Use of gasifier-based electric power stations for improving the economy of autonomous power supply systems in Russia

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Abstract. In Russia, significant amounts of waste of logging and woodworking that can be used for energy production are generated. In this paper, we consider an autonomous power supply system, including a wood biomass gasification power plant (BGPP), a diesel power plant (DPP), one or several wind turbines (WT), and electricity consumers with their load schedule. The mathematical formulation of the problem of optimizing the structure and modes of operation of the power supply system is reduced to minimizing the objective function with a number of additional constrains. The objective function is equal to total discounted costs for the construction and operation of the system or the cost of electricity produced. Additional constrains are balances for power, primary, secondary and final energy. The power supply system was modeled for different values of diesel and wood fuels prices, average long-term wind speed, technical and economic indicators of power plants. According to the results of calculations, the zones of technologies efficiency and the cost of electricity produced are determined. It is shown that biomass gasification power plants with gas storage tanks are much more economical than diesel power plants and can displace them at current diesel fuel prices. In areas with high average annual wind speeds, biomass gasification power plants should be used in conjunction with wind turbines.

1. Introduction

In autonomous power supply systems, in addition to energy sources using fossil fuel, renewable energy sources (RES) can be used, such as biomass, wind, sun, small rivers and geothermal energy. Providing a significant environmental effect, renewable energy in many cases is cost-effective and competitive with energy sources on fossil fuels [1–6].

Table 1 shows the production of the main types of the timber industry products in Russia (logging and wood processing) for 2010–2017.

According to the waste generation standards [7, 8], the following wood production wastes are produced in Russia annually: up to 70–72 Mm$^3$ of waste during logging, 11–12 Mm$^3$ of waste during sawing, 6–7 Mm$^3$ of waste in plywood production, and 8–9 Mm$^3$ of waste in the pulp industry. The total volume of wood waste is 95–100 m$^3$/year, or 16–18 Mtoe (toe – tons of oil equivalent).

This waste can be used for electrical and thermal energy production. At present, efficient technical solutions have been developed (in addition to direct biomass combustion), which make it possible to utilize logging and wood processing wastes [6, 9]. One of them is biomass gasification followed by the use of produced syngas.
### Table 1. Production of wood processing industry complex, Mm³/year.

| Product          | 2010  | 2011  | 2012  | 2013  | 2014  | 2015  | 2016  | 2017  |
|------------------|-------|-------|-------|-------|-------|-------|-------|-------|
| Timber harvesting| 173.6 | 196.9 | 191.0 | 193.3 | 202.8 | 205.1 | 213.9 | 212.4 |
| Industrial wood  | 21.8  | 22.5  | 21.1  | 21.7  | 21.5  | 22.0  | 23.7  | 25.1  |
| Plywood          | 2.7   | 3.1   | 3.2   | 3.3   | 3.6   | 3.7   | 3.8   | 3.8   |
| Cellulose*       | 7.5   | 7.8   | 7.7   | 7.2   | 7.5   | 7.9   | 8.2   | 8.3   |
| Wood mass*       | 2.4   | 2.4   | 2.3   | 2.1   | 2.1   | 2.2   | 2.3   | 2.3   |

Note: * − Mt. Source: Unified interdepartmental information and statistical system (https://fedstat.ru).

The purpose of this work is mathematical modeling and evaluation of the economic efficiency of a biomass gasification power plant fueled with wood waste as part of an autonomous power supply system in case of competition or collaboration with diesel power plants and wind turbine power plants.

2. **Design scheme**

Considered autonomous power supply system includes a biomass gasification power plant (BGPP) fed by woody biomass, a diesel power station (DPP), one or several wind turbines (WT), and electricity consumers, figure 1.

![Design scheme of the autonomous power supply system](image)

The BGPP consists of a) a module of wood fuel preparation (chipper for energy chips production and dryer); b) a gasification module (gas generator for gas production from wood and gas cooling and cleaning system); c) a gasholder (reservoir for gas accumulation and storage), d) a generation module (gas piston electrical unit operating on generating gas).

Industrial use of wood waste involves their processing into fuel chips, for which a series of chippers are developed that can process logs with a diameter in the butt of up to 1180 mm. Since the calorific value of the fuel and the cost of its transportation depend on the moisture content, dryers are used at the BGPP. The gasifier converts wood chips, sawdust or other wood fuel into syngas. Fuel can be loaded into the gas generator by means of a skip hoist connected to the automatic door mechanism of the gasifier.
3. Mathematical model
To optimize the structure and operating modes of the considered autonomous power supply system, the mathematical model proposed in [10] was used. The mathematical formulation of the problem is reduced to minimizing the objective function (total discounted costs for the construction and operation of the system or the cost of electricity produced):

\[ S = \frac{1}{Q} \sum_i F_i K_i + Z_i \rightarrow \min, \]  

under following constraints (balances of power, primary, secondary and final energy):

\[ P_{Dj} + P_{Wj} + P_{Gj} = L_j + U_j, \]  

\[ 0 \leq P_{ij} \leq P_{ij} \text{ max}, \]  

\[ U_j \geq 0, \]  

\[ P_{Wj} = P_{Wj} \text{ max} f(V_j) \]  

\[ P_{Gj} \leq P_{Rj} \eta_R \eta_G / \Delta t \]  

\[ P_{GGj} \leq (P_{R \text{ max}} - P_{Rj})/(\eta_G \Delta t) \]  

\[ P_{Rj} = P_{R(j-1)} + \left[ P_{GGj} \eta_G - P_{Gj} / (\eta_G \eta_R) \right] \Delta t. \]

The following notations were introduced here: \( S \) and \( Q \) are electricity cost and average annual volume of electricity supplied to consumers, \( F_i \) is the capital recovery factor, \( K \) is the capital investments, \( Z \) is the average annual costs (including fuel costs), \( T \) is lifetime, \( d \) is the annual discount rate, \( P \) is power source capacity (for a gas storage tank it is the amount of syngas contained), \( L \) is the consumers load, \( U \) is the excess power, \( V \) is the wind speed, \( f(V) \) is the wind turbine power curve, \( \eta \) is the efficiency, \( \Delta t \) is the time step; indices: \( i \) is the type of energy source (\( D \) – DPP, \( W \) – WT, \( G \) – BGPP electric generator, \( GG \) – gasifier, \( R \) – gas storage tank, \( j \) - time point, max - maximum power (installed capacity)).

Equation (2) is the balance of power at the \( j \)-th time point, (3) is the power limit, (4) is the condition of power supply without deficiency, (5) is the WT power depending on the wind speed at the \( j \)-th time point (random value), (6) is the limitation on the capacity of the BGPP electric generator by syngas supply, (7) is the limitation on the gasifier capacity by free capacity of the gas storage tank, (8) is the balance of syngas in the gas storage tank.

4. Numerical results and discussion
The main factors determining the economic efficiency of energy sources in the considered autonomous power supply system are:
- price of diesel and wood fuel;
- wind speed;
- technical and economic indicators of power plants.

In the first half of 2018, the price of diesel fuel in Russia was 38,000–55,000 rubles/t (520–750 €/t), the price of firewood and fuel chips was 400–1600 rubles/t (30–120 €/toe) [11]. The most important energy characteristic of wind is its average long-term speed, usually measured at the height
of the weather vane (about 10 m). In the present work, calculations were performed for average wind speeds of 4–8 m/s, which correspond to the range of wind conditions from “bad” to “very good” [12]. Table 2 shows the technical and economic indicators of the energy system elements under consideration adopted for the calculations based on the price lists of manufacturers (for other basic data, see [5]).

With cheap diesel fuel and low wind speeds, the only source of electricity in the system is diesel power plant, figure 2. With an increase in wind speed, it is efficient to use the DPP+WT system, which allows the reduction in the cost of electricity produced, figure 3. In the two-component system, the wind turbine generates cheap electricity, and the DPP is switched on either during peak periods, when electricity consumption increases, or during windless periods.

Table 2. Technical and economic indicators of power system elements.

| Name                      | Capital investment, €/kW | Fixed costs, % | Efficiency, % |
|---------------------------|--------------------------|----------------|---------------|
| DPP                       | 400                      | 7              | 34            |
| WT                        | 1500                     | 2              | 35            |
| gasifier$^2$              | 800                      | 10             | 45            |
| gas storage tank          | 700                      | 2              | 95            |
| (gasholder)$^3$           |                          |                |               |
| electrical unit$^1$       | 500                      | 7              | 33            |

$^1$ – including building costs, $^2$ – with chopper, dryers and fuel loader; capital investments are reduced to the output power of the electrical unit; $^3$ – €/m$^3$.

With the current prices for diesel fuel (more than 500 €/toe), BGPP is more economical than DPP. The presence of a gas storage tank allows syngas accumulation so the BGPP could work not only in the base mode, but also in the peak mode and, thus, could completely replace the DPP.

In the areas with average annual wind speeds at a wind vane height of less than 5.2 m/s, it is preferable to use BGPP alone, and at higher wind speeds, BGPP should be used together with WT. At the same time, the use of WT in this case leads to a very insignificant reduction in the cost of electricity as compared to the power supply from the BGPP alone, figure 3.

Figure 2. Energy technologies efficiency zones.

Figure 3. The cost of electricity (the price of diesel fuel is 1000 €/t).

It should be noted that the average annual wind speeds above 5.2 m/s are usually characteristic of the sea and ocean coasts and are rarely found in the continental regions of Russia (in particular, Siberia) [4, 12].

Figure 3 shows the cost of electricity produced by BGPP (about 0.13 €/kWh) that is typical of the power systems with a load of about 100 kW and expensive wood fuel (100 €/t). For larger power systems (more than 1 MW), the specific capital investment in BGPP decreases from approximately 1,300 €/kW to 700–1000 €/kW (for the whole system, including the cost of chippers, dryers, gasifier, electrical unit and building for a power plant).

Figure 4 shows the dependence of the cost of electricity produced by BGPP on the price of wood fuel for two values of specific capital investments.
Figure 4. The cost of BGPP-produced electricity (1 – at specific capital investments $k = 1300 \text{ €/kW}$, 2 – at $k = 700 \text{ €/kW}$).

It can be seen that when using cheap wood fuel (30–40 €/toe), the cost of electricity is significantly reduced, and for high-capacity BGPP it is about 0.06–0.07 €/kWh.

5. Conclusion
1. Based on mathematical modeling of an autonomous power supply system, including BGPP (wood fuel gasifier, gas storage tank for syngas and electrical unit) and energy sources competing with BGPPs (diesel and wind power plants), the optimal energy supply structure was found to ensure the minimum cost of electricity produced.
2. It is shown that gasification power plants with gasholders are much more economical than DPP. In areas with high average annual wind speeds (more than 5.2 m/s at a height of 10 m), they can co-operate with wind turbines.

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