wind speeds (4–6 m/s) are observed in some mountainous areas, coasts of large lakes and valleys of some large Siberian rivers. High wind speeds (above 6 m/s) are typical of the coastal areas of seas of the Arctic and Pacific Oceans, the coasts of the Baltic and Black Seas and also of some mountainous areas of the North Caucasus and Polar Urals [6].

As an energy resource biomass ranks below some fossil fuels in heating value, however, it has some serious advantages over them. Its main advantages are renewability, relatively lower emission of carbon dioxide during combustion, considerably lower content of harmful substances in ash versus mineral fuel, possibility for cultivation and procurement close to consumption areas, which leads to a multiple decrease of transportation distance from the area of cultivation to the area of consumption. Fuel wood (residues of logging and woodworking industries) is the main and most effective resource of biomass.

It should be underlined that if the volume of biomass procured on some territory for energy use does not exceed its buildup (for the case of timber) or is equal to this volume (for the cases of biomass fuel production from herbage of agricultural plants), then such method of power production does not cause the CO_2 content to increase in the atmosphere.

The study deals with the variable load of 100 kW maximum and the capacity factor equal to 0.5 which is typical of power supply systems of low capacity. The maximum load falls on the evening hours, in the nighttime hours the load is 10% of the maximum (such an essential nonuniformity is characteristic of the majority of isolated power systems).

Table 1 presents technical and economic indices of system components which are assumed in calculations. The system comprises Russian manufactured facilities: solar panels ED-240, solar controllers ECO Energia MPPT Pro 250/60, WT Condor Air WES-380/50 with a controller, voltage converters and inverters MAP Hybrid Energia and batteries MicroArt 720A, DPP of АД series in container design and also connecting cables. The cost of voltage converters (DC/DC for PV and AC/DC for WT), solar and wind controllers is included in capital costs on PV and WT, respectively.

In Russia the diesel fuel price at production plants amounted to 450–500 US$/toe in late 2016 and early 2017. By region of Russia it varies from 600–800 US$/toe (South of Russia and Center) to 700–1000 US$/toe (the northern remote areas of the country). The calculations were based on the following typical values: South – 600 US$/toe, Center – 700 US$/toe, North – 1000 US$/toe.

Table 1. Technical and economic characteristics of power supply system components

Components	Specific investments, US$/kW	O&M, % of investments	Efficiency, %	Life time, years
PV	1200	1	15	25
WT	2000	2	30	25
DPP	400	5	30	10
BGPP	1800	5	25	10
Inverters	200	2	95	25
Batteries	180 *	5	95	5

Note: * – US$/kWh.

The biomass price (first of all, fuel wood) depends on a great number of specific factors characterizing a concrete area. The main part of fuel wood resources is concentrated in the northern areas of the country, in the South they are considerably smaller. The fuel wood price of 50–70 US$/toe (the lower value – for the North, the higher value – for the South) which is typical of Russia is taken for calculations.

The change of variables over time in each season was modeled with a time step of 1 hour. The maximum wind speed is observed in the winter period and the maximum solar insolation falls on the summer noon.

5. Calculation Results and Their Analysis

The calculation results of the optimal structure of a power supply system for different climatic zones in terms of the described distinctions in diesel and fuel wood prices and characteristics of wind and solar radiation are presented in Table 2.

The results obtained show that in Russia PVs are effective only in the southern areas of the country with the annual solar insolation on the horizontal surface of above

1200–1250 kWh/m^2, BGPPs and WTs are effective in all climatic zones. The WT share in the power system is the largest in the northern and southern areas and is small in the Center of Russia, where the average wind speed seldom exceeds 4 m/s. BGPPs play the main role in the North with concentration of basic fuel wood resources and the minimum price of wood chips. In all the considered variants DPP plays a role of the peak power source for uninterrupted power supply.

In the southern areas of the country conditions for WTs and PVs are favorable (the average many-year wind speed is V=5 m/s and the incident solar radiation on the horizontal surface is Q=1400 kWh/m^2). Therefore, the optimal solution covers all the considered energy sources and the total discounted costs are the lowest among the variants presented in Table 2 (65.000 US$). Similar characteristics of wind and solar radiation are typical of the southern littoral areas of Russia (the coasts of the Black and Caspian Seas, the south of Primorye) [6].

Table 2. The optimal structure of power supply system for different climatic zones of Russia

Climatic zones	Installed capacities, kW			
	DPP	BGPP	PV	WT
North	30	70	0	100
Center	40	60	0	30
South	40	60	20	50

For this variant (South) the renewable energy sources were ranked in efficiency. In the process of optimization the constraints (ban on commissioning) were sequentially imposed on their capacity (Table 3). As far as the optimal variant includes all RES, such a ban increases costs on power supply to consumers (Fig. 2). The first four variants do not include BGPP, the other four variants include it.

Table 3. The optimal structure of power supply system

Variants		Installed capacities, kW			
		DPP	BGPP	PV	WT
1	DPP	100	–	–	–
2	DPP+PV	100	–	80	–
3	DPP+WT	90	–	–	75
4	DPP+PV+WT	80	–	40	75
5	DPP+BGPP	60	40	–	–
6	DPP+BGPP+PV	60	40	30	–
7	DPP+WT+BGPP	40	60	–	50
8	DPP+PV+WT+BGPP	40	60	20	50

At first we consider power supply only from DPP without RES (Variant 1). Addition of PV to the system (Variant 2) and WT (Variant 3) considerably improves economic efficiency (see Fig. 2). Joint use of wind and solar power plants and the DPP capacity backing them is optimal in the first group of variants (1-4). In the case of RES unavailability the load power should be backed completely by DPP. The use of WT makes it possible to decrease the DPP capacity up to 90 % of the maximum load and in combination with PV – up to 80 %.

In Variants 5–8 with WT and PV the BGPP on fuel wood is used additionally. Its inclusion improves economic efficiency of the power supply system. As is seen from Fig. 2, both statements are true: 1) supplement of BGPP to WT and PV cuts costs, 2) supplement of WT and PV to BGPP also cuts costs.

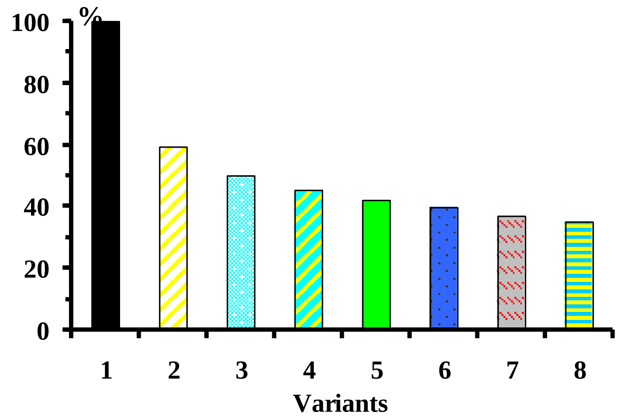

Fig. 2. Relative costs for different power supply system configurations (1 – DPP, 2 – DPP+PV, 3 – DPP+WT, 4 – DPP+WT+PV, 5 – DPP+BGPP, 6 – DPP+BGPP +PV, 7 – DPP+WT+BGPP, 8 – DPP+WT+PV+BGPP).

The contribution of different power sources in total electricity production without BGPP (Variant 4 in Table 3) and with BGPP (Variant 8) is compared in Fig. 3. In the variant with the least costs (Variant 8), the contribution of renewable energy sources to the total power generation is 88%.

The power supply system which comprises all components presented in Fig. 1 (Variant 8) is the least cost variant. WT and PV complement one another. The use of PV is highly effective in the summer time. However, the uninterrupted power supply can be supported by inclusion of WT to compensate for decreased power production by solar modules in the winter time and absence of their production at nights. Fig. 2 shows that exclusion of any of the components (WT, PV or BGPP) increases the cost of power supply systems.

It should be noted that the difference in costs in Variants 2–8 is not so great. It means that as a first approximation the considered RES are of equal economic efficiency and the use of any of them in addition to DPP essentially improves performances of the power supply system.

The additionally performed calculations showed that decrease in load power (to 1-10 kW) led to increase in the relative share of PV in the optimal structure, and the relative share of WT increased with the load growth. This is explained by the fact that difference in the specific investment in favor of PVs increases with the decreasing capacity.

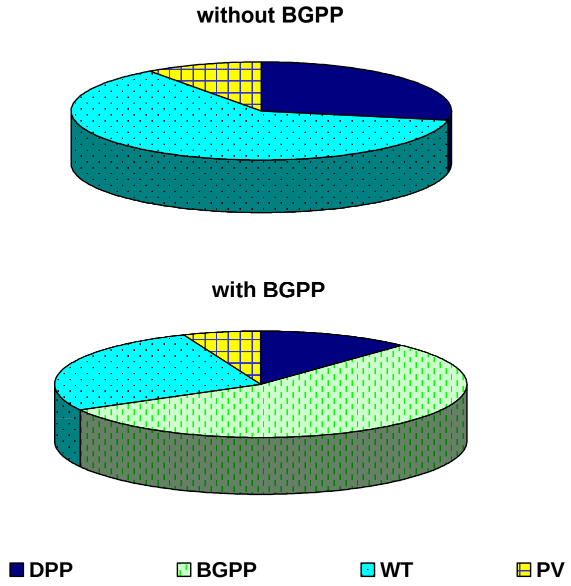

Fig. 3. Share of different power sources in total electricity production in the power supply system without BGPP and with BGPP.

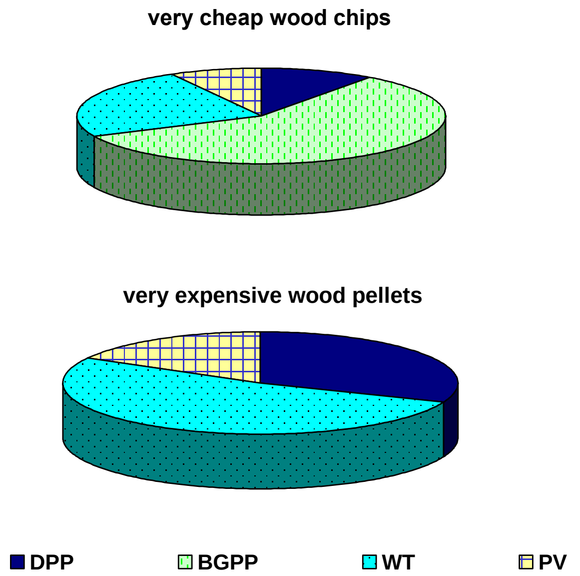

Fig. 4. Share of different power sources in total electricity production for very cheap wood chips and very expensive wood pellets.

The fuel wood cost differs depending on specific conditions. In some cases the wood resources may be taken as free of charge or even having a negative cost, if the territory is cleaned up of garbage and all charges on wood residue removal are compensated for by customers. The BGPP efficiency was analyzed in greater detail by calculations with variation of fuel wood cost in a wide range between 1 and 250 US$/toe. Fig. 4 presents the contribution of different power sources in total electricity production for very cheap wood chips and very expensive imported wood pellets. With cheap wood fuel, the main contribution to the total generation of electricity (more than 50%) is provided by BGPP. With expensive wood fuel, BGPPs become uneconomical and are replaced by other sources of energy. In the second variant in Fig. 4 (the use of expensive wood pellets) the battery capacity increases from 40 to 240 kWh due to increased generation of electricity from power sources with a random generation mode.

6. Conclusion

1. The economic efficiency of the 100 kW power supply system including PV, wind turbines, biomass gasification power plants on fuel wood, batteries and diesel power plant was assessed by the mathematical modeling. The efficiency of using renewable energy sources was shown for different climatic zones of Russia.

2. The results obtained demonstrate that the use of PV in Russia is effective only in the southern regions of the country with the solar insolation on the horizontal surface of above 1200–1250 kWh/m^2/yr, the use of BGPP and WT is effective in all climatic zones.

3. The calculation results show that the use of all indicated power system components will be the optimal solution in the areas with solar insolation of above 1200 kWh/m^2/yr. If any of the power system components (PV, WT or BGPP) is excluded, the costs rise by 10–15 %, and unavailability of RES leads to the rise of costs by more than 2.5 times.

4. In the case of cheap fuel wood the biomass gasification power plants can play a major role in the power supply system and as concerns expensive wood pellets the use of WTs in combination with PV is preferable.

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References

[1] Climate Change 2014. IPCC Fifth Assessment Synthesis Report, 2014.
[2] Global Energy Assessment – Toward a Sustainable Future. International Institute for Applied Systems Analysis, Vienna, Austria and Cambridge University Press, Cambridge, UK and New York, USA, 2012.
[3] L.S. Belyaev, O.V. Marchenko, S.P. Filippov, S.V. Solomin, T.B. Stepanova, and A.L. Kokorin, World energy and transition to sustainable development, Boston, Dordrecht, London: Kluver Academic Publishers, 2002.
[4] O.V. Marchenko, and S.V. Solomin, "System studies for analyzing the efficiency of renewable energy sources", Thermal Engineering, vol. 57, no. 11, pp. 919-924, 2010.
[5] O.V. Marchenko, and S.V. Solomin, "Efficiency of small autonomous wind/diesel/hydrogen systems in Russia", International Journal of Renewable Energy Research, vol. 3, no. 2, pp. 241-245, August 2013.
[6] O.V. Marchenko, and S.V. Solomin, **"**Economic efficiency of renewable energy sources in Russia", International Journal of Renewable Energy Research, vol.4, no. 3, pp. 548-554, October 2014.
[7] P. Lombardi, T. Sokolnikova, K. Suslov, N.I. Voropai, and Z.A. Styczynski, "Isolated power system in Russia: a chance for renewable energies?", Renewable Energy, vol. 90, no. 5, pp. 532-541, May 2016.
[8] L.S. Belyaev, O.V. Marchenko, and S.V. Solomin, "The Study of the Long-Term Trends in the Development of the Energy Industry of Russia and the World", Thermal Engineering, vol. 58, no. 13, pp. 1089-1095, December 2011.
[9] O.V. Marchenko, and S.V. Solomin, "The future energy: hydrogen versus electricity", International Journal of Hydrogen Energy, vol. 40, no. 10, pp. 3801-3805, March 2015.
[10] Russian Federation Presidential Decree of 30.09.2013, No. 752. − URL: http://kremlin.ru/acts/bank/37646 (Accessed date 27.02.2017) (in Russian).
[11] On the incentive mechanism of using renewable energy sources in the wholesale electricity and capacity markets. The RF Government Resolution of 28 May, 2013, No. 449. − URL: http://www.government.ru/docs/2121 (Accessed date 27.02.2017) (in Russian).
[12] A.B. Levin, "Fuel resource of forest bioenergy of RF", Lesnoy vestnik, no. 4, pp. 30-36, 2010 (in Russian).
[13] A.G. Bhave, "Hybrid solar-wind domestic power generating system – a case study", Renewable Energy, vol. 7, no. 3, pp. 355-358, July 1999.
[14] S. Diaf, D. Diaf, M. Belhamel, M. Haddadi, and A. Louche, "A methodology for optimal sizing of autonomous hybrid PV/diesel system", Energy Policy, vol. 25, no. 11, pp. 5708-5718, February 2007.
[15] M.S. Ngan and S.W. Tan, "Assessment of economic viability for PV/wind/diesel hybrid energy system in southern Peninsular Malaysia", Renewable and Sustainable Energy Reviews, vol. 16, no. 1, pp. 634-647, January 2012.
[16] L. Olatomiwa, S. Mekhies, M.S. Ismail, and M. Moghavvemi, "Energy management strategies in hybrid renewable energy systems: A review", Renewable and Sustainable Energy Reviews, vol. 62, pp. 821–835, May 2016.
[17] O. Erdinc, and M. Uzunoglu, Optimum design of hybrid renewable energy systems: Overview of different approaches", Renewable and Sustainable Energy Reviews, vol. 16, pp. 1412–1425, January 2012.
[18] S.L. Trazouei, F.L. Tarazouei, and M. Ghiamy, "Optimal Design of a Hybrid Solar-Wind-Diesel Power System for Rural Electrification Using Imperialist Competitive Algorithm", International Journal of Renewable Energy Research, vol.3, no. 2, pp. 403-411, August 2013.
[19] V.O. Okinda, and N.A. Odero, "Modeling, Simulation and Optimal Sizing of a Hybrid Wind, Solar PV Power System in Northern Kenya", International Journal of Renewable Energy Research, vol. 6, no. 4, pp. 1199-1211, December 2016.
[20] V. Bakić, M. Pezo, Ž. Stevanović, M. Živković, and B. Grubor, "Dynamical Simulation of PV/Wind Hybrid Energy Conversion System", Energy, vol. 45, no. 1, pp. 324-328, September 2012.
[21] S.G. Sigarchian, A. Malmquist, and T. Fransson, "Modeling and control strategy of a hybrid PV/Wind/Engine/Battery system to provide electricity and drinkable water for remote applications", Energy Procedia, vol.57, no.1, pp. 1401-1410, November 2014.
[22] Q. Huang, Y. Shi, Y. Wang, L. Lu, and Y. Cui, "Multi-turbine wind-solar hybrid system", Renewable Energy, vol. 76, no.4, pp.401-407, April 2015.
[23] J. L. Bernal-Agustin, and R. Dufo-Lopez, "Simulation and Optimization of Stand-Alone Hybrid Renewable Energy Systems", Renewable and Sustainable Energy Reviews, vol. 13, pp. 2111-2118, October 2009.
[24] R. Dufo-Lopez, J.L. Bernal-Agustin, and J. Contreras, "Optimization of control strategies for stand-alone renewable energy systems with hydrogen storage", Renewable Energy, vol. 32, no. 7, pp. 1102–1126, June 2007.
[25] Z. Girma, "Technical and Economic Assessment of solar PV/diesel Hybrid Power System for Rural School Electrification in Ethiopia", International Journal of Renewable Energy Research, vol. 3, no. 3, pp. 736-744, September 2013.
[26] S. Salehin, M.M. Rahman, and A.K.M. Sadrul Islam, "Techno-economic Feasibility Study of a Solar PV-Diesel System for Applications in Northern Part of Bangladesh", International Journal of Renewable Energy Research, vol. 5, no. 4, pp. 1220-1229, December 2015.
[27] D. Saheb-Koussa, M. Koussa, and N. Said, "Prospects of Wind-Diesel Generator-Battery Hybrid Power System: A Feasibility Study in Algeria", Journal of Wind Energy, vol. 2013, pp. 1-8, 2013.
[28] A. Stiel, and M. Skullas-Kazakos, "Feasibility Study of Energy Storage Systems in Wind/Diesel Applications Using the HOMER Model", Applied Sciences, vol. 2, no. 4, pp. 726-737, December 2012.

[29] H.S. Das, A. Dey, T.C. Wey, and A.Y. Yatim, “Feasibility Analysis of Standalone PV/Wind/Battery Hybrid Energy System for Rural Bangladesh”, International Journal of Renewable Energy Research, vol. 6, no. 2, pp. 402-412,June 2016.

[30] A.K. Pradhan, S.K. Kar, and M.K. Mohanty, “Off-Grid Renewable Hybrid Power Generation System for a Public Health Centre in Rural Village”, International Journal of Renewable Energy Research, vol. 6, no. 1, pp. 282-288, March 2016.

[31] M.N. Siddique, A. Ahmad, M.K. Navaz, and S.B.A. Bukhari, “Optimal integration of hybrid (wind/solar) system with diesel power plant using HOMER”, Turkish Journal of Electrical Engineering & Computer Sciences, vol.23, no. 6, pp. 1547-1557, December 2015.

[32] M.A. Elhadidy, and S.M. Shaahid, “Promouting applications of hybrid (wind+photovoltaic+diesel+battery) power generating systems in hot regions”, Renewable Energy, vol. 29, no. 4, pp. 517-528, April 2004.

[33] R. Srivastava, and V.K. Giri, “Optimization of Hybrid Renewable Resources using HOMER”, International Journal of Renewable Energy Research, vol. 6, no. 1, pp. 157-163, March 2016.

[34] M.M. Rhaman, “Hybrid Renewable Energy System for Sustainable Future of Bangladesh”, International Journal of Renewable Energy Research, vol. 3, no. 4, pp. 777-780, December 2013.

[35] S. Salahi, F. Adabi, and S.B. Mozafari, “Design and simulation of a hybrid micro-grid for Bisheh village”, International Journal of Renewable Energy Research, vol. 6, no. 1, pp. 199-211, March 2016.

[36] P. Arun, “Optimum Design of Biomass Gasifier Integrated Hybrid Energy Systems”, International Journal of Renewable Energy Research, vol. 5, no. 3, pp. 892-895, June 2015.

[37] G. Liu, M.G. Rasul, M.T.O. Amanullah, and M.M.K. Khan, “Feasibility study of stand-alone PV-wind-biomass hybrid energy system in Australia”, in Power and Energy Engineering Conference (APPEEC), Asia-Pacific, 25-28 March 2011, pp. 1-6.

[38] S. Dursun, I. Bostan, and B. Dursun, “Optimal wind/PV/biomass hybrid power system for forest watchtowers”, Mugla Journal of Science and Technology, vol. 2, no. 1, pp. 43-47, March 2016.

[39] S.G. Sigarchian, R. Paleta, A. Malmquist, and A. Pina, “Feasibility study of using a biogas engine as backup in a decentralized hybrid (PV/wind/battery) power generation system e Case study Kenya”, Energy, vol. 90, pp. 1830-1841, July 2015.

[40] B.F. Ronad, and S. Jangamshetti, “Optimal Cost analysis of Wind-Solar Hybrid System Powered AC and DC Irrigation Pumps using HOMER”, in 2015 International Conference on Renewable Energy Research and Applications (ICRERA), Palermo, Italy, 22-25 November 2015, pp. 1038-1042.

[41] E.C. Okonkwo, C.F. Okwose, and S. Abbasoglu, “Techno-Economic Analysis of the Potential Utilization of a Hybrid PV-Wind Turbine System for Commercial Buildings in Jordan”, International Journal of Renewable Energy Research, vol. 7, no. 2, pp. 908-914, June 2017.

[42] M.S.H. Lipu, Md. G. Hafiz, Md. S. Ullah, A. Hossain, and F. Y. Munia, “Design Optimization and Sensitivity Analysis of Hybrid Renewable Energy Systems: A case of Saint Martin Island in Bangladesh”, International Journal of Renewable Energy Research, vol. 7, no. 2, pp. 988-998, June 2017.

[43] M. Dahmane, J. Bosche, A. El-Hajjaji, and M. Dafarivar, “Renewable energy management algorithm for stand-alone system”, in 2013 International Conference on Renewable Energy Research and Applications (ICRERA), Madrid, Spain, 20-23 October 2013, pp. 621-626.

[44] G. Gursoy, and M. Baysal, “Improved Optimal Sizing of Hybrid PV/Wind/Battery Energy Systems”, in 2014 International Conference on Renewable Energy Research and Applications (ICRERA), Milwakee, USA, 19-22 October 2014, pp. 713-716.

[45] L.R.S. Paragond, S.P. Kurian, and B.K. Singh, “Design And Simulation of Solar and Wind Energy Conversion System in Isolated Mode of Operation”, in 2015 International Conference on Renewable Energy Research and Applications (ICRERA), Palermo, Italy, 22-25 November 2015, pp. 999-1004.

[46] K.D. Mercado, J. Jimenez, and C.G.M. Quintero, “Hybrid Renewable Energy System based on Intelligent Optimisation Techniques”, in 2016 International Conference on Renewable Energy Research and Applications (ICRERA), Birmingham, UK, 20-23 November 2016, pp. 661-666.

[47] M.S. Aziz, G.M. Mufti, and S. Ahmad, “Wind-hybrid Power Generation Systems Using Renewable Energy Sources- A Review”, International Journal of Renewable Energy Research, vol. 7, no. 1, pp. 111-127, March 2017.

[48] S. Belgana, A. Dabib, H. Bilil, and M. Maaroufi, “Hybrid Renewable Energy System Design Using Multobjective Optimization”, in 2013 International Conference on Renewable Energy Research and Applications (ICRERA), Madrid, Spain, 20-23 October 2013, pp. 955-960.

[49] O.V. Marchenko, “Mathematical modelling and economic efficiency assessment of autonomous energy systems with production and storage of secondary energy carriers”, International Journal of Low-carbon Technologies, vol. 5, no. 4, pp. 250-255, December 2010.

[50] O.V. Marchenko, and S.V. Solomin, “Modeling of hydrogen and electrical energy storages in wind/PV energy system on the Lake Baikal coast”, International Journal of Hydrogen Energy, vol. 42, March 2017, http://10.1016/j.ijhydene.2017.02.076.

[51] O. Ekren, and B.Y. Ekren, “Size optimization of a PV/wind hybrid energy conversion system with battery storage using simulated annealing”, Applied Energy, vol. 87, no.2, pp. 592–598, February 2010.

[52] Scientific and practical textbook "Climate of Russia", All-Russia Research Institute of Hydrometeorological Information-World Data Centre, Obninsk, Russia, 2011 (in Russian).

[53] Renewable Energy Resource Maps, GENI–Global Energy Network Institute, 2014, http://www.geni.org/globalenergy/library/renewable-energy-resources/index.shtml.