Economic Efficiency of Renewable Energy Sources in Autonomous Energy Systems in Russia

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Abstract- The paper aims to study the economic efficiency and the competitiveness of renewable energy sources in Russia in small autonomous energy systems. Levelised cost of energy is used as criterion. Three regions were considered in the territory of Russia (the South, the Center and the North). Consideration is given to the favorable and unfavorable conditions for renewable energy sources within a given region. The calculation results show that the use of renewable energy sources in autonomous energy supply systems proves to be economically efficient for a significant number of considered variants. The most efficient renewable energy sources are the small hydropower plants, biogas generators running on wood fuel, and wind turbines.

Keywords- economic efficiency; renewable energy sources; electricity cost; autonomous energy systems.

Nomenclature

d	annual discount rate
$E(\tau)$	cash flow ($/year)
CF	capacity factor
CRF	capital recovery factor (1/year)
h	annual number of utilization hours (hours/year)
H	8760 hours/year
k	specific investments ($/kW)
K	investments ($)
$LCOE$	levelised cost of energy ($/kWh)
NPV	net present value ($)
p_f	fuel price ($/toe)
S	energy cost ($/kWh)
T	lifetime (year)
Z	average annual costs ($/year)
η	efficiency
θ	energy equivalent (kWh/toe)
μ	specific constant costs (share of investments)
τ	time (years)
$	the US dollar

1. Introduction

The introduction of renewable energy sources (RES) in small autonomous (decentralized) power systems has the potential to reduce emissions and to increase the cost effectiveness of power supply [1-3]. Russian zones of decentralized power supply occupy about 70% of the country [4]. Therefore, investigation of the conditions at which using renewable energy sources is more preferable then alternative energy sources on fossil fuel is a very important topic for decision makers [5-8].

In order to assess the competitiveness of renewable energy sources first of all it is necessary to compare the cost of energy produced by them and the cost of energy generated by competing energy sources [9-11]. Since operation of some RES is uncontrolled (stochastic) and requires complete backup of their capacity, the cost of energy generated by them should be compared not with the overall cost but only with the fuel component of the energy cost produced by fossil fuel-fired energy sources [6].

Such an approach makes it possible to assess if the use of RES in these conditions is reasonable in principle. In the event that the result is negative, further, a more labor-intensive stage, feasibility study, can be excluded. However, if the renewable energy sources are competitive according to the criterion of energy cost a more detailed mathematical modeling will be required [3, 5, 12-16]. This modeling should take into consideration system effects caused by stochastic operation of renewable energy sources using energy of wind, sun and small rivers to determine what number of RES should be put in operation in the system (with backup energy sources operating on fossil fuel) and what economic effect will be gained [3, 5, 16, 17].

This paper aims to study the economic efficiency of renewable energy sources in Russia for a wide range of parameters. It addresses the following options of RES use: biogas generators (generators fuelled by gas, produced from wood), small hydropower plants, wind turbines, photovoltaic (PV) systems and solar heat systems. Competing alternative energy sources are diesel power plants fuelled by liquid diesel fuel (diesel-L), diesel power plants fuelled by natural gas (diesel-NG) and boiler units on coal or heavy oil.

2. Levelised Cost of Energy

The levelised cost of energy (LCOE) is defined as the ratio of the net present value of total capital and operating costs of an energy source to the net present value of the energy generated over its service life [10].

It is easy to show that in the assessment of energy technology efficiency the LCOE criterion follows from a more general criterion of net present value (NPV). The latter value represents a sum of all project revenues reduced to the initial time instant [11]. In the case of nonnegative NPV, participation in the project is more preferable than its rejection; the project with the maximum NPV is the best. However, the NPV criterion has a downside: it can be used to assess the efficiency of capital investment variants but not the technologies of energy production. In order to assess the efficiency of energy technologies it is desirable to exclude the project scale effect and focus on specific indices. Therefore, in [9-11], as in many other studies the researchers use energy cost (in particular the cost of electric or thermal energy) instead of NPV. The energy source providing the least energy cost is the best. If, contrary to [9-11], to make a more plausible assumption that the revenues from the project come not once a year but are distributed in time [18]

$$NPV = \int_0^T E(\tau)\exp(-\sigma\tau)\,d\tau\ , \qquad (1)$$

where T is the lifetime, $E(\tau)$ is the cash flow; $\sigma = \ln(1+d)$; d is the annual discount rate.

For many energy sources, including RES, it is possible to use the following simplified model, which describes their construction and operation [18]. Construction takes a short time and requires capital investment K. Right after the construction the energy source starts to operate under nominal conditions with average annual costs Z and energy (electricity or heat) supply Q. Costs Z can be divided into two parts: constant components (that do not depend on electricity output) and variable components that consist mainly of fuel costs. Then the formula for the levelised cost of energy is [18]

$$S = \frac{k}{h}CRF + \frac{k}{h}\mu + \frac{p_f}{\theta \cdot \eta} \qquad (2).$$

Here k is the specific capital investments (per power unit); $h = CF{\cdot}H$ – annual number of utilization hours (CF is the capacity factor, H = 8760 h/year); $CRF = \sigma/[1-\exp(-\sigma T)]$ is the capital recovery factor; μ is the specific constant costs (share of investments); p_f is the fuel price; η is the efficiency and $\theta = 11.6 \cdot 10^3$ kWh/toe is the energy equivalent.

The terms in the right-hand side of equality (2) represent the capital, O&M and fuel components of the energy cost, respectively. Fuel price for the energy sources based on energy of the wind, sun or rivers equals zero ($p_f = 0$), while the value of capacity factor CF significantly depends on meteorological conditions [16, 17].

The energy cost represents the minimum price, at which the project is still cost effective (net present value equals zero), and the best variant ($NPV = \max$) should be chosen on the basis of the criterion of minimum energy cost [9].

3. Initial Data

The factors that determine the expediency of using renewable energy sources in addition to energy plant on fossil fuel (or instead of it) in the autonomous power systems are:

– climatic and meteorological conditions;
– fuel price;
– maximum power and degree of load unevenness;
– technical and economic indices of power plants.

To form the calculation variants the problem of considering a diversity of operating conditions for renewable energy sources in Russia under the minimum number of considered sites has been posed. Three regions were considered in the territory of Russia (the South, the Center and the North) with the values of peak load utilization hours and fossil fuel prices that are characteristic of the regions. In the first approximation the division into climatic zones (the South, the Center and the North) corresponds to the amount of solar radiation reaching the earth's surface (Fig.1) [19, 20].

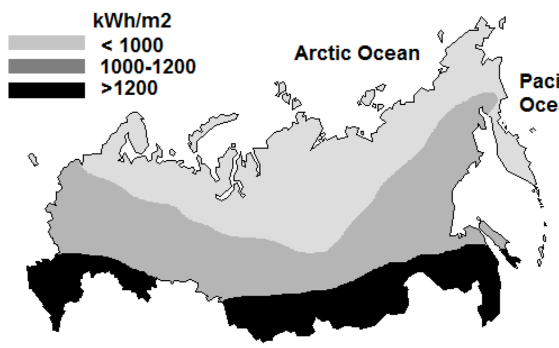

Fig. 1. Annual amount of solar radiation in the territory of Russia, according to the data of Russian climate reference books and maps and [19, 20], kWh/m^2.

Consideration is given to the favorable (Variant A) and unfavorable (Variant B) conditions for renewable energy sources within a given region. The variants differ in the technical and economic indices of energy sources and in the annual number of capacity utilization hours which depend on climatic and meteorological conditions (insolation, wind speed, temperature, etc.) as well as the price of wooden fuel (in Variant A the fuel price for biogas generator corresponds to the low price scenario, in Variant B – to the scenario of high prices).

It is assumed that insolation in the South makes up 1200-1300 kWh/m^2 (conditions of Krasnoyarsk Territory), in the Center – 1000-1100 kWh/m^2 (conditions of Moscow region), in the North – 800-900 kWh/m^2 (conditions of the Extreme North, 70° N) (Fig.1). The average long-term wind speed in the South varies in the interval 5-6 m/s, in the Center – 3-4 m/s, in the North – 6-7 m/s (the boundaries of the intervals correspond to variants B and A) [19].

Small hydropower plants with the minimum impact on the environment (without dams, diversion power plants) also have been considered. Such small hydropower plants as a rule cannot work during cold period of the year due to freezing of small rivers. Even in the southern areas of Russia the use of the pressure pipelines in winter may turn out to be impossible. The calculations assumed that the small hydropower plants do not operate in the South for 2 months (December, January), in the Center – 4 months (November-February), and in the North – 6 months (October -March).

Table 1 presents the technical and economic indices of renewable energy sources and competing fossil fuel - fired sources that were taken for calculation. They depend on a unit capacity of the plants which is determined by the consumer load. The paper considered three groups of consumers (load patterns 1, 2 and 3) with maximum electric load 25, 250 and 2500 kW and thermal load 50, 500 and 5000 kW, respectively.

For the chosen regions three scenarios of fossil fuel prices in the areas of decentralized power supply have been formed (Table 2). This makes it possible to analyze the external conditions for the assessment of RES competitiveness in the widest range.

The data on the price of energy sources were assumed according to the price lists of the Russian equipment manufacturers [23], data on fuel price – from the reports of local authorities [23, 24], climatic and meteorological data – from the reference books of Russia as well as from [12, 16-20].

4. Calculation Results and Their Analysis

The values of capacity factors calculated depending on the types of consumers and climatic and meteorological

Table 1. Technical and economic characteristics of energy sources [21–23]

Energy sources	*k*, $/kW			δ, %			η, %			*T*, year
	1*	2	3	1	2	3	1	2	3	
Diesel-L	500	350	320	7	5	5	32	34	35	10
Diesel-NG	650	450	370	5	5	5	35	36	37	10
Coal-fired boiler plant	450	300	225	5	5	5	75	75	75	30
Heavy oil-fired boiler plant	300	200	150	5	5	5	80	80	80	30
Biogas generator	2200	1200	1000	10	10	10	20	20	22	10
Hydro	4000	2500	1800	3	3	3	90	90	90	30
Wind turbines	2500	1800	1300	3	3	3	35	32	30	20
PV	4900	4600	4000	2	2	2	14	14	14	25
PV (prospective)**	1500	1400	1200	3	3	3	30	30	30	30
Solar heat	600	500	480	2	2	2	50	50	50	20
Solar heat (prospective)**	500	420	400	2	2	2	60	60	60	25

Note: * – load pattern, ** – prospective (2020–2025) technical and economic indices.

Table 2. Fuel price, $/toe [23, 24]

Region	Fuel				
	Diesel fuel	NG	Coal	Heavy oil	Wood
Low fuel prices					
South	570	100	36	200	43
Centre	500	110	36	170	72
North	860	130	43	285	57
Medium fuel prices					
South	930	200	57	329	72
Centre	860	185	57	300	100
North	1215	230	72	430	86
High fuel prices					
South	1290	285	100	460	115
Centre	1215	270	100	430	140
North	1570	315	115	570	130

conditions are presented in Table 3. The capacity factors were determined using the mathematical models described in [3-6].

Table 4 shows the calculated values of the fuel component, and Table 5 – the values of the overall energy cost of fossil fuel-fired energy sources for the indicated regions and groups of consumers. Energy cost was calculated at the discount rate *d*=10%.

The cost of energy generated from RES (Table 6) is calculated under the favorable (variant A) and unfavorable (variant B) conditions for RES in the given region. The table indicates the areas of RES economic competitiveness (electricity cost of biogas generators is lower than the electricity cost of the diesel generators (Table 5) or the energy cost for RES operating under uncontrolled conditions (small hydropower plants, wind turbines, photovoltaic systems, and solar heat systems) is lower than the fuel component of competing energy sources (Table 4)).

The calculations show that biogas generators operating on wood fuel and small hydropower plants are competitive with diesel-L in all the regions and practically under all the considered conditions.

Wind turbines are competitive with diesel-L in all the fuel price scenarios in the South and North. Here the best conditions for the RES application are created in the regions situated near the coasts; the average long-term wind speed can exceed 6-7 m/s. In central Russia the wind conditions are much worse, and RES can compete with diesel power plants only if the diesel price rises. They are inferior to small hydropower plants and biogas generators in terms of economic indices and can be used only in order to save expensive diesel, when the use of other cheaper RES (hydro resources and biomass) is impossible.

In some variants biogas generators, small hydropower plants, and wind turbines turn out to be competitive with diesel-NG (in medium and high gas price scenarios). Besides, biogas generators and small hydropower plants are more efficient in the South (cheaper wood fuel for biogas generators and high capacity factor for small hydropower plants), and RES are more efficient in the North (the average long-term wind speed on the coasts of the Pacific Ocean and arctic seas is the highest).

The use of solar heat systems can be cost effective only in the South, where their rivals are the boiler plants operating on expensive fuel oil. As for the coal-fired boiler

Table 3. Calculated values of capacity factors

Energy sources	Variant A (favorable for RES)			Variant B (unfavorable for RES)		
	Load pattern			Load pattern		
	1	2	3	1	2	3
South						
Diesel-L	0.34	0.42	0.54	0.34	0.42	0.54
Diesel-NG	0.34	0.42	0.54	0.34	0.42	0.54
Coal-fired boiler plant	0.42	0.44	0.46	0.42	0.44	0.46
Heavy oil-fired boiler plant	0.42	0.44	0.46	0.42	0.44	0.46
Biogas generator	0.70	0.70	0.70	0.50	0.50	0.50
Hydro	0.70	0.70	0.70	0.60	0.60	0.60
Wind turbines	0.36	0.42	0.45	0.27	0.32	0.35
PV	0.17	0.17	0.17	0.15	0.15	0.15
Solar heat	0.15	0.15	0.15	0.14	0.14	0.14
Centre						
Diesel-L	0.37	0.45	0.57	0.37	0.45	0.57
Diesel-NG	0.37	0.45	0.57	0.37	0.45	0.57
Coal-fired boiler plant	0.54	0.56	0.58	0.54	0.56	0.58
Heavy oil-fired boiler plant	0.54	0.56	0.58	0.54	0.56	0.58
Biogas generator	0.70	0.70	0.70	0.50	0.50	0.50
Hydro	0.60	0.60	0.60	0.50	0.50	0.50
Wind turbines	0.17	0.21	0.24	0.09	0.11	0.12
PV	0.15	0.15	0.15	0.13	0.13	0.13
Solar heat	0.11	0.11	0.11	0.10	0.10	0.10
North						
Diesel-L	0.40	0.48	0.60	0.40	0.48	0.60
Diesel-NG	0.40	0.48	0.60	0.40	0.48	0.60
Coal-fired boiler plant	0.58	0.60	0.62	0.58	0.60	0.62
Heavy oil-fired boiler plant	0.58	0.60	0.62	0.58	0.60	0.62
Biogas generator	0.70	0.70	0.70	0.50	0.50	0.50
Hydro	0.50	0.50	0.50	0.40	0.40	0.40
Wind turbines	0.45	0.50	0.53	0.36	0.42	0.45
PV	0.06	0.06	0.06	0.05	0.05	0.05
Solar heat	0.06	0.06	0.06	0.05	0.05	0.05

Table 4. Fuel component of electricity and heat cost of fossil fuel-fired energy sources, cent/kWh

Energy sources	South			Centre			North		
	Load pattern			Load pattern			Load pattern		
	1	2	3	1	2	3	1	2	3
Low fuel prices									
Diesel-L	15.4	14.5	14.0	13.4	12.6	12.3	23.0	21.7	21.1
Diesel-NG	2.5	2.4	2.3	2.6	2.6	2.5	3.2	3.1	3.0
Coal-fired boiler plant	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.5	0.5
Heavy oil-fired boiler plant	2.1	2.1	2.1	1.8	1.8	1.8	3.1	3.1	3.1
Medium fuel prices									
Diesel-L	25.0	23.5	22.8	23.0	21.7	21.1	32.6	30.7	29.8
Diesel-NG	4.9	4.8	4.6	4.6	4.4	4.3	5.6	5.5	5.3
Coal-fired boiler plant	0.7	0.7	0.7	0.7	0.7	0.7	0.8	0.8	0.8
Heavy oil-fired boiler plant	3.5	3.5	3.5	3.2	3.2	3.2	4.6	4.6	4.6
High fuel prices									
Diesel-L	34.5	32.5	31.6	32.6	30.7	29.8	42.2	39.7	38.6
Diesel-NG	7.0	6.8	6.6	6.7	6.5	6.3	7.7	7.5	7.3
Coal-fired boiler plant	1.1	1.1	1.1	1.1	1.1	1.1	1.3	1.3	1.3
Heavy oil-fired boiler plant	4.9	4.9	4.9	4.6	4.6	4.6	6.1	6.1	6.1

Table 5. Electricity cost of fossil fuel-fired energy sources, cent/kWh

Energy sources	South			Centre			North		
	Load pattern			Load pattern			Load pattern		
	1	2	3	1	2	3	1	2	3
Low price scenario									
Diesel-L	19.3	16.5	15.5	17.1	14.6	13.7	26.4	23.5	22.4
Diesel-NG	7.2	5.0	4.0	7.0	5.0	4.1	7.2	5.4	4.5
Medium price scenario									
Diesel-L	28.9	25.5	24.3	26.7	23.6	22.4	36.0	32.5	31.1
Diesel-NG	9.6	7.4	6.3	8.9	6.9	5.9	9.6	7.8	6.8
High price scenario									
Diesel-L	38.5	34.6	33.0	36.3	32.6	31.2	45.6	41.5	39.9
Diesel-NG	11.7	9.5	8.3	11.0	8.9	7.9	11.7	9.8	8.8

Table 6. Energy cost of RES, cent/kWh

Energy sources	Variant A (favorable for RES)			Variant B (unfavorable for RES)		
	Load pattern			Load pattern		
	1	2	3	1	2	3
South						
Biogas generator	***11.5***	**7.1**	**6.1**	18.4	12.3	***10.6***
Hydro	8.6	***5.4***	**3.9**	10.1	***6.3***	**4.5**
Wind turbines	11.4	7.0	***4.7***	15.2	9.2	***6.1***
PV	41.5	39.0	33.9	47.1	44.2	38.4
PV (prospective)	13.4	12.5	10.7	15.1	14.1	12.1
Solar heat	6.1	5.1	***4.9***	6.5	5.4	5.2
Solar heat (prospective)	***4.8***	***4.0***	***3.8***	5.1	***4.3***	***4.1***
Centre						
Biogas generator	12.7	***8.3***	***7.2***	19.6	13.5	11.7
Hydro	10.1	***6.3***	***4.5***	12.1	7.6	***5.4***
Wind turbines	24.1	14.0	8.9	45.5	26.8	17.7
PV	47.1	44.2	38.4	54.3	51.0	44.3
PV (prospective)	15.1	14.1	12.1	17.5	16.3	14.0
Solar heat	8.3	6.9	6.6	9.1	7.6	7.3
Solar heat (prospective)	6.6	5.5	5.2	7.2	6.1	5.8
North						
Biogas generator	12.1	**7.7**	**6.6**	19.0	12.9	11.2
Hydro	12.1	7.6	***5.4***	15.1	9.5	***6.8***
Wind turbines	9.1	***5.9***	**4.0**	11.4	***7.0***	**4.7**
PV	117.8	110.6	96.0	128.4	120.6	104.8
PV (prospective)	56.7	53.1	45.3	61.8	57.9	49.5
Solar heat	15.2	12.7	12.2	18.3	15.2	14.6
Solar heat (prospective)	12.0	10.1	9.6	14.4	12.1	11.5

plants, solar heat systems can compete with them only in terms of environmental factors (in the case the fines for harmful emissions are introduced) [6].

The cost of electricity generated by modern photovoltaic systems is too high. This does not exclude the possibility of using modern PV systems and solar heat systems for supply to low-capacity consumers and if there is no possibility of using other energy sources. The important advantages of photovoltaic and solar heat energy sources are that they are compact and modular, allow the creation of low-budget energy supply systems, and have a niche, where they can be adopted.

The prospective PV systems will be feasible for the southern regions and in some favorable condition in the Centre.

Note to the table 6: the cells highlighted in grey represent the variants, where RES are competitive with diesel-L at any fuel prices, horizontally hatched cells – at medium and high fuel prices, vertically hatched cells – only at high fuel prices; variants in bold are the variants, where RES are competitive with diesel-NG at medium and high gas prices; variants in bold italics – with diesel-NG (solar heat system with heavy oil-fired boiler plant) only at high fuel prices.

5. Conclusion

The paper presents the analysis of using renewable energy sources in autonomous energy systems of Russia, depending on load levels, fossil fuel price and climate characteristics. The levelized cost of energy is used as a criterion.

The main results of the study are as follows:

1. The use of renewable energy sources in autonomous energy supply systems proves to be more economically efficient than competing energy sources for a significant number of considered variants (groups of consumers and location areas).

2. The most efficient renewable energy sources are the small hydropower plants, biogas generators running on wood fuel, and wind turbines. In most of the cases these energy sources are competitive with diesel generators operating on liquid fuel and at medium and high gas prices – with diesel generators running on natural gas. Moreover, biogas generators and small hydro plants are more efficient in the South, and wind turbines – in the North.

3. Modern photovoltaic systems are not competitive with other types of energy sources for the considered model consumers. The use of these systems can be economically feasible only if the load is small or if there is no possibility of using other energy sources, for instance, when eco-friendly energy is needed and other renewable resources are restricted. The prospective PV systems will be feasible for the southern regions and in some favorable condition in the Centre.

4. The use of the solar heat system can be economically efficient only in the southern regions of the country, where their rivals are the boiler plants running on expensive fuel. As for the coal-fired boiler plants, solar heat systems can compete with them only in terms of environmental factors (in the case the fines for harmful emissions are introduced).

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