Justification of the capacity of wind-driven power-plants as part of an autonomous energy complex

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Abstract. The article considers the way of reliable energy supply of small towns by the development of an autonomous energy complex. It consists of a source using organic fuel and a source based on renewable energy. An urgent issue of such a combination is to determine the optimal ratio of installed capacity. Here we have developed the methodology to solve it. The daily and annual quantitative parameters of the autonomous energy complex were calculated, including gas turbines, wind power plants, and peak boilers. Taking into account the reservation of electric power, the optimal value of the wind turbine relative power was determined and appeared to be in the range of 0.45–0.55.

1. Introduction

The annual rise in natural gas prices in the world and in our country makes one of the most important tasks the one to increase the fuel use efficiency in the production of electricity and heat energy. This is achieved by building a high-efficient combined-cycle power plant in the European part of the Russian Federation with an electric efficiency factor of 55–60%, and by updating heat energy transport systems using advanced technologies [1,2]. At the same time, there are small cities and settlements within the Russian Federation territory, provided with natural gas, in which electric power supply is performed from power plants via long power transmission lines, which have low reliability. Under the conditions of natural disasters, which appear in the European part in the form of hurricane winds, showers, and icing, a reliable supply of electric energy to such small cities becomes problematic. The heat supply of small cities and settlements is also unsatisfying due to the high moral and physical deterioration of the heat and power equipment of boiler houses and heat networks. This leads to a loss in the supply of heat-storage medium to consumers.

One of the effective directions of small cities and settlements' reliable energy supply is the development of autonomous energy complexes without communication with the electric power system. These complexes are based on organic fuel and renewable energy sources (RES), providing the generation of electricity and heat energy [3,4]. In this case, there is no need to lay long power transmission lines with a low load, and the required capital costs are reduced that ensures reliable power supply to consumers. Gas-turbine unit (GTU) and gas-reciprocating engines (GRE), wind-driven power-plant (WDPP), and photovoltaic converters (PC) can be considered as electric power installations. In this case, the urgent issue is the choice installed capacity of the installations of generation. With an increase in the electric capacity of renewable sources, the fuel consumption at plants using fossil fuels reduces. But at the same time, the total investment in the energy complex increases, since renewable energy per unit of installed capacity is more expensive than traditional
sources. Moreover, there is a change in the cost of redundant facilities, providing compensation for energy underproduction on RES. A change in these cost flows leads to an optimal value of the electric capacity of RES.

The purpose of this article is to develop methodic guidelines to determine the optimal RES capacity of an energy complex that includes cogenerating GTU and WDPP. Figure 1 shows the scheme of the energy complex.

![Figure 1. The scheme of the energy complex with GTU and WDPP.](image)

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

2. Theoretical positions

As an economic criterion, the amount of discounted costs (DC), RUB was chosen.

\[
DC = \sum_{i=0}^{T} \left[ c_i \cdot \left( \sum_{j=1}^{12} b_{GTU,j} \cdot P_{GTU,j} + \sum_{j=1}^{12} b_{PB,j} \cdot Q_{PB,j} \right) + \frac{1}{(1 + DR)^{-t}} \cdot \frac{C_{WDPP} + C_{GTU} + C_{PB}}{} \right]
\]

where \( c_i \) – fuel cost, RUB/KgCE; \( b_{GTU,j}, b_{PB,j} \) – specific fuel consumption for GTU electric power and heat in the peak boiler (PB) generation in j-month, KgCE/kWh; \( P_{GTU,j} \) – electricity output in j-month, kWh/month; \( Q_{PB,j} \) – heat energy generation in the PB in j-month, kWh/month; \( P_{WDPP}, P_{GTU}, P_{PB} \) – factors taking into account depreciation, repair and maintenance of power plants, 1/year; DR – discount rate; \( C_{WDPP}, C_{GTU}, C_{PB} \) – capital investments in WDPP, GTU, PB, RUB; T – Service life of the energy complex, year.

Daily electricity consumption, kWh/day.

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

where \( N_{con,i} \) – electrical load of consumers during the i-hour of the daily period of j-month, kW.

The daily output of electrical energy from a WDPP is determined by the expression, kWh/day.
\[ P_{\text{WDPP},i}^{\text{day},j} = \sum_{i=1}^{24} N_{\text{WDPP},i} \cdot \tau_i \]  

(3)

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

The daily amount of electrical energy generated by the GTU in the \( j \)-month, kWh/day.

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

(4)

The annual amount of electric energy generated by wind-driven power plant turbines, kWh/year.

\[ P_{\text{WDPP},\text{year}} = \sum_{j=1}^{12} P_{\text{WDPP},\text{day},j} \cdot n_j \]  

(5)

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

The annual amount of electric energy generated by the gas turbine, kWh/year.

\[ P_{\text{GTU},\text{year}} = \sum_{j=1}^{12} P_{\text{GTU},\text{day},j} \cdot n_j \]  

(6)

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

\[ Q_{\text{im},\text{day},j} = (Q_{\text{heat},\text{day},j} + Q_{\text{hws},\text{day},j}) \cdot 24 \]  

(7)

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

The heat load of exhaust-heat boiler (EHB), kWh/day.

\[ Q_{\text{EHB},\text{day}} = \frac{P_{\text{GTU},\text{day},j}}{y_{\text{day},j}} \]  

(8)

where \( y_{\text{day},j} \) – specific electric energy generation of gas turbines based on heat consumption.

The heat load of peak boilers in \( j \)-month, kWh/day.

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

(9)

Annual parameter of heat output, kWh/year.

\[ Q_{\text{con},\text{year}} = \sum_{j=1}^{12} Q_{\text{con},\text{day},j} \cdot n_j \]  

(10)

\[ Q_{\text{EHB},\text{year}} = \sum_{j=1}^{12} Q_{\text{EHB},\text{day},j} \cdot n_j \]  

(11)

\[ Q_{\text{PB},\text{year}} = \sum_{j=1}^{12} Q_{\text{PB},\text{day},j} \cdot n_j \]  

(12)

The ratio of installed wind power to the maximum load of the consumer is defined by 
\[ \delta_{\text{WDPP}} = \frac{N_{\text{WDPP}}}{N_{\text{con},\text{max}}} \]. Then the standby electric power (SEP) of the GTU energy complex will be, kW.

\[ N_{\text{SEP},\text{GTU}} = N_{\text{con},\text{max}} \cdot \left( \delta_{\text{WDPP}} + \frac{1}{n_{\text{w,GTU}}} - \delta_{\text{WDPP}} \right) \]  

(13)

where \( n_{\text{w,GTU}} \) – the number of currently working GTU.

Installed GTU capacity, considering working and standby installations, kW

\[ N_{\text{GTU}} = N_{\text{con},\text{max}} \cdot \left( 1 + \frac{1 - \delta_{\text{WDPP}}}{n_{\text{w,GTU}}} \right) \]  

(14)

Capital investments in the energy complex elements are calculated according to the expressions, RUB.
The electric capacity of WDPP is
\[ C_{WDPP} = c_{WDPP} \cdot N_{WDPP}^{\text{instal.}} \] (15)
The electric capacity of GTU is
\[ C_{GTU} = c_{GTU} \cdot N_{GTU}^{\text{instal.}} \] (16)

The electric capacity of PB is
\[ C_{PB} = c_{PB} \cdot (Q_{\text{min}}^{\text{con.}} - Q_{\text{EHB}}^{\text{min}}) \] (17)

where \( c_{WDPP}, c_{GTU}, c_{PB} \) – unit costs of WDPP, GTU, and PBs, RUB/kW; \( Q_{\text{con.}}^{\text{max}} \) – maximum heat load of the consumer, kW; \( Q_{\text{EHB}}^{\text{min}} \) – minimum heat power of gas turbine exhaust-heat boiler in winter, kW.

3. Results
Using the above dependencies, we calculated the quantitative annual parameters of the energy complex for various wind turbine electric power and \( \delta_{WDPP} \) value.

In the calculations, the following initial data were taken: location - the Middle Volga region; the maximum electrical load of the consumer \( N_{\text{con.}}^{\text{max}} = 16000 \) kW; maximum thermal load \( Q_{\text{con.}}^{\text{max}} = 80000 \) kW; \( \delta_{WDPP} = 0.1–0.6 \); electrical efficiency factor of a gas turbine, varying in dependence on the outdoor air temperature and load intensity, in the range 0.24 – 0.28. The electric capacity of WDPP is determined depending on the hourly wind speed at the energy complex location. For \( \delta_{WDPP} = 0.5 \), the daily parameters of the energy complex are shown in table 1.

| Month | \( P_{WDPP}^{\text{day,j}}, \) ths. kWh/day. | \( P_{GTU}^{\text{day,j}}, \) ths. kWh/day. | \( Q_{\text{EHB}}^{\text{day,j}}, \) ths. kWh/day. | \( Q_{\text{PB}}^{\text{day,j}}, \) ths. kWh/day. |
|-------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| 1     | 82.8                            | 163.0                           | 362.2                           | 1106.6                          |
| 2     | 91.4                            | 154.4                           | 343.1                           | 1108.9                          |
| 3     | 82.5                            | 163.3                           | 362.9                           | 906.7                           |
| 4     | 72.6                            | 173.2                           | 384.9                           | 555.9                           |
| 5     | 72.0                            | 124.6                           | 276.9                           | 107.1                           |
| 6     | 63.8                            | 132.8                           | 295.1                           | 88.9                            |
| 7     | 35.4                            | 161.5                           | 358.9                           | 25.1                            |
| 8     | 54.7                            | 141.9                           | 315.3                           | 68.7                            |
| 9     | 47.4                            | 149.2                           | 331.6                           | 52.4                            |
| 10    | 65.3                            | 180.5                           | 401.1                           | 537.3                           |
| 11    | 61.3                            | 184.5                           | 410.0                           | 775.6                           |
| 12    | 68.1                            | 177.7                           | 394.9                           | 953.9                           |

As can be seen from table 1, the generation of electric energy by wind turbines during the summer period reduces to 40% from the maximum winter load, and the lack of energy is provided by GTU. The peak boiler operates throughout the entire annual period.

Figures 2 and 3 show the changes in the annual parameters of the energy complex operation depending on the proportion of the installed capacity of WDPP.

Figure 2 shows that the increase in the proportion of WDPP power to (\( \delta_{WDPP} = 0.6 \) of the maximum consumer load), its annual electricity generation does not exceed 20% of the total electricity demand. Thus, in the annual period, the largest contribution to ensuring the annual schedule of electric load is accounted for by GTU.

The values of the standby and installed capacity of GTU are shown in table 2.

According to table 2, the increase in the wind-driven power plant capacity leads to a decrease in the installed capacity of a gas turbine, but the standby component increases. The standby capacity provides compensation for the underproduction of energy in case of an accident at a gas turbine installation and the calm weather of a wind power installation.
The calculation of the optimal relative power of WDPP is performed with the following initial data: 
\[ c_f = 5 \text{ RUB/KgCE}, \quad b_{\text{GTU}} = 0.47 \text{ KgCE/kWh}, \quad b_{\text{PB}} = 0.136 \text{ KgCE/kWh}, \quad n_{w,\text{GTU}} = 2, \quad c_{\text{WDPP}} = 100000 \text{ RUB/kW} \ [3,4], \quad c_{\text{GTU}} = 65000 \text{ RUB/kW} \ [5,6], \quad c_{\text{PB}} = 1500 \text{ RUB/kW}, \quad p_{\text{WDPP}} = 0.03 \text{ 1/year}, \quad p_{\text{GTU}} = 0.12 \text{ 1/year}, \quad p_{\text{PB}} = 0.05 \text{ 1/year}, \quad E = 0.1, \quad T = 25 \text{ years}.

The results of the relative capacity of wind turbines optimization are shown in Figure 4.

**Figure 2.** Change in electricity generation by GTU, WDPP, and heat supply from exhaust-heat boilers and peak boilers.

**Figure 3.** Change in annual fuel consumption by GTU and PBs.
Table 2. Standby and installed capacity of GTU as part of the energy complex, depending on the proportion of WDPP capacity.

| GTU capacity value | Relative capacity of WDPP |
|--------------------|---------------------------|
|                    | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 |
| Standby capacity of GTU, ths. kW | 8.8 | 9.6 | 10.4 | 11.2 | 12.0 | 12.8 |
| Installed capacity of GTU, ths. kW | 23.2 | 22.4 | 21.6 | 20.8 | 20.0 | 19.2 |

An analysis of the obtained results shows the presence of an economic optimum of the WDPP relative capacity in the range of $\delta_{\text{WDPP}}^{\text{opt}} = 0.45–0.55$. The value of $\delta_{\text{WDPP}}^{\text{opt}}$ significantly depends on the initial cost data and the value of the gas turbine standby capacity.

![Figure 4. Changes in discounted costs depending on the relative capacity of wind-driven power plants.](image)

Conclusions
1. A mathematical model has been developed to determine the optimal capacity of a wind-driven power plant as part of the energy complex.
2. The daily and annual quantitative parameters of the autonomous energy complex were calculated, including gas turbines, wind-driven power plants, and peak boilers.
3. Taking into account the reservation of electric power, we determined the optimum value of the wind turbines relative capacity, which is in the range of 0.45–0.55. Consequently, 0.45–0.55 of the maximum load is provided by GTU. The value of the relative capacity of wind-driven power plants is significantly affected by the cost of fuel and capital investments in electric power installation.

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