Research of the Combined-Cycle Cogeneration Plant's Behaviour According to the Temperature Chart

D. A. Treshchev, M. A. Treshcheva, D. L. Kolbantseva, and A. A. Kalyutik

1 Introduction

Cogeneration is the most efficient way of using fuel heat, so expanding the use of cogeneration in Russia can be one of the most important elements in forming coherent energy policy 1 [1–7].

According to industry reports (Table 1), currently about 46–48% of the total heat supply in district heating systems comes from thermal power plants (TPP) that is comparable with heat supply from large heat boiler stations (52–53%).

Thermal power plants comprise 67% of the installed capacity structure of Russian power plants. At the same time, 78% of them operate on the basis of steam-power plants. However, over the last 20 years, the share of combined cycle plants (CCPs) has dramatically increased, reaching 16% by the moment.

According to the energy strategy of the Russian Federation for the period until 2035, in 2018 the actual specific reference fuel consumption (SRFC) for electricity supply at cogeneration sources with installed capacity of 25 MW or more was 309.8 goe/kWh (which is 26.2 goe/kWh lower than in 2008). Further SRFC decrease, planned by the «Energy Strategy», can be achieved mainly through further large-scale implementation of combined cycle power plants (CCPPs) in upgrading and construction of old and new TPPs [8–10].

Determining the optimum value of the heat load connected to the CCP (otherwise the share of the system heat load covered by the plant) and justification of the value of the extraction factor are the most crucial aspects in the design and operation of highly efficient CCPs for cogeneration needs. These tasks are directly related for CCPs, as well as for the more common in the domestic power industry steam turbine plants (STPs).

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Table 1 Structure of heat supply by type of energy units

Heat supply source	Years				
	2014	2015	2016	2017	2018
Heat generation in district heating systems, mln. Gigacalories (Gcal)	1240.2	1194.8	1269.1	1262.6	1286.1
Power plants, mln. Gcal, including:	598	567	591.8	591.6	599.5
TPPs, mln. Gcal	594.6	563.7	588.4	588.2	596.2
Atomic power stations, mln. Gcal	3.4	3.3	3.4	3.4	3.3
Heating boilers plants with a load of 20 Gcal/h and more, mln. Gcal	639.1	625.2	674.5	668.5	684.1
Other heat sources, mln. Gcal	3.1	2.6	2.8	2.5	2.5

In Russia, the STPs' development is focused on increasing the initial steam parameters and correspondingly increasing the extraction factor—α of TPP (α_{TPP}) (from 0.5 to 0.65). Given the climatic characteristics of the Russian climate, the use of the 150/70 temperature schedule caused the need for peak heat sources (hot water boilers (HWB)) at TPPs.

The first CCCP in the Russian Federation (Severo-Zapadnaya TPP, St. Petersburg) was designed with the operating capability at the extraction factor equal to 1. The use of high- and low-pressure loops steam in the peak heaters of heating-system water, provided by the thermal scheme of this CCCP, allowed to exclude the use of hot-water boilers [11, 12].

Determining the optimum extraction factor, depending on the conditions of TPP design, according to the scientific works of L.S. Khrilev, I.A. Smirnov, G.B. Leventhal, L.A. Melentyev, is possible in two main ways, providing different results:

1. Determination of the optimal version of coverage the given heat load of the power system;
2. Determination of the optimal value of the heat load connected to a given power plant.

Russian power systems tend to have a significant heat load and a relatively low value of electric capacity. For example, the determination of the optimal value of the connected heat load to the existing plant is the most relevant task for areas with an established structure of energy consumption. Setting a higher value of the extraction factor, we increase the operation time of the unit with condensing pass, and thus worsen its technical and economic parameters, but at the same time reduce the operating period, and therefore the fuel consumption of hot-water boilers, and vice versa.

A number of scientific schools were studying this question for TPPs. L. S. Khrilev, I. A. Smirnov, G. B. Leventhal, L. A. Melentiev, E. Y. Sokolov, A. I. Andryushchenko, and R. Z. Aminov formed the basis for the research, but no similar research for CCCPs has been conducted so far.

Table 2 GTE-160 parameters of the ISO standard conditions

Parameter	Value
Air temperature, °C	15
Electric capacity, MW	155.3
Coefficient of performance, %	34.12
Flue gas temperature from GTU, °C	537
Flue gas flow rate, kg/s	509

The purpose of this work is to study the optimal value of the heat load connected to the CCCP.

The object of the study is a CCCP on the basis of GTE-160 (two-boiler single-turbine unit). The process flow diagram of the double-loop CCCP includes two heating-system water heaters, and two water-water heat exchangers (WWHEs).

The steam turbine operates on variable pressure parameters. The temperature of the heating-system water is regulated after the top heating-system heater during CCCP operation according to the temperature chart. The temperature is regulated by changing the pressure in the draw-off sections. Range of pressure change in the top draw-off section is limited by the strength and reliability of the steam turbine compartments. For modern steam turbines it is 0.05–0.2 MPa. To unify the flow ranges this parameter is accepted the same for steam turbine units in the CCP for further studies.

Characteristics of the CCCP during its operation according to the temperature chart were obtained for the 450 MW CCP unit (PGU-450), based on the gas turbine system (GTU) GTE-160. Table 2 shows the values of the main design parameters of CCP, reduced to normal conditions according to ISO requirements at the lower heat value of natural gas 50 MJ/kg.

The calculations assumed an open heat supply system. The temperature chart is 150/70. Central ratio governing by the combined load of heating and hot water supply is accepted. Basic parameters of outdoor temperatures and heating period duration were determined according to the standards for St. Petersburg.

Since the potential heat supply of a heating power plant never coincides with the heat consumption schedule, the CCCP unit could be integrated into the heating system in various ways, depending on the time the hot-water boilers are in use during the heating period.

1—an option appropriate for the maximum heat load of the TPP (the base part of the heat load is supplied by the CCCP, the variable part by the peak water-heating boilers (PHWB) switched on at the very beginning of the heating period);

2—an option corresponding to the minimum heat load of the TPP (the sliding grid closes at −24 °C; the steam turbine runs with condensation pass for most part of the heating period, whereas PWHB does not operate);

3—several options relevant to the intermediate heat loads of the TPP (the sliding grid is closed at different heating period temperatures).

The main criterion used in the optimization calculations for STP in terms of the planned economy is the relative fuel savings compared to separate generation.

This parameter can also be used in current economic conditions for optimization calculations of the CCCP units since it is directly linked to the incremental economic effect of the cogeneration plant as well as to its parameters and structure [13].

Thus, the efficiency of the CCCP method of operation in the heat system (or the optimum value of the extraction factor) can be assessed by analyzing the increase in relative fuel savings compared to separate generation, depending on the connected heat load level.

In Eq. (1) for the incremental integral economic effect of combined generation compared to separate generation (ΔNPV), the sum ΔC_t represents the fuel savings compared to separate generation [13],

$$\Delta NVP = \sum_{t=0}^{T} \frac{\Delta A_t}{(1+E_n)^t} + \sum_{t=0}^{T} \frac{\Delta C_t}{(1+E_n)^t} + \sum_{t=0}^{T} \frac{\Delta E_t}{(1+E_n)^t}, \tag{1}$$

where

ΔA_t—additional cash flow from the combined generation in the respective year t;
ΔC_t—savings in capital investment compared to separate generation;
ΔE_t—savings in annual operating expenses due to increased efficiency compared to separate generation.

Assuming equal amounts of electricity and heat generation in the combined and separate cycles, the total additional cash inflow from combined generation ΔA_t equals 0, so the maximum integral effect of the CCCP will correspond to the maximum reduction of the total discounted costs (2),

$$\sum_{t=0}^{T} \frac{\Delta C_t}{(1+E_n)^t} + \sum_{t=0}^{T} \frac{\Delta E_t}{(1+E_n)^t} \rightarrow \max. \tag{2}$$

Equation (2) tends to the maximum when each of the components individually tends to the maximum,

$$\sum_{t=0}^{T} \frac{\Delta C_t}{(1+E_n)^t} \rightarrow \max; \ \sum_{t=0}^{T} \frac{\Delta E_t}{(1+E_n)^t} \rightarrow \max. \tag{3}$$

Capital investment change compared to separate generation for the CCCP can be summarized as follows:

$$\Delta C = C_{\text{sep}} - C_{\text{com}} = (C_{\text{CPP}} + C_{\text{HWB}}) - (C_{\text{CCCP}} + C_{\text{PHWB}}), \tag{4}$$

where

C_{sep}—the capital investment in separate generation unit;

C_{com}—the capital investment in combined generation unit;
C_{CPP}—capital investment in condensing power plant (CPP) (separate generation);
C_{HWB}—capital investment in hot water boilers (separate generation);
C_{CCCP}—capital investment in the CCCP (combined generation);
C_{PHWB}—capital investment in PHWB (combined generation).

The capital costs of the power plant depend on the equipment and its unit output, determined by the connected/actual heat and electricity load of the consumer. These costs can be expressed in the following way (5–8):

$$C_{\text{CPP}} = k_{\text{CPP}} \times N_{\text{e}}, \tag{5}$$

$$C_{\text{HWB}} = k_{\text{HWB}} \times Q_{\text{C}}^{\text{inst}}, \tag{6}$$

$$C_{\text{CCCP}} = k_{\text{CPP}}^{\text{CCCP}} \times N_{\text{e}} + k_{\text{CP}} \times Q_{\text{CCCP}}^{\text{inst}}, \tag{7}$$

$$C_{\text{PHWB}} = k_{\text{HWB}} \times Q_{\text{PHWB}}^{\text{inst}} = k_{\text{HWB}} \times \left(Q_{\text{C}}^{\text{inst}} - Q_{\text{CCCP}}^{\text{inst}}\right), \tag{8}$$

where

k_{CPP}, k_{HWB}, $k_{\text{CPP}}^{\text{CCCP}}$, k_{CP}—specific capital investments in the substituting CPP, substituting hot water boilers, CPP based on CCCP equipment, and cogeneration plant, respectively;
$Q_{\text{C}}^{\text{inst}}$—the installed heating capacity of the consumer in the separate and combined cycle;
$Q_{\text{CCCP}}^{\text{inst}}$, $Q_{\text{PHWB}}^{\text{inst}}$—the installed heating capacity of the steam tapping and of CCCP and PHWB, accordingly;
N_{e}—installed electric capacity in separate and combined cycle.

Since in this case, the CPP can be replaced by a condensing CCP based on the same GTU used in the CCCP, and the heat supply under the separate cycle can be carried out from the hot water boiler with the same efficiency as in the PHWB, Eq. (4) will be as follows:

$$\Delta C = (k_{\text{HWB}} - k_{\text{CP}}) \times Q_{\text{CCCP}}^{\text{inst}}. \tag{9}$$

Savings of annual operating costs as compared to separate generation (ΔE) are mainly formed at the expense of the fuel component; therefore, Eq. (10) is relevant:

$$\begin{aligned}\Delta E \approx \Delta Q_{\text{f}} \times P_{\text{f}} &= \left(Q_{\text{f}}^{\text{sep}} - Q_{\text{f}}^{\text{com}}\right) \times P_{\text{f}} \\ &= \left[\left(Q_{\text{f}}^{\text{CPP}} + + Q_{\text{f}}^{\text{HWB}}\right) - \left(Q_{\text{f}}^{\text{CCCP}} + Q_{\text{f}}^{\text{PHWB}}\right)\right] \times P_{\text{f}},\end{aligned} \tag{10}$$

where

ΔQ_{f}—fuel savings compared to separate generation, toe;
P_{f}—price of fuel equivalent, rubles/toe;
$Q_{\mathrm{f}}^{\mathrm{sep}}$—fuel-consumption rate during separate generation, toe;
$Q_{\mathrm{f}}^{\mathrm{com}}$—fuel-consumption rate during combined generation, toe;
$Q_{\mathrm{f}}^{\mathrm{CPP}}$—fuel-consumption rate by CPP (separate generation), toe;
$Q_{\mathrm{f}}^{\mathrm{HWB}}$—fuel-consumption rate of hot water boilers (separate generation), toe;
$Q_{\mathrm{f}}^{\mathrm{CCCP}}$—fuel-consumption rate of CCCP (combined generation), toe;
$Q_{\mathrm{f}}^{\mathrm{PHWB}}$—fuel-consumption rate of PHWB (combined generation), toe.

Then Eq. (2) can be transformed as follows (11):

$$\sum_{t=0}^{T}\left[(k_{\mathrm{HWB}}-k_{\mathrm{CP}})\times Q_{\mathrm{PHWB}}^{\mathrm{inst}}\right]+\sum_{t=0}^{T}\left[\left(Q_{\mathrm{f}}^{\mathrm{CPP}}+Q_{\mathrm{f}}^{\mathrm{HWB}}-Q_{\mathrm{f}}^{\mathrm{CCCP}}-Q_{\mathrm{f}}^{\mathrm{PHWB}}\right)\times P_{\mathrm{f}}\right]\rightarrow\max. \quad (11)$$

If the capital costs are incurred for the period $T = 1$ year, and the calculation period of annual costs is $T = 30$ years, Eq. (11) can be transformed as follows:

$$(k_{\mathrm{HWB}}-k_{\mathrm{CP}})\times Q_{\mathrm{PHWB}}^{\mathrm{inst}}+\left(Q_{\mathrm{f}}^{\mathrm{CPP}}+Q_{\mathrm{f}}^{\mathrm{HWB}}-Q_{\mathrm{f}}^{\mathrm{CCCP}}-Q_{\mathrm{f}}^{\mathrm{PHWB}}\right)\times P_{\mathrm{f}}\times T\rightarrow\max. \quad (12)$$

We can switch to relative values independent of the power level of generating equipment of TPP and extend the results of the study to all thermal systems with different loads by dividing both terms in Eq. (12) by the following expression $\left(Q_{\mathrm{f}}^{\mathrm{CPP}}+Q_{\mathrm{f}}^{\mathrm{HWB}}\right)$. Thus, we get the Eq. (13) to determine the specific integral economic effect of replacing the combustion of a ton of fuel equivalent at separate generation for combined heat and electricity generation (mln. rub./toe.):

$$\delta\mathrm{NPV}=\frac{(k_{\mathrm{HWB}}-k_{\mathrm{CP}})\times Q_{\mathrm{CCCP}}}{Q_{\mathrm{f}}^{\mathrm{CPP}}+Q_{\mathrm{f}}^{\mathrm{HWB}}}+\left[\frac{Q_{\mathrm{f}}^{\mathrm{CPP}}+Q_{\mathrm{f}}^{\mathrm{HWB}}-Q_{\mathrm{f}}^{\mathrm{CCCP}}-Q_{\mathrm{f}}^{\mathrm{PHWB}}}{Q_{\mathrm{f}}^{\mathrm{CPP}}+Q_{\mathrm{f}}^{\mathrm{HWB}}}\right]\times P_{\mathrm{f}}\times T. \quad (13)$$

Then, according to (12), $\delta\mathrm{NPV}\rightarrow\max$ or:

$$\frac{(k_{\mathrm{HWB}}-k_{\mathrm{CP}})\times Q_{\mathrm{CCCP}}}{Q_{\mathrm{f}}^{\mathrm{CPP}}+Q_{\mathrm{f}}^{\mathrm{HWB}}}+\left[\frac{Q_{\mathrm{f}}^{\mathrm{CPP}}+Q_{\mathrm{f}}^{\mathrm{HWB}}-Q_{\mathrm{f}}^{\mathrm{CCCP}}}{Q_{\mathrm{f}}^{\mathrm{CPP}}+Q_{\mathrm{f}}^{\mathrm{HWB}}}-\frac{Q_{\mathrm{f}}^{\mathrm{PHWB}}}{Q_{\mathrm{f}}^{\mathrm{CPP}}+Q_{\mathrm{f}}^{\mathrm{HWB}}}\right]\times P_{\mathrm{f}}\times T\rightarrow\max. \quad (14)$$

In Eq. (14), the expression in square brackets represents the relative fuel savings at the TPP compared to separate generation $(\overline{\Delta Q_{\mathrm{f}}})$, and the first component of the expression in square brackets represents the relative fuel savings of the CCCP compared to separate generation.

According to (3), the maximum of (14) is reached when each of the summands in the equation tends to the maximum. If specific capital investments for construction of a hot water boiler plant and cogeneration plant are comparable, the specific integral economic effect δNPV will have the maximum value when:

$$\overline{\Delta Q}_{\mathrm{f}} \times P_{\mathrm{f}} \times T \rightarrow \max . \tag{15}$$

The expression for determining the relative fuel savings compared to separate generation can be presented as follows (16):

$$\overline{\Delta Q}_{\mathrm{f}} = 1 - \frac{\frac{\eta_{\mathrm{CPP}}}{\eta_{\mathrm{fhu}}} \times \left(1 + \frac{1}{y}\right)}{1 + \frac{1}{y} \times \frac{\eta_{\mathrm{CPP}}}{\eta_{\mathrm{HWB}}}} - \frac{\frac{Q_{\mathrm{C}}}{\eta_{\mathrm{HWB}}} - \frac{Q_{\mathrm{CCCP}}}{\eta_{\mathrm{HWB}}}}{\frac{W_e}{\eta_{\mathrm{CPP}}} + \frac{Q_{\mathrm{C}}}{\eta_{\mathrm{HWB}}}}, \tag{16}$$

or

$$\overline{\Delta Q}_{\mathrm{f}} = 1 - \frac{\frac{\eta_{\mathrm{CPP}}}{\eta_{\mathrm{fhu}}} \times \left(1 + \frac{1}{y}\right) \times \alpha_{\mathrm{TPP}}}{\alpha_{\mathrm{TPP}} + \frac{1}{y} \times \frac{\eta_{\mathrm{CPP}}}{\eta_{\mathrm{HWB}}}} - \frac{1 - \alpha_{\mathrm{TPP}}}{1 + y \times \alpha_{\mathrm{TPP}} \times \frac{\eta_{\mathrm{HWB}}}{\eta_{\mathrm{CPP}}}}, \tag{17}$$

where

η_{fhu}—coefficient of fuel heat utilization;
η_{HWB}—efficiency of the replacing hot water boiler plant;
η_{CPP}—efficiency of the replacing CPP;
α_{TPP}—extraction factor;
y—specific power generation on thermal consumption;
Q_{C}—total heat supply to the consumer in the separate and combined cycle;
Q_{CCCP}, Q_{PHWB}—heat supply from CCCP and PHWB draw-offs, respectively;
W_e—power generation in separate and combined cycle.

Thus, taking into account (15), expression (13) transforms into (18):

$$\left[1 - \frac{\frac{\eta_{\mathrm{CPP}}}{\eta_{\mathrm{fhu}}} \times \left(1 + \frac{1}{y}\right) \times \alpha_{\mathrm{TPP}}}{\alpha_{\mathrm{TPP}} + \frac{1}{y} \times \frac{\eta_{\mathrm{CPP}}}{\eta_{\mathrm{HWB}}}} - \frac{1 - \alpha_{\mathrm{TPP}}}{1 + y \times \alpha_{\mathrm{TPP}} \times \frac{\eta_{\mathrm{HWB}}}{\eta_{\mathrm{CPP}}}}\right] \times P_{\mathrm{f}} \times T \rightarrow\rightarrow \max . \tag{18}$$

Expression (18) allows us to determine the optimal value of the connected heat load of the CCCP.

We applied the simulation method of the CCCP operation modes as the research method of the considered power unit operation. Modeling of the basic heat balance diagram was carried out using the software product "United Cycle", which provides simulation and calculation of steady-state modes of operation of thermal power plants and systems.

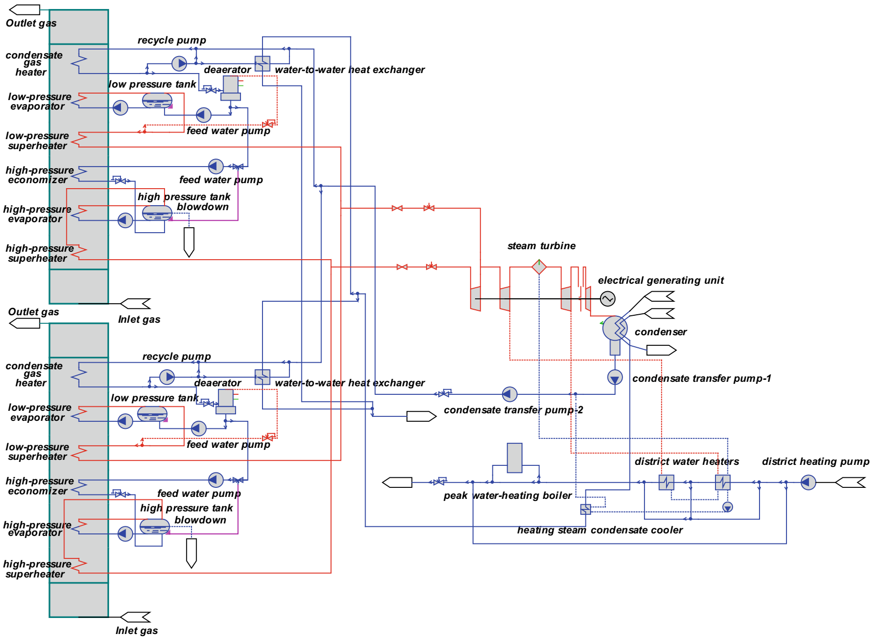

Fig. 1 Basic diagram of a double-loop combined-cycle CCCP, simulated in the CAD "United Cycle"

Figure 1 shows the design model of a CCCP unit based on GTE-160, simulated in the CAD "United Cycle", including two vertical heat recovery steam generators (HRSGs) of two pressures and stationary heat recovery steam turbine, designed to work in the binary combined-cycle unit PGU-450, consisting of two GTUs type GTE-160, as well as peak water heating boilers.

The scheme parameterization is based on the warranted performance of the cogeneration unit, as well as on the thermal balance of the HRSG heating surfaces. The operation mode for nominal parameters under the factory characteristics of the equipment was simulated to check the adequacy of the model construction.

Adequacy test of the created mathematical model in relation to the real TPP, functioning on the basis of GTE-160 (Pravoberezhnaya TPP-5 public joint-stock company "TGK-1") was carried out by method of stage-by-stage analysis of mode parameters, calculated with CAD "United Cycle", and factory parameters of the combined cycle unit (HRSG and cogeneration unit). We compared the model for winter mode operation at the outside air temperature of −24 °C. Table 3 provides the calculated characteristics of the model for this mode.

The study assumes the following:

- The assumed temperature diagram of the heating-system is 150/70, and the flow rate of heating-system water is constant and equal to 5000 t/h;

Table 3 Calculated parameters of the nominal mode of operation of the power plant unit simulated by CAD "United Cycle"

Parameter	Measurement unit	Value
Gas turbine unit GTE-160		
Outside air temperature	°C	−24
Outside air pressure	kPa	0.1013
Gas temperature at GTU outlet	°C	530.9
Gas flow rate at GTU outlet	t/h	1861.3
GTU capacity	MW	165.5
GTU efficiency	%	34.07
Heat recovery steam generator (HRSG)		
High pressure steam flow rate	t/h	221.65
Temperature of high-pressure steam at the outlet of HRSG	°C	508
High-pressure steam pressure	kg/cm^2	72.74
Temperature drop at the hot end of the low-pressure loop	°C	22.09
Pinch point of the low-pressure loop	°C	9.94
Low-pressure steam flow rate	t/h	52.14
Temperature of low-pressure steam at the outlet of the HRSG	°C	218.19
Low-pressure steam pressure	kg/cm^2	6.18
Temperature drop at the hot end of the low-pressure loop	°C	17.35
Pinch point of the low-pressure loop	°C	12.84
Water temperature at the inlet of HRSG	°C	64.93
Flue gas temperature	°C	106.47
Steam turbine		
High-pressure steam flow rate	t/h	443.31
Temperature of high-pressure steam at the outlet of HRSG	°C	507.19
Low-pressure steam flow rate	t/h	104.27
Temperature of low-pressure steam at the outlet of HRSG	°C	217.71
Calculated pressure in the condenser	kg/cm^2	0.02
Heating-system water flow rate	t/h	5460
Heating-system water temperature at the inlet to the district water heaters	°C	67
Heating-system water temperature at the outlet of the district water heaters	°C	117.26
Net electrical power	MW	96.73

- The water temperature at the inlet to the HRSG is maintained at 65 °C with the use of recirculation pumps;
- The reduced pressure in the condenser is 3 kPa in all calculated modes;
- WWHEs are switched off;
- The cooling water temperature at the condenser inlet during the considered heating period is constant and is 5 °C;
- No blowdown water losses in high- and low-pressure drum-type boilers.

The relative value of the deviation of the calculated parameters from the control parameters is less than 4%. Deviations are related to the simplification of the design model of the cogeneration unit, the non-simulation of turbine blowing and glands, and the assumptions that have been made.

2 Results

Figure 2 shows variants of integrating the CCCP into the heating system.

Line 1 indicates the change in the available heat load of the CCCP over the heating period.

Line 2 identifies the change in the TPP heat load, at the maximum connected heat load of 1354.94 MW—option 1. In this case, the sliding grid is closed completely at the beginning of the heating period, and the heat load is regulated entirely by the hot-water boilers, operating for the whole heating period. In this variant of integrating the CCCP into the heating system, the extraction factor is about 0.24.

Line 3 indicates the change in TPP heat load when the connected heat load corresponds to the minimum possible heat load. Here, the heat supply capacity is regulated by changing position of the sliding grid. The CCCP operates with condensing pass during the whole heating period. Peak water heating boilers are switched off. The extraction factor for this variant of CCCP integration into the heat system equals 1.

Lines 4–8 characterize the heating loads of the TPP, corresponding to the intermediate values of the extraction factor.

Figure 2 can be represented as the function of the plant total heat load on the number of hours of outside air temperatures during the year for the heating period for St. Petersburg, shown in Fig. 3.

Integral parameters of the considered variants of CCCP operation in the heating system during the heating period are shown in Table 4.

The relative fuel savings compared to separate generation for different values of the extraction factor were determined based on Eq. (17), and the calculated characteristics is presented in Table 4. The efficiency value of the substituting hot water boiler plant was assumed to be 93%, and the efficiency value of the substituting CPP—40%. Figure 4 shows a diagram of the dependence of the relative fuel savings in compared with the separate generation on the value of the extraction factor. According to Fig. 4, the relative fuel savings compared to the separate generation have a distinct maximum at $\alpha_{\text{TPP}} \approx 0.49$.

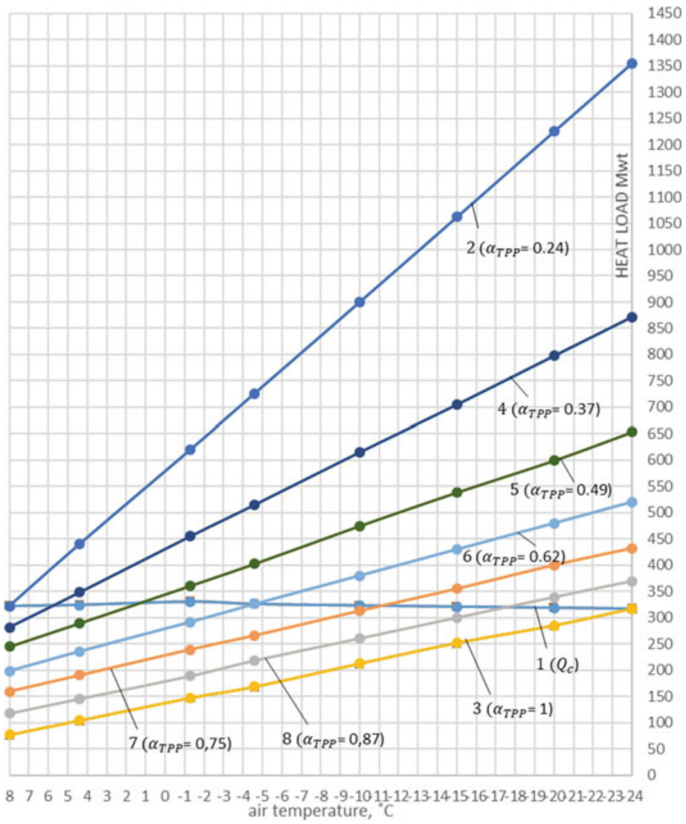

Fig. 2 Ways of integrating the CCCP into the thermal system: 1—available heat load of CCPP; 2—maximum connected heat load to CCPP; 3—minimum connected heat load to CCCP; 4—extraction factor of CCCP included in the heat system $\alpha_{TPP} = 0.37$; 5—extraction factor of CCCP included in the heat system $\alpha_{TPP} = 0.49$; 6—extraction factor of CCCP included in the heat system $\alpha_{TPP} = 0.62$; 7—extraction factor of CCCP included in the heat system $\alpha_{TPP} = 0.75$; 8—extraction factor of CCCP included in the heat system $\alpha_{TPP} = 0.87$

Excluding construction and installation costs, the unit cost of hot water boilers (according to data currently being realized at Avtovskaya TPP-15 of public joint-stock company «TGK-1» in St. Petersburg) is 1.3 million rubles per Gcal of installed capacity. With similar cost of piping connection for heating-system water, the specific capital costs of steam heat exchangers of similar capacity in the calculations are based on a different ratio between the specific costs of a water heating boiler plant (k_{HWB}) and steam heat exchangers (k_{CP}): $\frac{k_{\text{HWB}}}{k_{\text{CP}}} = 0.5;\ 1;\ 2;\ 4;\ 8;\ 10.$

The increase of specific integral economic effect δNPV for different values of the extraction factor at different ratio of specific cost of HWB and steam heat exchangers, calculated by Eq. (18), is shown in Fig. 5.

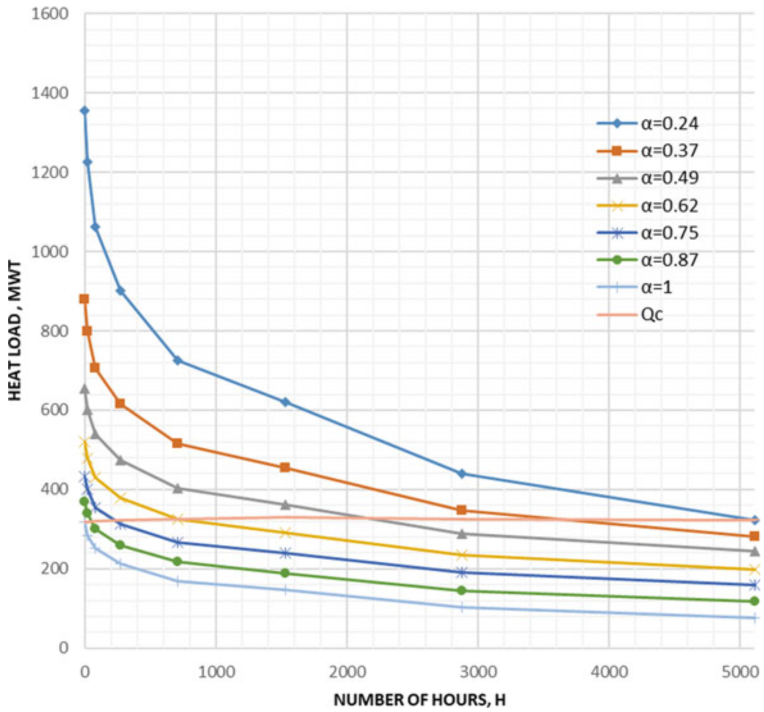

Fig. 3 Dependence of the plant total heat load on the number of hours of outside air temperatures during the year for the heating period of St. Petersburg (Rossander's diagram)

Figure 5 shows that regardless of the value of capital costs, the maximum specific integral economic effect δNPV is achieved at $\alpha_{TPP} \approx 0.49$. The maximum relative fuel saving compared to separate generation is achieved at this value.

3 Discussion

The selection of the optimal mix of equipment is a key issue for the construction of new, high-efficiency power plants. It affects not only the initial capital investment, but also the expected operating costs (fuel costs form the largest part of them). Determination of the optimal extraction factor, as in the design of thermal power plants designed not only for electric power supply but also for heat supply of the consumer, is an important aspect of this issue and requires a comprehensive analysis.

Whereas for CCCPs, regarded as traditional for the Russian energy sector, this task was solved, but we do not have a unified approach to solving this issue for CCCPs.

Table 4 Operating parameters of CCCP operation during the heating period with different connected heat loads

Parameters	Value $\left(Q_{\text{fuel}} = 50\frac{\text{MJ}}{\text{kg}},\ \eta_{\text{CPP}} = 40\%,\ \eta_{\text{HWB}} = 93\%\right)$						
Extraction factor α_{TPP}	0.24	0.37	0.49	0.62	0.75	0.87	1.00
Total heat supply to consumers from CCCP, thousand Gcal	2369.0	1786.1	1448.0	1171.3	953.0	748.9	559.2
Heat supply from CCCP, thousand Gcal	1427.2	1388.3	1300.0	1136.6	945.3	747.7	559.2
Heat supply from hot water boilers, thousand Gcal	941.9	397.7	148.0	34.8	7.7	1.2	0.0
Total fuel consumption, t	438,949	389,916	367,415	357,209	354,767	354,186	354,077
Fuel consumption for the CCCP, t	354,077	354,077	354,077	354,077	354,077	354,077	354,077
Fuel consumption for hot water boilers, t	84,872	35,839	13,339	3133	691	109	0
Electricity generation, thousand MW*h	2139	2146	2164	2199	2243	2288	2316
Fuel heat utilization coefficient, (η_{fhu}), %	77.26	76.50	74.77	71.61	67.97	64.23	60.33
Specific electric power generation at thermal consumption, y, MW/MW	1.29	1.33	1.43	1.66	2.04	2.63	3.56
Relative fuel savings compared to separate generation, ΔQ	0.266	0.288	0.293	0.287	0.275	0.261	0.242

Under the conditions of a planned economy for a TPP based on a steam turbines unit the problem of finding the optimal extraction factor was solved by using the rate of relative fuel savings compared to the separate production of electricity and heat. In the conditions of the formed market economy, the selection and final justification of technical solutions relies primarily on investment analysis with an assessment of the profitability, cost-effectiveness, and payback period of the project [14–16].

NPV is one of the main factors that characterize the investment prospects of a project. As shown by earlier studies [13], it is possible to correlate an increase in NPV using combined generation and the relative fuel savings compared to separate generation. This fact nowadays allows us to use the latter parameter, among other things, to optimize the coefficient of thermal efficiency of CCCP.

This article proposes an approach to optimizing the coefficient of thermal efficiency of CCCP, based on the basic elements of the method traditional for the Russian energy sector, which is quite applicable with a slight adaptation to modern economic conditions.

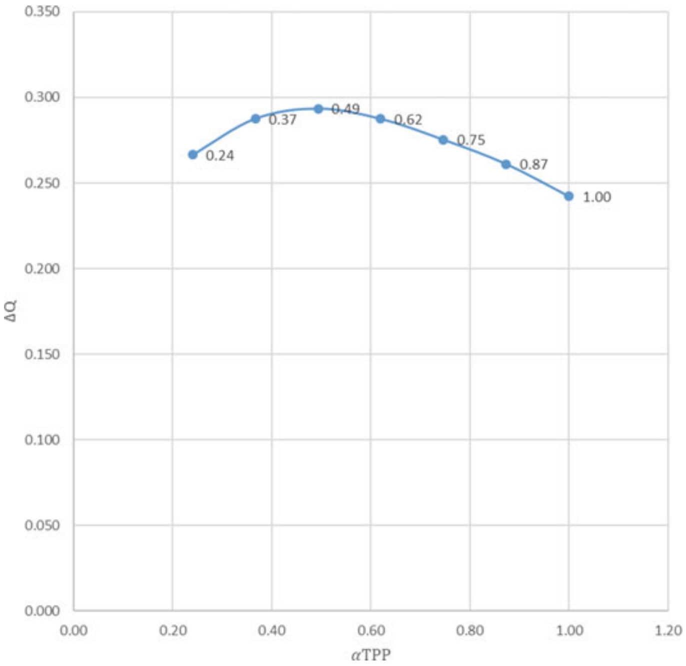

Fig. 4 Increase in relative fuel savings compared to separate generation for different values of the extraction factor

This method can be used to analyze and optimize the mix of CCCP equipment regardless of the geographic area, type of power system, energy resources cost, market conditions, and the characteristics of the used equipment.

In a competitive market environment absolute quantitative performance of power generating companies are less important than the relative indicators, qualitatively characterizing the degree of use of available resources. Thus, the use of the relative fuel savings, as a criterion of optimality, will allow in the future to form the most balanced, efficient energy systems, as well as create all conditions necessary to maximize profits of energy companies while optimizing the prices for electricity and heat and ensuring a reliable and uninterrupted power supply to the consumer.

4 Conclusion

1. In the current economic conditions, the relative fuel savings rate compared to separate generation can be used as an optimization criterion for solving the problem of selecting and justifying the thermal efficiency coefficient for CCCP.
2. For CCCP based on GTE-160 (two-boiler single-turbine unit) the value of the optimal extraction factor determined by the relative fuel economy rate,

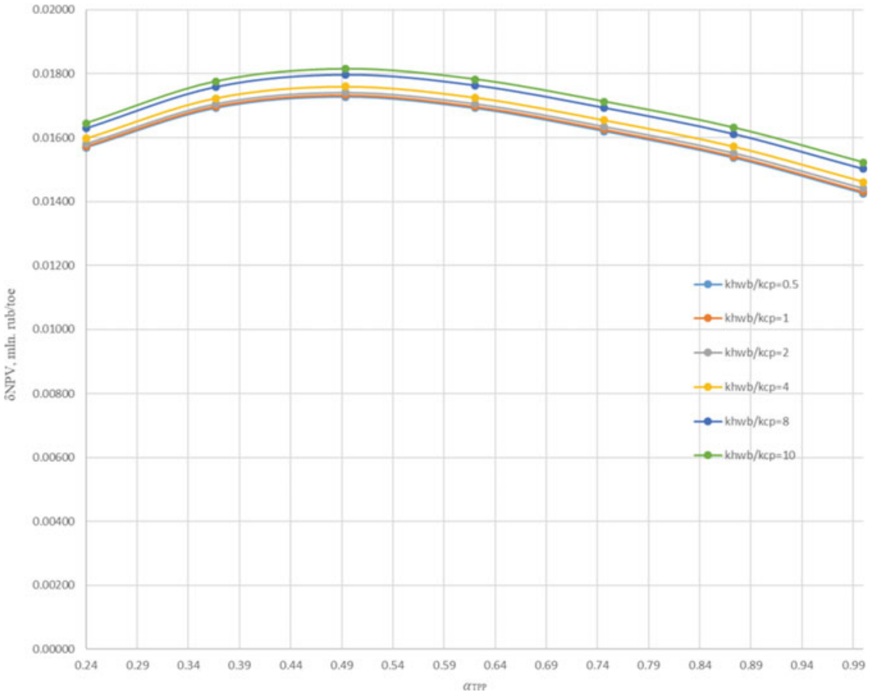

Fig. 5 Increase of specific integral economic effect δNPV for different values of the extraction factor at different ratio of the specific cost of hot water boilers and steam heat exchangers

compared to separate generation equals 0.49 under the climatic conditions of St. Petersburg.

3. For a similar CCCP, the value of the optimal extraction factor, determined from the condition of maximizing the specific integral economic effect, is also 0.49. It should be noted that the ratio of specific capital investments in hot-water boilers and heat-exchange equipment of the CCCP has no significant impact on the obtained result.

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