Analysis of fuel economy of small energy complex schemes based on gas turbine and wind-driven power plants

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Abstract. Here the energy complex is considered, representing a combination of gas turbine and wind power plants. The combination of plants that operate on different types of fuel (renewable and organic) reduces fuel consumption in a gas turbine installation. Four schemes are described and a comparative analysis of the fuel economy of each scheme is compared with the separate production of electric energy at a conventional thermal power station. For this, a mathematical model for calculating the energy characteristics was developed. The analysis revealed that the energy complex, including a gas turbine without regeneration, a current converter, and a peak boiler, has the greatest cost-effectiveness.

The rising cost of fossil fuels in the world and the need to reduce harmful discharge into the environment created the prerequisites for the construction of sources using renewable energy supply (wind, sun, etc.). Changes in incoming natural energy during the daily and annual periods required the linking of renewable energy to electric power systems. Despite the complication of the electric power system work, this solution is being used in many countries and particularly in Russia [1].

There are small cities and settlements in Russia along with large urban agglomerations, that are remote from large power systems. The power supply of such objects is carried out by long power lines that are low reliable, especially during natural disasters (icing, hurricane winds). In this case, it is advisable to install a own generation source in the center of electrical loads [2]. Energy complexes that use renewable energy resources and organic fuels can realize this role. Taking into account the need for such cities not only in electricity, but also in thermal energy for heating, ventilation and hot water supply of the housing, utility sector, and small enterprises, the energy complexes should be performed with combined electricity and heat generation. Different versions of the energy complex schemes are shown in Figures 1–4, including a wind-driven power plant (WDPP), gas turbine unit (GTU), and a peak boiler (PB) using fossil fuels. These schemes will further be numbered with 1,2,3,4 numbers.

A feature of scheme 1 given in [1] is the use of unstable electric energy of a wind turbine for heating the air in front of the combustion chamber in the electric heater element (EHE). This eliminates the need to install a Converter to generate the required current frequency.

Scheme 2 differs by the inclusion of a current converter after the WDPP and parallel operation with the GTU to supply the electricity to consumers.

Scheme 3 includes electric batteries. Here a constant-current generator is installed on the WDPP, from which the batteries are charged. The use of batteries provides the storage of the wind turbines’ electric energy during the electrical load schedule dip and its usage during periods of maximum power consumption.
Figure 1. The diagram of the energy complex using wind energy for heating air in front of the gas turbine combustion chamber.

1 – gas-turbine compressor; 2 – regenerative heat exchanger; 3 – electric heaters for air; 4 – combustion can; 5 – gas turbine; 6 – electric power generator; 7 – chimney slide valve; 8 – exhaust-heat boiler; 9 – peak boiler; 10 – network pump; 11 – wind-driven power-plant.

Figure 2. The diagram of an energy complex using WDPP to supply electricity to consumers.

1 – gas-turbine compressor; 2 – regenerative heat exchanger; 3 – combustion can; 4 – gas turbine; 5 – chimney slide valve; 6 – electric power generator; 7 – exhaust-heat boiler; 8 – peak boiler; 9 – network pump; 10 – wind-driven power-plant; 11 – current converter.
Figure 3. The diagram of an energy complex with electric batteries.
1 – gas-turbine compressor; 2 – regenerative heat exchanger; 3 – combustion can; 4 – gas turbine; 5 – chimney slide valve; 6 – electric power generator; 7 – exhaust-heat boiler; 8 – peak boiler; 9 – network pump; 10 – wind-driven power-plant; 11 – electrical accumulator; 12 – current converter

Figure 4. The diagram of an energy complex with GTU without regeneration and with WDPP energy usage to supply electricity to consumers.
1 – gas-turbine compressor; 2 – combustion can; 3 – gas turbine; 4 – electric power generator; 5 – wind-driven power-plant; 6 – current converter; 7 – exhaust-heat boiler; 8 – peak boiler; 9 – network pump

The difference between scheme 4 and those discussed above is the use of GTU without regenerative air heating. Reducing the heat load of the consumer (in the summer) leads to a partial emission of
combustion products after gas turbine without utilization in an exhaust-heat boiler. The WDPP works in parallel with the GTU analogous to scheme 2.

Despite the knownness of these schemes, no comparative analysis of their fuel efficiency was reported in the literature. Moreover, it is necessary to develop a mathematical model of the energy complex functioning to assess their quantitative parameters, which was the subject of the current study.

The thermal economic efficiency of schemes for a given electrical and thermal load of the consumer can be determined from the amount of fuel consumption by the energy complex or relative fuel economy. The latter is determined in comparison with the separate production of electric energy at a conventional thermal power station (CTPS) and a local boiler house, taking into account the losses during the transportation of electricity.

The expression of relative fuel economy will be as follows,

\[
\Delta B = \frac{(B_{SD} - B_{EC}) \cdot 100}{B_{SD}}
\]

where \( B_{SD}, B_{EC} \) – annual fuel consumption in a separate power supply diagram (SD) and the energy complex (EC), KgCE/year.

Fuel consumption in a separate diagram, KgCE/year

\[
B_{SD} = \frac{P_{\text{con}}}{Q_{l.c.v} \cdot \eta_{CTPS} \cdot \eta_{e}} + \frac{Q_{\text{con}}}{Q_{l.c.v} \cdot \eta_{bh}}
\]

where \( P_{\text{con}}, Q_{\text{con}} \) – annual electrical and thermal loads of the consumer, kJ/year, \( Q_{l.c.v} \) – a lower calorific value (l.c.v.) of reference fuel, kJ/KgCE, \( \eta_{CTPS}, \eta_{e} \) – electric efficiency factor of conventional thermal power station and electric power transport, \( \eta_{bh} \) – boiler house efficiency factor.

Fuel consumption in the energy complex, KgCE/year

\[
B_{EC} = B_{GTU} + B_{PB}
\]

where \( B_{GTU}, B_{PB} \) – annual fuel consumption of GTU and PB, KgCE/year.

In the considered schemes, wind power generation varies depending on the wind speed in the daily and annual periods. Therefore, the gas turbine provides the required daily production of electrical energy. The daily electric power generation of wind turbines in the \( j \)-month is determined based on hourly multi-year wind speeds and characteristics of the wind-driven power plant, kWh/day.

\[
P_{\text{WDPP}}^{\text{day}, j} = \sum_{i=1}^{24} N_{\text{WDPP}, i} \cdot \tau_{i}
\]

where \( N_{\text{WDPP}, j} \) – electric power of wind-driven power plant during the \( i \)-hour of the daily period, kW, \( \tau_{i} \) – the duration of the \( i \) – period, hours/day.

The amount of heat released in the electric heater element (for scheme 1), kWh/day.

\[
Q_{\text{EHE}}^{\text{day}, j} = P_{\text{WDPP}}^{\text{day}, j} \cdot \eta_{\text{EHE}}
\]

where \( \eta_{\text{EHE}} \) – electric heater element efficiency factor.

The daily amount of electrical energy produced by the GTU in the \( j \)-month (for schemes 2, 3, 4), kWh/day.

\[
P_{\text{GTU}}^{\text{day}, j} = P_{\text{con}, j}^{\text{day}, j} - P_{\text{WDPP}}^{\text{day}, j}
\]

where \( P_{\text{con}, j}^{\text{day}, j} \) – the daily amount of electricity discharged by the consumer, kWh/day.

Electric energy consumption, kWh/day.

\[
P_{\text{con}, j}^{\text{day}, j} = \sum_{i=1}^{24} N_{\text{con}, i} \cdot \tau_{i}
\]

where \( N_{\text{con}, j} \) – electric load of consumers during \( i \) – an hour of the daily period, kW.

The electrical power of the GTU was defined as
The amount of accumulated electrical energy (for scheme 3), kWh/day.

\[ P_{\text{day, } j}^{\text{batt.}} = P_{\text{day, } j}^{\text{WDPP}} \cdot \eta_{\text{batt.}} \cdot \eta_{\text{CC}} \cdot (1 - \gamma) \]

where \( \eta_{\text{batt.}}, \eta_{\text{CC}} \) - efficiency factor of the battery (batt.) and current converter (CC), \( \gamma \) - the depth of battery discharge.

The daily amount of heat generated in the exhaust-heat boiler (EHB) was determined based on the results of calculating the thermodynamic cycle of GTU \( Q_{\text{day, } j}^{\text{EHB}} \). Then the heat load of the peak boiler, kWh/day.

\[ Q_{\text{day, } j}^{\text{PB}} = Q_{\text{day, } j}^{\text{con.}} - Q_{\text{day, } j}^{\text{EHB}} \]

The heat load of the consumer in the j-month was determined by the average monthly outdoor air temperature, kWh/day

\[ Q_{\text{day, } j}^{\text{con.}} = (Q_{\text{heat, } j} + Q_{hws, j}) \times 24 \]

where \( Q_{\text{heat, } j}, Q_{hws, j} \) - heat loads of heating and hot water supply (hws), kW.

In the diagrams (Fig. 1, 2, 3), the regenerator is switched off in winter to maximize the displacement of the heat load of the peak boiler. With a decrease in the load during the summer period, the GTU was calculated with a regenerator. Electric efficiency factor, fuel consumption, and the amount of utilized heat of GTU were determined from the calculation of the thermodynamic cycle performed in [3]. The calculations of the considered schemes were performed with the following initial data: the nominal electrical power of the WDPP is 1000 kW, the maximum power of the consumer is 5000 kW, the estimated thermal load of the consumer is 17500 kW, the location is the Middle Volga region. The daily consumption of electric energy for the annual period varied in the range of 61500-76800 kWh/day. As battery devices in scheme 3, we considered lithium-ion batteries with an electrical efficiency \( \eta_{\text{batt.}} = 0.9 \), discharge depth \( \gamma = 0.2 \), and current converter efficiency factor \( \eta_{\text{CC}} = 0.95 \) [4, 5]. The calculation results of the energy characteristics of energy complexes are given in tables 1, 2.

**Table 1.** The calculated characteristics of energy complexes for schemes 1, 2.

| Month | \( P_{\text{day, } j}^{\text{WDPP}}, \text{ ths.} \) | \( P_{\text{day, } j}^{\text{GTU}}, \text{ ths.} \) | \( Q_{\text{day, } j}^{\text{EHB}}, \text{ ths.} \) | \( Q_{\text{day, } j}^{\text{PB}}, \text{ ths.} \) |
|-------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
|       | \( \text{kWh/day.} \) | \( \text{kWh/day.} \) | \( \text{kWh/day.} \) | \( \text{kWh/day.} \) |
| \( \text{Diagram 1, } j \) | \( \text{Diagram 2, } j \) | \( \text{Diagram 1, } j \) | \( \text{Diagram 2, } j \) | \( \text{Diagram 1, } j \) | \( \text{Diagram 2, } j \) |
Table 2. The calculated characteristics of energy complexes for circuits 3.4.

| Month | Diagram 3,4 | Diagram 3 | Diagram 4 | Diagram 3 | Diagram 4 | Diagram 3 | Diagram 4 |
|-------|-------------|------------|------------|------------|------------|------------|------------|
|       | kWh/day     | kWh/day    | kWh/day    | kWh/day    | kWh/day    | kWh/day    | kWh/day    |
| 1     | 9.83       | 7.45       | 69.35      | 66.97      | 182.50     | 176.24     | 141.50     | 147.80 |
| 2     | 10.85      | 8.22       | 68.60      | 65.95      | 180.50     | 173.55     | 191.90     | 145.65 |
| 3     | 9.79       | 7.42       | 69.40      | 67.01      | 182.65     | 176.30     | 93.85      | 100.20 |
| 4     | 8.63       | 6.54       | 70.25      | 68.17      | 184.90     | 179.40     | 12.90      | 18.40  |
| 5     | 8.55       | 6.48       | 54.95      | 52.90      | 34.54      | 139.20     | 63.50      | 0      |
| 6     | 7.58       | 5.75       | 55.70      | 53.90      | 35.04      | 141.80     | 63.40      | 0      |
| 7     | 4.20       | 3.18       | 58.25      | 57.30      | 36.64      | 150.80     | 61.80      | 0      |
| 8     | 6.50       | 4.92       | 56.55      | 54.85      | 35.54      | 144.60     | 62.90      | 0      |
| 9     | 5.63       | 4.27       | 57.20      | 55.82      | 36.04      | 146.90     | 62.50      | 0      |
| 10    | 7.75       | 5.87       | 70.95      | 69.05      | 186.73     | 181.70     | 11.07      | 16.10  |
| 11    | 7.28       | 5.52       | 71.30      | 69.52      | 187.7      | 182.95     | 69.10      | 73.90  |
| 12    | 8.09       | 6.13       | 70.70      | 68.70      | 185.9      | 180.80     | 115.10     | 120.16 |

According to the analysis of the results shown in tables 1 and 2, in some months the amount of generated heat energy by the exhaust-heat boiler of GTU exceeds the load of consumers. In this case, gas turbines operate with a partial release of combustion products without utilization. Based on the calculation of the schemes options daily parameters, we determined the monthly and annual characteristics of energy flows and fuel consumption. Fuel consumptions of gas turbines, PBs, and energy complex are given in table 3. The difference between the obtained costs of the considered options does not exceed 3%, which reveals their almost similar fuel economy.

Table 3. Fuel consumption of GTU and PB variants of energy complexes schemes.

| Fuel consumption, mlm. KgCE/year | Scheme variants |
|----------------------------------|-----------------|
| GTU                              | 1   | 2   | 3   | 4   |
| PB                               | 3.17| 3.90| 3.91| 2.56|
| Energy complex                   | 15.77| 15.37| 15.75| 15.29|

The efficiency of energy complex schemes comparing with a separate power supply scheme was determined using combined cycle gas turbine (CCGT) and steam turbine (STP) plants at conventional thermal power station (CTPS) with an efficiency factor of 0.55 and 0.4, an electric power transport efficiency factor of 0.9, a local boiler house efficiency factor of 0.92. The calculations according to expressions (1) and (2) are shown in table 4.

Table 4. Relative fuel economy of energy complexes.

| Relative fuel economy, % | Scheme variants |
|--------------------------|-----------------|
| Replaced CTPS-CCGT       | 3.25 | 5.74 | 3.40 | 6.20 |
| Replaced CTPS-STP        | 15.53| 17.73| 15.64| 18.10|

According to the obtained results, the greatest relative fuel economy (6.2-18.1%) is achieved for scheme 4. It includes a GTU without regeneration and a wind turbine with a current converter, working
in parallel to the consumer's electrical network. At the same time, in the summer period, about 10% of the thermal energy from the annual output is released without utilization to the exhaust-heat boiler.

The lowest fuel economy (3.25-15.53%) is achieved in scheme 1, where electric energy is used to heat the air before the GTU combustion can. The obtained result is the consequence of double conversion of unstable electrical energy of the wind turbine into thermal energy, and then again into electrical energy with a constant current frequency through the GTU. Scheme 2 has less fuel economy than scheme 4 as a result of increased aerodynamic drag of the gas-air path caused by the presence of a regenerator. Scheme 3 also has lower efficiency compared with scheme 4 due to additional losses in the energy storage of a wind-driven power plant and its usage to cover the peaks of the electrical load. At the same time, each of the considered schemes has several advantages. Thus, scheme 1 does not require the installation of a current converter but provides for the installation of an electric heater element before the combustion can of the GTU. In schemes 2 and 4, the wind energy is sent through a current converter to the consumer's electrical network, and the GTU provides the required capacity to the consumer when changing the energy generation at the wind-driven power installation. Scheme 3 allows for the accumulation of wind energy in batteries and its usage during hours of maximum load, which at different tariffs for electric energy during the day and night periods can increase its economic efficiency. The overall positive effect of all the considered schemes is the achieved savings in organic fuel, which reduces greenhouse gases and nitrogen oxide emissions into the environment. Therefore, economic calculations are required to select a rational scheme of the energy complex.

**Conclusions**

1. A mathematical model has been developed for calculating the energy characteristics of energy complexes, including GTU, WDPP, electric accumulator, providing electric and thermal energy to small cities and settlements.
2. An analysis of the fuel economy of four energy complex schemes has been performed. As an efficiency criterion, the value of the relative fuel economy in comparison with a separate power supply scheme (CTPS and boiler house) was used. Depending on the type of CTPS (with steam-gas or steam-turbine installations), the most economical (6.2–18.1%) is the energy complex, including a GTU without regeneration, a current converter, and a peak boiler.
3. Economic calculations are required to choose a rational scheme of the energy complex.

**References**

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