ASSESSMENT OF TECHNICAL AND ECONOMIC EFFICIENCY INDICATORS OF COGENERATION IN MODERN MARKET CONDITIONS

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ABSTRACT

In this work we discuss issues of economic justifiability of usage of combined production of heat and electric energy in the existing market realities basing on the analysis of the main criteria of efficiency of cogeneration in the planned economy of
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the Soviet Union. A criterion of added value maximum for energy products is proposed to assess the feasibility of technology usage. When comparing the options we used the value of reduced annual cost, including the costs related to capital expenses, depreciation, fuel costs, operating costs and capital costs for construction of the facility. In relation to the performance comparison of combined and separate production of electricity we used the value of specific income from sale of energy products (heat and electricity) produced per a unit of consumption of 1 toe of equivalent fuel. The relationship between CHPP and boiler income from the sale of thermal and electric energy at various tariffs is presented. It is shown that with increasing the share of heat supply to external consumers, the increase in income from the sale of thermal energy exceeds the decrease in income from the sale of electric energy and total specific revenue of the CHPP is increased. So, the CHPP has the largest total specific income at maximum specific heat load equal to 2/3, due to the high yield from the sale of thermal energy at existing tariffs for heat and electricity. We developed a basic computational model for analysis of consolidated energy and economic indicators of various sources of thermal and electric energy. It is established that the final choice of shares of each alternative sources, involved in coverage of thermal loads is based on multiple optimization calculations taking into account many factors: investment in the sources and distribution network, fuel cost, graphics of thermal loads, operation modes of sources, including diagrams of thermal networks and others.

Key words: cogeneration, combined heat and power plant (CHPP), efficiency, expenses, tariffs, boiler house, profitability, calculation model

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1. INTRODUCTION

The Russian Federation is the world leader in the development of cogeneration and district heating [1-6]. This became possible due to favorable combination of objective (low temperatures in winter and a long heating period) and subjective (targeted state policy and large investments in the development of district heating) factors. The main criterion of efficiency of cogeneration in the conditions of planned economy of the USSR was fuel savings at heat and electric power that was replaced by means of cogeneration in a separate scheme for production of heat and electricity (the fuel consumption for heat production at CHPP and in boiler house were assumed to be the same). This criterion is fully consistent with the conditions of the unified state national economic complex of the country [7].

However, in the current market conditions with a fragmented ownership structure of energy generating assets, fuel savings on a power plant replaced by a cogeneration owned by another owner are not an incentive for the development of a heat supply from a specific investor [8]. And therefore, for the further successful development of cogeneration in market conditions, Russia needs to create preferences for obtaining the maximum benefit from cogeneration for both producers and consumers of heat and electricity due to a competent tariff policy for heat and electricity.
Boiler houses and power plants are enterprises for processing fuel into energy products: heat and electricity. Taking into account the fact that fuel costs make up more than 80% in the structure of their cost, the maximum cost of energy products generated from a fixed amount of fuel of a given quality can be considered as a powerful incentive to improve the efficiency of energy generating enterprises [9-12]. In particular, for CHPP, the total income $D_{CHPP}$ from the sale of energy products produced from a given amount of fuel $B$ is obtained using heat tariffs $\phi_h$, rub/GJ and electricity tariffs $\phi_e$, rub/kW·h according to the formula:

$$D_{CHPP} = \phi_h \cdot Q_h + \phi_e \cdot E$$  \hspace{1cm} (1)

where $Q_h$, GJ and $E$, kW·h is generation of heat and electrical energy from CHPP from the given fuel amount $B$;

$\phi_h$ is heat tariff for a heat-grid company, rub/GJ;

$\phi_e$ is the weighted average tariff for electricity purchased by an electric grid company, rub/kW·h.

This indicator can be used when comparing the efficiency of combined power generation both at different types of CHPP (steam turbine, gas turbine, steam-gas, etc.) among themselves, and when comparing the combined power and heat generation with a separate circuit.

In relation to the comparison of the efficiency of combined and separate power generation, it is convenient to use the income $D_{CHPP}$, rub/toe, from the sale of energy products (heat and electricity), generated per unit of standard fuel consumption in the amount of 1 ton of fuel equivalent [13].

The method of calculating these quantities is illustrated using the principal thermal scheme of a steam-turbine heat and power plant shown in Fig 1. The proposed method has a number of assumptions and is applicable only to assess the efficiency of cogeneration in the conditions of accepted restrictions.

**Figure 1** Energy balance of the steam turbine cogeneration plant. SG is steam generator, T; K is cogeneration and condensation turbines; RHT, RHC are conventional regenerative heaters of condensate of cogeneration and condensation turbine; CO is condenser; NH is network heater; $q_c$ and $q_t$ is specific energy supplied to condenser and cogeneration cycles; $E_c$ and $E_T$ is electrical energy generation according to function; $q_{PK}$ and $q_{PT}$ is specific heat energy for regenerative heating, $\tau_1$ and $\tau_1$ is temperature chart for heat network.

For methodical purposes, a cogeneration extraction turbine is presented as two turbines: a heat and power plant with back pressure and condensation, and the steam flow through the flow part of the turbine is conventionally divided into heat and power “T” and condensation “C”. For backpressure turbines of type P, $QC_{turb} = 0$ (all power generation is based on heat.
consumption), for turbines with no extraction, on the contrary, QTturb = 0 and power generation is purely condensation.

The value of DCHPP is calculated based on the energy balance of the heat equivalent of 1 ton of fuel equivalent in the CHPP cogeneration turbine (see Fig 1) using the formula:

\[ D_{CHPP} = \phi_T \cdot q_T + \phi_e \cdot e = \phi_T \cdot q_T + \phi_e \cdot \left( q_T \cdot \bar{E}_T + \left[ 1 - q_T \cdot (1 + \bar{E}_T) \right] \cdot \eta_C \right) \]  \hspace{1cm} (2)

where \( q_T \), \( e \) is specific generation of heat (heat load) GJ/t.o.e. and electrical power, kW·h/t.o.e. for CHPP for a unit fuel consumption, \( \bar{E}_T \) is specific dimensionless combined generation of electrical power at CHPP, \( \eta_C \) is efficiency for electrical energy generation at CHPP during condensation cycle.

The considered thermal equivalent shows an estimate of the performance of CHPP (generation of heat and electricity), referred to 1 t.o.e., consumed in the boiler unit, taking into account all stages of energy conversion in the cycle. In other words, this term refers to the amount of thermal energy in the amount of 29,300 MJ, supplied to the head of the cogeneration turbine.

This indicator reflects the close relationship between the generation of heat and electrical energy at CHPP (an increase in one parameter leads to a decrease in the other and vice versa) per unit of consumption of fuel equivalent and therefore it is suitable (together with equation 3) for solving such major problems in the field of heating such as: the choice of CHPP cogeneration coefficient \( \alpha_{CHPP} \), the identification of the optimal ratio of heat and electricity tariffs for CHPP, stimulating cogeneration and others.

A comparative analysis of the impact of selling tariffs of heat and electricity on the income of power generating company (CHPP, CES, boiler house) was carried out. The calculations are performed in thermal equivalents of 1 t.o.e., burned in a steam (CHPP, CES) or hot water boiler.

The following initial conditions are taken into account: numerical values correspond to the nominal operating mode of the equipment, specific dimensionless values are assumed fixed (\( \overline{E}_T=0.5 \) and \( q_{t \ max}=0.67 \)), the efficiency of the condensation cycle is 40% and does not depend on the CHPP load.

The maximum value of the specific heat load of CHPP bleed is determined from the relationship:

\[ q_{t \ max} = 1/(1 + \overline{E}_T) \]

where \( \overline{E}_T \) is specific dimensionless combined generation of electricity at CHPP. For modern cogeneration installations we take \( \overline{E}_T = 0.5 \), so \( q_{t \ max}=0.67 \).

With a full load of bleeds in the amount of 2/3 of the heat \( q_0 \) supplied to the head of the turbine, a decrease in electricity generation compared to the condensation regime will be 18%. Fig 2 shows relationship between the CHPP income and the sale of electricity generated from 1 t.o.e., at a tariff of 3 rub/kW·h while varying the value of the specific heat load \( q_t \).

The starting point \( q_t = 0 \) corresponds to CES (all the heat supplied by the turbine is used only for generating electricity with a corresponding efficiency (in this case, for convenience and clarity of calculation, an electrical efficiency of 40% is assumed).
Figure 2 Relationship between the CHPP income and the sale of electricity while varying the value of the specific heat load (1 – condensation generation, 2 – cogeneration, 3 – summarized generation).

As the share of heat supply to an external consumer increases, the CHPP income from the sale of heat energy grows at various heat tariffs. Fig 3 presents the results of calculating the income from the sale of heat energy generated from 1 t.o.e., by varying the selling tariff for heat in the range from 350 to 600 rub/GJ. At the same time, the income from the sale of electric energy is decreased.

Figure 3 Relationship between income for heat power sales (rub.) and specific heat load (1 – 350 rub./GJ, 2 – 475 rub./GJ, 3 – 600 rub./GJ).

Fig 4 presents the results of calculating the income from the sale of electric energy with consumption of 1 t.o.e. and the variation of the selling tariff for electric energy in the range from 2 to 4 rub/kWr·h.
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Figure 4 Relationship between income for electrical power sales (rub.) and specific heat load (1 – 2 rub/kW·h, 2 – 3 rub/kW·h, 3 – 4 rub/kW·h).

It should be noted that with an increase in the share of heat supply to the external consumer \( q_t \), the increase in income from the sale of heat energy exceeds the decline in income from the sale of electrical energy and the total income of CHPP increases. Thus, CHPP has the highest total income at \( q_t = 2/3 \). This is due to the high yield from the sale of thermal energy at the existing tariffs for heat and electricity.

Fig 5 presents the results of calculating the total income from the sale of heat and electricity from CHPP and heat from the boiler house.

Figure 5 Relationship between total income from selling heat and electrical energy and the tariff for heat at given electricity tariff from 2 to 4 rub/kW·h (1 – boiler house, 2 – 2 rub/ kW·h, 3 – 3 rub/ kW·h, 4 – 4 rub/ kW·h).

As it is shown in Fig 5, the CHPP income is higher than in the boiler house when tariffs are growing, respectively: for electricity, 2 rub/kW·h and heat 475 rub/GJ, at 3 rub/kW·h - 835 rub/GJ, at 4 rub/kW·h - 1075 rub/GJ. When the heat tariff is less than 475 rub/GJ, the boiler house loses to CHPP in the whole range of variation of the electricity tariff.

Fig 6 shows the results of comparing the profitability of CHPP, CES and the boiler house with the average of the considered tariff ranges for heat equal to 475 rub/GJ and electricity 3 rub/kW·h.
Figure 6 Income from selling of heat and electrical energy from CHPP, boiler house and CES for tariffs: 475 rub/GJ and 3 rub/kW·h.

As can be seen from the Fig, the CHPP yield from the sale of electrical and heat energy is 1.5 - 2 times higher than the yield of the boiler house and CES when burning an equal amount of fuel. The absolute indicators of the profitability of the CHPP and the boiler house in a separate scheme are determined by the degree of loading of their capacities in annual terms Z in accordance with the schedules of thermal loads connected to them by consumers.

The annual load factor of the thermal power of the source Z, for example, for $\alpha_{\text{CHPP}} = 0.5$ (the ratio of thermal power covered by the CHPP and the total power):

$$Z = \frac{\text{area}(0 - 1 - 2 - 4 - 5)}{\text{area}(0 - 1 - 3 - 5)}$$

As $\alpha_{\text{CHPP}}$ increases, Z decreases. At the same time, the absolute values of the annual heat supply $Q_{\text{year}}$ and the electricity generation at the heat consumption $E_{\text{year}}$ increase (see Fig 7).

Figure 7 Annual graph of heat load depending on duration.

As an example, calculations of the values of $Q_{\text{year}}$ and $E_{\text{year}}$ were carried out for the “reference” CHPP with maximum selection load of 2/3 of the heat supplied to the turbine and $E_{\text{t}}=0.5$ with the design parameters indicated in the Table 1:
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Table 1. Initial data for the calculation of the heat load graph.

<table>
<thead>
<tr>
<th>Q_{ot}, GJ/h</th>
<th>h, hours</th>
<th>Q_{HWSSW}, GJ/h</th>
<th>Q_{HWSS}, GJ/h</th>
<th>N_{CHPP}, MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>5000</td>
<td>80</td>
<td>72</td>
<td>60</td>
</tr>
</tbody>
</table>

Fig 8 shows a graph presenting relationship between income of power generating plants (CHPP and boiler house) from the sale of electricity and heat and the share of heat load covered by CHPP bleeds ($\alpha_{CHPP}$).

![Graph showing income from sales of heat and electrical energy at the boiler house and CHPP at varying $\alpha_{CHPP}$](image)

**Figure 8** Income from sales (million rubles) of heat and electrical energy at the boiler house and CHPP at variation of $\alpha_{CHPP}$ (1 - thermal energy at CHPP, 2 - electrical energy at CHPP, 3 - peak boiler room).

As can be seen from Fig 8, the increase in CHPP income markedly decreases (especially when $\alpha_{CHPP} > 0.5$) as $\alpha_{CHPP}$ increases. This is due to the rapid decrease of the load factor of the thermal power of the source Z at $\alpha_{CHPP} > 0.5$.

Similarly, the annual fuel consumption of plants varies (Fig 9).

![Graph showing fuel consumption at the boiler house and CHPP at varying $\alpha_{CHPP}$](image)

**Figure 9** Fuel consumption (t.o.e.) for generation of heat and electrical energy at the boiler house and CHPP at varying $\alpha_{CHPP}$ (1 - CHPP, 2 - peak boiler room).

As it can be seen from the Fig, the annual fuel consumption required for CHPP is about 30% more than for a boiler house that generates the same amount of heat per year.

The final choice of the shares of each of the alternative sources involved in covering heat loads is made on the basis of multivariate optimization calculations taking into account a large
number of factors: investment in sources and distribution networks, cost of fuel, heat load graphs, operating modes of sources, including temperature charts of heat networks and others.

As a criterion of efficiency when comparing options, we used the value of discounted annual expenditures $Z$, calculated by the formula:

$$Z = Z_c + Z_d + Z_f + Z_e = \sum_0^\infty \left[ C \cdot \left( f + \frac{1}{f} \right) + 1.2 \cdot Z_f \right] \cdot (1 - i)^n$$

where, $Z_c$ is costs related to capital investments, $Z_d$ is depreciation deductions, $Z_f$ is expenses for fuel, $Z_e$ is exploitation costs, $C$ is capital expenses for construction of object, $f$ is share of depreciation charges ($f=0.05$), $T$ is payment period for credit for construction of facility, $n$ is lifetime of the facility, $i$ is annual rate.

It should be noted that in this calculation the costs were determined without taking into account taxation and duties. To illustrate the comparison, the specific capital costs for the construction of facilities as an example were taken equal to 150 mln.rub/MW for CHPP and 3.7 mln. rub/GJ for the boiler room. Fig 10 shows relationship between investments for CHPP and alternative boiler house construction and $\alpha_{CHPP}$.

**Figure 10** Capital expenses (mln rub) for the construction of a boiler house and CHPP with varying $\alpha_{CHPP}$ (1 - CHPP, 2 - peak boiler house).

We assume that the target construction loan is allocated for 8 years with the same construction period for CHPP and the boiler house for 3 years. Then the payment of the loan with interest must be secured for 5 years (Fig 11).

**Figure 11** Annual costs (mln. rub) for CHPP and boiler house at varying $\alpha_{CHPP}$ (1 - CHPP, 2 - peak boiler house).
In this case, the optimality factor of $\alpha_{\text{CHPP}}$ can be the value of specific costs for generation of thermal energy at CHPP and peak boiler house (Fig 12).

**Figure 12** Annual specific expenses (rub/GJ) for CHPP and boiler house at $\alpha_{\text{CHPP}}$ varying (1 - peak boiler, 2 - CHPP).

From Fig 12 it follows that with the considered ratios of tariffs and annual costs, CHPP has the best performance in the interval up to $\alpha_{\text{CHPP}} = 0.2$ and over 0.6. In the interval $0.2 < \alpha_{\text{CHPP}} < 0.6$, the technologies have an approximate equal value of the annual specific expenses for generation of thermal energy (rub/GJ).

Below is an example of calculating annual income for CHPP with $\alpha_{\text{CHPP}} = 0.4$:

1. The annual heat load covered by CHPP will be equal to the corresponding area under the graph in Fig 7, i.e. 1020720 GJ/year.
2. With a tariff of 475 rub/GJ, the CHPP income from the sale of heat energy is approximately 485 mln rub/year.
3. With a fixed value $\bar{E}_r = 0.5$, the generation of electricity from heat consumption in terms of heat energy of steam will be $0.5 \times 1020720 = 510360$ GJ/year.
4. When converting the amount of electricity generation on heat consumption from GJ to kW·h (1 GJ = 278 kW·h) and taking into account the tariff for electricity 3 rub./kW·h, CHPP income from the sale of heat energy will be $510360 \times 278 \times 3 = 426$ mln rub./year. In this example, when $q_{\text{max}} = 0.67$, the share of electricity generation in the condensation mode is equal to zero.
5. The total CHPP income for a given heat graph and $\alpha_{\text{CHPP}} = 0.4$ will be 911 mln rub./year.
6. Fig 13 shows the cost-benefit comparison for the CHPP option under consideration. To return the target loan within 5 years after the completion of construction, it is necessary to have somewhat overestimated tariffs or subsidies for both CHPP and peak boiler-house in order to ensure timely return of funds for a given $\alpha_{\text{CHPP}}$. 
Figure 13 Annual expenses/income (mln rub) for CHPP at varying $\alpha_{\text{CHPP}}$ (1 – expenses within the credit payment period, 2 - income, 3 - costs after the credit is repaid).

In the case of an increase in the tariff for electric energy from 3 to 7 rub/kW·h (Fig 13), expenses/income equality is achieved at $\alpha_{\text{CHPP}} = 0.6 - 0.7$ with a credit payment period of 5 years. A similar effect is observed with an increase in the heat tariff from 475 to 1075 rub/GJ.

Fig 14 shows a similar annual expenses chart for peak boiler house.

Figure 14 Annual expenses/income (mln rub) for peak boiler house at varying $\alpha_{\text{CHPP}}$ (1 – expenses within the credit payment period, 2 - income, 3 - costs after the credit is repaid).

The proposed approach can be applied and improved taking into account the real characteristics of the region under consideration (heat load graph, heat and electricity tariffs, the amount of investment in new construction, credit conditions, etc.). In other words, the value of the optimal $\alpha_{\text{CHPP}}$ will vary from the initial conditions of each specific task.

Currently, at MPEI a computational model for analyzing the enlarged energy and economic indicators of various sources of thermal and electrical energy (CHPP, CES, boiler house, etc.) is being developed. This model can be easily adapted and improved for each individual task, region, source of heat energy, seasonality of consumers and other factors. Graphic results presented in this work are illustrative and reflect a generalized criterial approach.
REFERENCES


