Competitiveness of the combined production of chpp with the best available technologies for the separate production of electric energy and heat

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Abstract. Further development of the Russian energy sector involves the use of the best available technologies. An important issue is the identification of bats. Increasing the fuel efficiency of power plants is carried out by increasing the unit capacity of generating equipment, increasing the parameters of the working medium to supercritical and super-supercritical. Unfortunately, when forming the list of bats, performance indicators are not always taken into account in real operating modes of the equipment. The calculations have shown that combined production of PTU-CHP plant with subcritical parameters of the working body on the basis of steam turbines of the type P, T and PT given the mandatory process releases steam into the condenser and the gas turbine CHP based on gas turbines of a small capacity has the best specific fuel consumption for generation of electric energy and heat compared to the separate generation of the best available technologies (BAT).

Keywords: energy system, electricity, heat, best available technologies, fuel efficiency, combined generation, competitiveness.

1. Introduction

The development of cogeneration is recognized as a priority for improving efficiency and combating climate change [1,2]. Taking into account climatic and geographical features, the development of cogeneration is the main direction of reducing greenhouse gas emissions in the Russian Federation [3].

Further development of the Russian energy sector involves the use of the best available technologies (BAT) [4,5]. The government of the Russian Federation has defined "a set of measures aimed at avoiding the use of outdated and inefficient technologies, switching to the principles of the best available technologies and introducing modern technologies" [6,7].

Identifying the best available technologies is an important issue. Unfortunately, when forming the list of bats, performance indicators are not always taken into account in real operating modes of
the equipment. The criteria are taken as the values of electrical efficiency and greenhouse gas emissions when the equipment operates at rated modes.

It should be noted that increasing the fuel efficiency of power plants is carried out by increasing the unit capacity of generating equipment, increasing the parameters of the working medium to supercritical (SCP-24 MPa, 540°C /540°C) and super-supercritical (SSCP-more than 24 MPa and/or a temperature of more than 565°C), as well as the use of a combined cycle.

Modern thermal power plants with super-supercritical steam parameters (SSSP), using coal and brown coal as fuel, are characterized by a unit capacity of power units from 600 to 1100 MW, fresh steam pressure from 255 to 285 bar, temperature from 576 to 600 °C, and electric efficiency from 43 to 45.7%.

The best indicators of electric efficiency are CCPPs based on large gas turbines of the companies Siemens, General Electric, and Mitsubishi (table 1) [8,9].

Table 1. The parameters of gas turbines and CCPP

| Name of values | Siemens | GE | Mitsubishi |
|----------------|---------|----|------------|
| Power at the terminals, MW | 450 | 481 | 593 | 314 | 446 | 571 | 385 | 478 | 563 |
| Efficiency at the terminals, % | >41 | 42.6 | >42.6 | 38.6 | 43.1 | 44 | 41.9 | 42.3 | 43.6 |
| Gas temperature before the turbine, °C | 1510 | 1670 | 1670 | ----- | ----- | ----- | ----- | ----- | 1700 |
| The gas temperature of the exhaust, °C | 630 | 680 | 680 | 632 | 629 | 640 | 631 | 630 | 649 |

The parameters of the CCPP (1+1):

| Power of CCPP at terminals, MW | 665 | 708 | 841 | 493 | 660 | 838 | 566 | 701 | 818 |
| Efficiency of CCPP on the terminals, % | 61 | >63 | >63 | 60.7 | 63.5 | 64.1 | 62 | 62.3 | 64 |
| Year of commissioning | 2008 | 2017 | 2017 | 2003 | 2011 | 2014 | 1992 | 2014 | 2015 |

The efficiency of CCPP based on GTU class H exceeds 60% [10,11]. The value of the electrical efficiency CCPP more than 60% is achieved due to the growth of power gas and steam turbines, the temperature rise in the combustion chamber of a gas turbine, growth temperature and pressure fresh steam to the super-supercritical steam turbine. The exhaust gas temperature of HL class GTU with an electric efficiency of 42.6% will increase to 680 °C. The capacity of a CCPP with an efficiency of more than 63% will exceed 800 MW.

It should be noted that the increase in unit capacity units leads to an increase of the required value of the reserve electric power, increase the length of the network infrastructure, growth of electricity losses in electric networks.
2. Methodical approach
The quality of design of the Unified energy system of the Russian Federation determines the reliability and efficiency of energy supply to consumers. The structure of generating capacity should correspond to the structure of consumption [12].

When making strategic decisions about the target structure of generating capacity in the Russian energy system, it is necessary to ensure a correct comparison of the efficiency of production of electricity and heat from combined generation and separate production sources. When comparing, it is necessary to take into account the same list of goods and services provided by sources of electric and thermal energy, for the same electrical and thermal loading modes of generating equipment.

The methodological approach is based on assessing the competitiveness of combined heat and power generation with best available technologies (BAT) for separate heat and power generation, taking into account losses in the electrical and thermal networks, differences in fuel costs, and electrical and thermal loading modes of equipment [13]. The considered methodological approach allows us to compare the results of using most existing methods of separating the fuel consumption of a CHP plant between electric and thermal energy.

The dependence of the specific fuel consumption of a CHPP for heat generation on the specific fuel consumption for electricity generation can be represented by the formula [13]:

\[ b^*_{h} = 142.86 \times (1 - \eta_{el} \times b^*_{el}/123.83) / (\eta_{CHP} - \eta_{el}) \]  

(1)

The pee coefficient is a characteristic of the generating equipment of the CHP, and the pcit is determined by the operating mode of the power plant. For fixed values of pcit and pee, the relationship between the specific consumption of conventional fuel for the production of heat and electricity is a linear function.

Combined generation should ensure the competitiveness of the CHP in the electricity and heat markets at the same time. The system of inequalities (2) and (3) determines the competitiveness of combined output (output) TPP with BAT separate production (release) of electric and heat energy:

\[ b^*_{el} \leq b^*_{el}^{BAT} \times \Delta_{el} \times c_{el} \]  

(2)

where: \( b^*_{el}^{BAT} \) - specific fuel consumption for electric power generation by the best available technologies of separate production.

\[ b^*_{h} \leq b^*_{h}^{BAT} \times \Delta_{h} \times c_{h} \]  

(3)

where: \( b^*_{h}^{BAT} \) - specific fuel consumption for heat generation by the best available separate production technologies.

Correction coefficients related to losses of electric and thermal energy can be presented as follows:

\[ \Delta_{el} = \Delta_{el}^{BAT} / \Delta_{el}^* \]  

(4)

where: \( \Delta_{el}^{BAT} \) - losses of electric energy during transmission from the reference power plant to the consumer; \( \Delta_{el}^* \) - losses of electric energy during transmission from the CHP to the consumer.

\[ \Delta_{h} = \Delta_{h}^{BAT} / \Delta_{h}^* \]  

(5)

where: \( \Delta_{h}^{BAT} \) - heat energy losses during transmission from the reference boiler house to the consumer; \( \Delta_{h}^* \) - heat energy losses during transmission from the CHP to the consumer.

Fuel cost correction factors for comparison with reference power plant and boiler house can be presented as follows:
where: $C_{el}^{BAT}$ - the fuel cost of the reference power plant; $C_{el}^{*}$ - the cost of the CHPP fuel.

$$C_{h} = \frac{C_{BAT}^{h}}{C_{h}^{*}}$$  \hspace{1cm} (7)$$

where: $C_{BAT}^{h}$ - fuel cost of the reference boiler house; $C_{h}^{*}$ - CHP fuel cost.

Figure 1 shows the results of calculating the specific indicators of the PT-135 / 165-130 / 15 turbine unit, carried out on the basis of 11 different methods for dividing fuel consumption between the production (supply) of electric energy and heat [14,15]. The obtained values of specific indicators lie on a single line. To ensure the competitiveness of combined production in comparison with BAT of separate production, it is necessary to select points that lie within the "rectangle of competitiveness".

**Figure 1.** An example of calculating the specific indicators of a PT-135 / 165-130 / 15 turbine unit
1 - Energy method; 2 - "Physical" method; 3 - Method of alternative heat production; 4 - Method of separation of savings and risk; 5 - Economy spreading method; 6 - Proportional distribution method from ORGRES; 7 - Exergetic method; 8 - Method that takes into account the under-generated electricity; 9 - Method based on the linearized flow characteristic of a steam turbine; 10 - Method of alternative electricity generation; 11 - Method taking into account the thermal value of steam.

In the scientific and technical literature, the position that there is no scientifically-based method for separating fuel consumption between the production of electric energy and heat has become widespread. Despite the lack of scientific-based methods, specific fuel consumption indicators are actively used to justify strategic decisions when designing the development of electric power and heat power systems.

Currently, for the purpose of forming state statistical reports on the fuel efficiency of production and distribution of electric and thermal energy, the ORGRES method and the physical method are used. When using the physical method, the CHP loses competition in the heat market, and when using the ORGRES method, it loses competition in the electricity market. Both methods cannot
be used in the process of making strategic decisions on the formation of the structure of generating capacity for electricity and heat supply to consumers, as they give false signals.

It should be noted that the specific indicators of PT-135/165-130/15, obtained using ten of the eleven methods, lie outside the "rectangle of competitiveness" of combined power and heat generation of thermal power plants with BAT of separate production. The use of methods that correspond to the first and second laws of thermodynamics also does not ensure the competitiveness of thermal power plants in the electricity and heat markets at the same time.

In the development of most of the methods for spreading fuel consumption, the main disputes were about what is the main, and what is a by-product of combined electricity and heat generation. The indicators of fuel efficiency of production (release) of electric energy and heat obtained with their help during the preparation of reports within the framework of state statistical reporting are characterized by a significant amount of cross-subsidizing of various types. Cross-subsidization distorts the competitiveness of combined generation.

3. Production of electric energy and heat
The electricity consumption schedule is characterized by pronounced daily and seasonal irregularities. The schedule of heat energy consumption is seasonal. The loading of power plants and boiler houses must comply with the schedules for the consumption of electrical and thermal energy.

To operate in the "basic" part of the daily load schedule, NPPs, combined generation of CHPPs, HPPs without regulated flow, sanitary releases of HPPs, power plants operating on the principles of MSW utilization are used. For work in the "half-peak" and "peak" parts of the daily load schedule, hydroelectric power plants, state district power plants, combined cycle power plants, and gas turbines are used.

The operation of the CHPP in the combined generation mode is carried out in the interests of the electric power and heat power systems. Condensation generation of the CHPP is carried out by the commands of the system operator in the interests of ensuring electrical modes in the electric power system of the Russian Federation.

Different power plants provide a different scope of services for the functioning of the power system of the system, its reliability and survivability. Unlike condensing power plants, CHP plants supply electric energy to external consumers, and also spend it on heat supply to consumers, on the provision of services for the preparation of chemically purified water for the heat supply system, for ensuring the thermal regimes of the heating network (accumulation of thermal energy), for maintaining reserve fuel, and so on. Further.

Thus, it is important to correctly determine the effective supply of electrical energy and heat, the distribution of fuel consumption between the production of electrical energy and heat.

4. An example of calculations:

When working in the basic part of the daily load schedule
A significant volume of combined generation of electric energy and heat in the power system of the Russian Federation is carried out on generating equipment with subcritical parameters of the working fluid. For comparison with BAT for separate production of electricity and heat, we will choose power plants based on steam turbines with steam pressures of 130 and 90 bar, and gas turbines with a temperature in the combustion chamber of 1100-1200 °C.

The best available technologies for gas-fired separate production include CCGT units with an electrical efficiency of 62% and gas hot water boilers with an efficiency of 95%.

Figure 2 shows the results of calculations of the specific fuel consumption for the generation of electricity and heat from gas power plants. The values of specific fuel consumption for all types of generating equipment are within the “competitiveness rectangle” with BAT for separate production of electricity and heat.
Thus, the performed calculations showed that the combined generation of STU-CHPP based on steam turbines of the P, T and PT types, taking into account the obligatory technological releases of steam into the condenser, has better specific indicators of fuel consumption for the generation of electrical energy and heat in comparison with BAT of separate production at work in the basic part of the daily load schedule.

It should be noted that the segments characterizing the dependence of the specific fuel consumption for the production of electricity and heat in Figure 2 intersect at one point: $b_{el} = 144.51$ gcf/kWh and $b_{h} = 168.08$ kgcf/Gcal.

In general, the coordinates of the points of intersection of the segments for the same values of CHP Total for the generation of electric energy and heat can be represented as follows:

$$b_{el} = \frac{122.83}{\eta_{CHP}} \quad \text{and} \quad b_{h} = \frac{142.86}{\eta_{CHP}}.$$ 

The best available technologies for separate production, operating on solid fuels, include STU with an electrical efficiency of about 46% and coal-fired hot water boilers with an efficiency of 92%. Figure 3 shows the results of calculations of the specific fuel consumption for the generation of electricity and heat from coal-fired power plants.
Figure 3. Power plants and solid fuel boilers

Combined production: 1. - P-25-90; 2. - T-100-90; 3. - T-100-130;
Separate production: 4. - BAT for electricity production; 5. - BAT of heat production.
Specific consumption of equivalent fuel: A - ; B -; C -.

The values of specific fuel consumption of all types of generating equipment are located inside the "competitiveness rectangle" with BAT for separate production of electric energy and heat.

Thus, calculations have shown that combined production of CCPP-CHP plant with subcritical parameters of the working body has the best specific fuel consumption for generation of electric energy and heat compared to the separate production of BAT when working with basic daily schedule loads.

When working in the half-peak and peak parts of the daily load schedule

As a result of the active development of renewable energy sources, power plants operating in the semi-peak and peak parts of the daily load schedule with daily starts/stops of generating equipment are required to maintain electric modes. Currently, in order to maintain electrical modes in the power system, the thermal power plant's heating equipment is loaded in inefficient condensation modes at the commands of the System operator.

Bats for separate production of electric energy intended for operation in the basic part of the daily load schedule may not be required in the power system. For example, for operational reasons, modern CCPP-600 based on the SGT5-8000H gas turbine and the sst5-5000 steam turbine manufactured by Siemens with a declared electrical efficiency of more than 60% will be unclaimed in the German power system [16].

Thus, it is necessary to compare the fuel efficiency of a thermal power plant with bats for separate production of electric energy intended for operation in the semi-peak and peak parts of the daily load schedule.

The best available technologies for separate production, running on gas fuel with the possibility of daily starts/stops, include GTU with an electric efficiency of 42% and gas hot water boilers with an efficiency of 95%.
We consider the operation of power plants in the mode with daily starts/stops with the production of electric energy at rated power during the peak and half-peak parts of the daily load schedule (14 hours) and stop for the period of passing the daily minimum (10 hours). Heat supply to consumers for 10 hours is provided by hot water boilers.

Figure 4 shows the results of calculating the specific fuel consumption for electricity and heat generation by gas power plants and hot water boilers.

The values of specific fuel consumption of all types of generating equipment are located inside the "competitiveness rectangle" with bats for separate production of electric energy and heat, intended for operation on gas fuel with daily starts/stops.

The segments that characterize the dependence of specific fuel consumption on electricity and heat production in figure 4 intersect at one point: $b_{el} = 144.51 \text{ gcf/kWh}$ and $b_{h} = 157.75 \text{ gcf/Gcal}$.

In general, the coordinates of the intersection points of segments for the same values of the KITT of electric power and heat generation when operating power plants in the mode of daily starts/stops of generating equipment can be represented as follows:

$$b_{el} = \frac{122.83}{\eta_{kitt}}$$

$$b_{h} = \left( \frac{t}{24 \times \eta_{kitt}} + \frac{24-t}{24 \times \eta_{b}} \right) \times 142.86$$

where: $\eta_{b}$ - efficiency of hot water boilers; $t$ - duration of electricity production during the day.

The best available technologies for separate production that use solid fuels include gas-fired boilers with an electric efficiency of about 37% and coal-fired hot water boilers with an efficiency of 92%. Figure 5 shows the results of calculating the specific fuel consumption for generating electricity and heat from coal-fired power plants and hot water boilers.
The values of specific fuel consumption of all types of generating equipment are located inside the "competitiveness rectangle" with bats for separate production of electric energy and heat, intended for operation on solid fuel with daily starts/stops.

Figure 6 shows the results of calculations of specific fuel consumption for electric power and heat generation for various modes of high-maneuverable GTU-TPP intended for operation in the half-peak and peak parts of the daily load schedule, and hot water boilers.
Figure 6. Fuel heat utilization coefficient of highly maneuverable GTU-TPP and hot water boilers when working with daily starts/stops of generating equipment.

Combined production: 1. – fuel heat utilization coefficient =85%; 2. – fuel heat utilization coefficient =75%; 3. – fuel heat utilization coefficient =65%; 4. – fuel heat utilization coefficient =55%.

Separate production: 5. – the most available technologies heat production; 6. – the most available technologies electricity production.

Specific fuel consumption: A –; B –; C –; D - .

The values of specific fuel consumption of a high-maneuverable GTU-TPP for operating modes with fuel heat utilization coefficient from 55% are located inside the "rectangle of competitiveness" with BAT for separate production of electric energy and heat, intended for operation on gas fuel with daily starts/stops.

The segments that characterize the dependence of specific fuel consumption on electricity and heat production in figure 6 intersect at one point: $b_{el} = 350.94 \text{ gcf} / \text{kWh}$ and $b_h = 87.72 \text{ kgcf/Gcal}$.

In General, the coordinates of the intersection points of segments for the same values of electric efficiency and different values of fuel heat utilization coefficient of electric energy and heat generation when power plants operate in the mode of daily starts/stops of generating equipment can be represented as follows:

$$b_{el} = \frac{122.83}{\eta_{el}} \quad \text{and} \quad b_h = \frac{24-t}{24\times\eta_{h}} \times 142.86$$

where: $\eta_{el}$ - electrical efficiency; $t$ - duration of electricity production during the day.

5. Conclusion
1. The best available technologies for separate electric power generation include a CCPP designed to operate in the basic part of the daily load schedule, with an electrical efficiency of more than 60%.

The electric efficiency value of more than 60% is achieved by increasing the power of gas and steam turbines, increasing the temperature in the combustion chamber of the gas turbine above 1600°C, increasing the temperature and pressure of fresh steam to super-supercritical parameters in the steam turbine.

2. Combined production of STU gas-cogeneration plant with subcritical parameters of the working body on the basis of steam turbines of the type P, T and PT given the mandatory process releases
steam into the condenser has the best specific fuel consumption for generation of electric energy and heat compared to the separate production of NDT when working with basic daily schedule loads.

3. Combined production of coal-fired STU-TPP with subcritical parameters of the working body has the best specific indicators of fuel consumption for the production of electric energy and heat in comparison with BAT of separate production when working in the basic part of the daily load schedule.

4. Highly Maneuverable GTU-TPP when operating in the half-peak and peak parts of the daily schedule of electrical loads with daily starts/stops has a higher fuel efficiency compared to the BAT of separate production.

5. The increase in unit capacity units leads to an increase of the required value of the reserve electric power, increase the length of the network infrastructure, growth of electricity losses in electric networks.

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