The effectiveness of combining sources on fossil fuel and renewable energy resources

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Abstract. The article is devoted to the study of the economic effectiveness of the combined circuit diagram power supply, including small combined heat and power plant and wind-driven power plant. A feature of the considered scheme is the use of generated electricity to heat the air in front of the combustion can of the gas turbine unit, which eliminates voltage converters and reduces the cost of the wind-driven power plant. The method is developed and calculations of annual quantitative and economic indicators of the combined circuit diagram power supply are executed. The results of economic calculations showed the low effectiveness of the combined circuit diagram power supply.

In Russia, about 20% of the population lives in small towns of up to 100 thousand people. Power supply of such cities is carried out by power lines from thermal and nuclear power plants. Heat supply on the basis of small boilers using different fuels (gas, fuel oil, coal, wood briquettes). The state of power supply systems of small towns does not meet modern requirements for the level of efficiency, reliability and quality of services provided. The analysis of power supply systems showed a high level of wear of equipment and networks (60–80%), low efficiency of heat sources (80–85%), the loss of electricity, and heat in transportation reach 10–15% or more. The introduction of energy-saving measures is carried out at a low rate, which causes a constant increase in energy tariffs and the creation of social tension in society [1].

One of the promising areas for improving power supply schemes of town is the construction of small power sources with a combined generation of electric and thermal energy – small combined heat and power plant (small CHPP). If natural gas is available, gas-piston or gas-turbine plants can be installed on them, in the absence of natural gas, these plants can be used with preliminary gasification of coal, wood waste or pellets. The coefficient of useful energy use of fuel at small CHPP reaches 80–90% [2].

Further increase in the efficiency of energy supply systems can be achieved by combining small CHPP and sources using renewable energy resources (SRER) (wind, sun, etc.). However, sources operating on wind and solar energy are characterized by unstable energy production, which is caused by changes in wind speed, solar radiation both during the day and in the annual period. For the autonomous operation of SRER requires the installation of batteries, current converters, which increases their cost. The connection of SRER to the centralized power supply system allows to compensating the specified uneven of power generation by work of installations of the power system.

For power supply systems of small towns, the change in the generation of electricity by SRER can be compensated by the operation of electric-power installation small CHPP, and with the emergence of excess electricity generation - by converting it into thermal energy [3]. Thus, the work of the SRER is...
closely linked with the operation of electric-power installation of a small CHPP. In figure 1 shows the scheme of a small combined heat and power plant with a combination of gas turbine (GTU) and wind-driven power plants (WDPP). A feature of the scheme is the use of generated electricity for heating air and combustion products, which provides fuel economy in the combustion can of the gas turbine. A feature of the scheme is the use of generated electricity for heating air and combustion products, which provides fuel economy in the combustion can of the gas turbine. In this case, the alternating current of the wind turbine is supplied to the heaters 4 and 7 without conversion of voltage and frequency. Heating of air in the regenerative heat exchanger is carried out in the period of low thermal loads, during the winter period at high thermal loads the regenerative heat exchanger is switched off.

**Figure 1.** Cycle arrangement of small CHPP with GTU and WPP.

1 – gas-turbine compressor; 2 – regenerative heat exchanger; 3 – closing switch; 4, 7 – electric heaters for air and combustion products; 5 – combustion can; 6 – drive turbine of the compressor; 8 – power turbine; 9 – electric power generator; 10 – wind-driven power-plant; 11 – exhaust-heat boiler; 12 – peak boiler; 13 – network pump.

The operation of the installation according to the scheme of figure 1 is determined by the value of the electric load, the temperature of the outside air, the heat load and the wind speed. When the installation is operated according to the electric load schedule, the generation of the electric power of the GTU is determined by the load of the consumer.

The electrical power of the wind-driven power plant (WDPP) is determined by the wind speed at the location of the power supply source, the technical characteristics of the installation. The dependence of the electric power of WDPP on wind speed according to the manufacturer's data is shown in figure 2.
Figure 2. Characteristic curve of the electric capacity of the WDPP in relative units on the wind speed.

The hourly change in wind speed averaged over a 20-year period for each month of the year at the location of the power supply source is determined by statistical data [4] and shown for the city of the Lower Volga region in figure 3.

Using the data of hourly changes in wind speed and characteristics of WDPP can determine its electrical capacity for any hour of the month. The amount of heat that can be obtained from the generated electricity using WDPP is determined by the expression, kW

$$Q_{WDPP,i} = \eta_{heh} \cdot N_{WDPP,i}$$  \hspace{1cm} (1)

where $\eta_{heh}$ – efficiency heat and electric heater (HEH), $N_{WDPP,i}$ – the electric capacity of the WDPP at i-mode, kW.

The electric power and the amount of generated heat in the heat exhaust-heat boiler at the GTU on i-mode will be determined by the load of the consumer and the average monthly outside air temperature. Then the daily amount of electric, thermal energy produced by GTU in j-month is determined by the expressions, kWh/day.
\[ P_{\text{day},j} = \sum_{i=1}^{n} N_{\text{GTU},i} \cdot \tau_i \]  \hspace{1cm} (2)

\[ Q_{\text{GTU}}^{\text{day},j} = \sum_{i=1}^{n} Q_{\text{GTU},i} \cdot \tau_i \]  \hspace{1cm} (3)

where \( N_{\text{GTU},i}, Q_{\text{GTU},i} \) – electric and thermal capacity produced by GTU on i-mode, kW, \( \tau_i \) – duration of the mode, hour.

The daily amount of heat generated by the peak boiler (PB), kWh / day.

\[ Q_{\text{day},j}^{pb} = Q_{\text{day},j}^{GTU} - Q_{\text{day},j} \]  \hspace{1cm} (4)

where \( Q_{\text{day},j} \) – daily amount of heat energy supply to consumers, kWh / day.

Daily fuel consumption, KgCE/day.

\[ B_{\text{day},j} = \sum_{i=1}^{n} (B_{\text{GTU},i} + B_{\text{pb},i}) \cdot \tau_i \]  \hspace{1cm} (5)

where \( B_{\text{GTU},i}, B_{\text{pb},i} \) – fuel consumption of GTU and PB in i-mode, KgCE/s.

Annual costs of electricity, heat, fuel GTU and peak boiler are calculated by expressions, kWh / year, KgCE / year.

\[ P^{\text{year}} = \sum_{j=1}^{m} P_{\text{day},j} \cdot n_j \]  \hspace{1cm} (6)

\[ Q^{\text{GTU}}_{\text{year}} = \sum_{j=1}^{m} Q_{\text{GTU},j} \cdot n_j \]  \hspace{1cm} (7)

\[ Q^{\text{pb}}_{\text{year}} = \sum_{j=1}^{m} Q^{pb}_{\text{day},j} \cdot n_j \]  \hspace{1cm} (8)

\[ B^{\text{year}} = \sum_{j=1}^{m} B_{\text{day},j} \cdot n_j \]  \hspace{1cm} (9)

where \( n_j \) – number of days in j-month, \( m \) – number of months.

As an example, a small CHPP with an electric capacity of 4 MW, a connected heat load of 16.5 MW, was considered. As part of the power plant, an innovative gas turbine with regenerative air heating, a peak boiler and a 100 kW wind power plant. The power supply is reserved from the power system, the heat supply reservation is provided by the peak boiler. Calculations were carried out under the condition of heating the air in front of the combustion can of the gas turbine. The quantitative indicators of the combined circuit diagram are given in table 1. As can be seen from table 1, due to the operation of the GTU on the electric load graph, the heat output from the PB is 31% greater than from the GTU exhaust-heat boiler. The heat transferred to the heated air is 595.39 kWh / year, while the air heating is 4–6.5 °С. Electrical efficiency GTU increases by 0.1–0.2%.

**Table 1.** Quantitative indicators of the combined circuit diagram of energy supply.

| Name of the indicator                  | Units measure  | Numerical value |
|---------------------------------------|----------------|-----------------|
| Electrical supply                     | mn. kWh/year   | 22.39           |
| Heat energy supply of GTU             | thnd. GJ/year  | 101.46          |
| Heat energy supply of PB              | thnd. GJ/year  | 132.92          |
Electrical generation of WDPP kWh/year 601.44
Heat transferred by HEH to the air kWh/year 595.39
Fuel Consumption GTU mn. KgCE/year 8.96
Fuel Consumption PB mn. KgCE/year 4.17
Electrical efficiency GTU (winter/summer) - 0.26/0.395

The economic efficiency of the combined circuit diagram is determined by the method [5] with the calculation of net present value (NPV), profitability index (PI), internal rate of return (IRR) and payback time (PT). NPV is determined by the expression, RUB.

\[ NPV = \sum_{i=0}^{T} \left( t_e P_{\text{year}} + t_q Q_{\text{year}} - t_f B_{\text{year}} - p_{\text{CHPP}} C_{\text{CHPP}} - p_{\text{WDPP}} C_{\text{WDPP}} \right) (1 - tp) \cdot (1 + DR)^{-t} - \left( C_{\text{CHPP}} + C_{\text{WDPP}} + c \right) \]  

(10)

where \( t_e \), \( t_q \) – tariff for electricity and heat energy, RUB / kWh, RUB / GJ; \( Q_{\text{year}} \) – annual heat energy supply, GJ/year; \( t_f \) – tariff of fuel, RUB/KgCE; \( p_{\text{CHPP}} \), \( p_{\text{WDPP}} \) – factors taking into account depreciation, repair and maintenance of small CHPP and WDPP, 1/year; \( tp \)-factor taking into tax penalty; \( C_{\text{CHPP}} \), \( C_{\text{WDPP}} \) – capital investment in small CHPP and WDPP, RUB; \( DR \)-discount rate; \( c \) – cost for connection to electric networks, RUB.

Economic calculations are made in constant prices \( t_e = 2.5 \) RUB/kWh, \( t_q = 344 \) RUB/GJ, \( t_f = 4.5 \) RUB/KgCE, the unit cost of small CHPP 62000 RUB/kW, the unit cost of WDPP 80000 RUB/kW, the unit cost for connection to electric networks 25000 RUB/kW, \( p_{\text{CHPP}} = 0.12 \) 1/year, \( p_{\text{WDPP}} = 0.05 \) 1/year, \( tp = 0.5 \), \( DR = 0.1 \). The results of economic calculations are given in table 2. It follows from Table 2 that the combined circuit diagram under consideration does not have high efficiency indicators (IRR 10.9%) and (PT= 8.9 years) when calculated in modern prices. It is possible to expect improvement of economic indicators at the increase in prices for electric, heat energy, the decrease in cost of the equipment of WDPP and placement of the combined source in the area of higher wind speeds (6–8 m/s).

Table 2. The economic performance of combined circuit diagram of power supply.

| Name of the indicator                  | Numerical value |
|---------------------------------------|-----------------|
| Payback time, year                    | 8.9             |
| Internal rate of return, %            | 10.9            |
| Profitability index                   | 1.505           |
| Net present value for 15 years, mn. RUB | 325.72         |

Conclusion

1. The method of calculation of annual quantitative and economic indicators of the combined circuit diagram power supply on the basis of small CHPP and wind-driven power plant is developed. In this scheme, the electric power of the wind turbine is used to heat the air entering the combustion can of the gas turbine.

2. The results of economic calculations showed low efficiency (IRR =10.9%, PT=8.9 years) due to high capital investment in WDPP and moderate wind speeds. With an increase in energy tariffs, a decrease in the cost of WDPP and the placement of a combined circuit diagram in areas with high wind speeds (6–8 m/s), economic indicators can be expected to improve.
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