

# Optimization of schemes and ways to expand the adjustment range for the power supply of combined heat and power plants

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**Abstract.** The article assesses the possibility of using low-flow operating modes at steam turbine with an additional boiler and steam and combined-cycle cogeneration plants for heat supply schemes, taking into account the storage properties of heat networks and buildings. It is shown that the use of low-flow operation modes of the turbine plant during the night period allows the combined heat and power plant to participate more effectively in covering the variable part of the electric load schedule. The dependence of the share of participation of an additional boiler in covering the heat load on the prices for fuel and electricity is determined. Comparison of the performance indicators of the steam turbine CHPP in low-flow modes with the release of the thermal energy necessary to the consumer from an additional boiler with the mode of its complete shutdown and the release of thermal energy from the peak hot water boiler made it possible, taking into account the accumulating properties of heat networks and buildings, to recommend a low-flow operation mode at night. For a combined-cycle cogeneration plant it is shown that it is advisable to reduce the electric power at night, while ensuring the nominal heat supply, by unloading the gas turbines with the transfer of the steam turbine to the motor mode.

## 1 Introduction

One of the important tasks in the development and operation of generating capacities is the reliable regulation of the variable part of the electrical load schedule of power systems, as well as the reliable and efficient supply of electricity demand. An increase in the unevenness of energy consumption schedules and limited possibilities for regulating the load in power systems has led to the fact that the operation modes of combined heat and power plants differ significantly from the basic ones, and low electricity prices in the wholesale electricity and power market during the night have led to the need for their deep unloading [1–5].

Power consumption modes change under the influence of various factors: technological features of production, climatic factors, etc. The dynamics of power consumption volumes in the considered period can be represented in the form of daily, weekly, seasonal, and annual load schedules. Of great importance for the operation of power plant equipment are the daily schedules of electrical loads.

In most of the energy systems of Russia, a significant number of combined heat and power plants with industrial and heating steam extractions are in operation. The possibilities of daily unloading on the electrical load of the CHPPs are limited by the load of regulated extractions [6, 7]. In winter, at low outdoor temperatures, the regulated extractions of a heating CHPPs are usually fully loaded and there are practically no control capabilities of the power plant [8–10]. At the same time,

during these periods, the issues of ensuring the daily schedule of electrical loads are most acute [11–13].

Under these conditions, an urgent task is to assess the possibility of using low-flow modes of operation at steam turbine CHPPs (using the example of a T-100-130 cogeneration turbine with a capacity of 100 MW for heat supply schemes with an additional boiler plant) and combined-cycle cogeneration plant (using the example of CCGT-450T with a capacity of 450 MW) taking into account the storage properties of heat networks and buildings.

## 2 Materials and methods

For operation in a variable mode, several measures have been developed and are being used to expand the adjustment range limits of thermal power plants [14–18]. Such measures include the following: transfer of power units to the auxiliary load or to idling in case of generator shutdowns and load shedding; transfer of the steam turbine to the motor mode; CHPP unloading by transferring the thermal load of the turbine to a pressure-reducing cooling station or peak boilers.

In the practice of CHPPs operation, a forced reduction in electric power is used by throttling part of the live steam in the pressure-reducing cooling station. If there is a reserve of thermal power of peak hot water boilers, it is also possible to reduce the load of heating extractions by transferring it to these boilers. With forced unloading, a partial or complete transition from combined generation of electric and thermal energy to

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separate is carried out, which is associated with a significant deterioration in the efficiency of the CHPPs, so it can only be used when the adjustment capabilities of the power plant have been exhausted.

In the motor mode, the main steam is not supplied to the steam turbine, and the electric generator is not disconnected from the network and operates as an engine, rotating the turbine rotor, consuming active power from the network to overcome ventilation, mechanical and other losses both in the turbine and in the generator. To cool the exhaust part of the turbine, a small amount of cooling steam is supplied to it through a pressure-reducing unit from constant sources (a general station auxiliary collector), and a normal vacuum is maintained in the condenser to condense the cooling steam. Such a result can also be achieved with a complete shutdown of the power unit, however, the motor mode has several advantages: switching the unit to motor mode takes less time; the power system is not deprived of a hot power reserve, since the unit operating in the motor mode is easily transferred to the generator mode; starting the unit from a warm and even hot state after stopping it for the night is much more difficult and lasts longer.

## 2.1 Comparative analysis of operating modes of the turbine T-100-130 heat plant

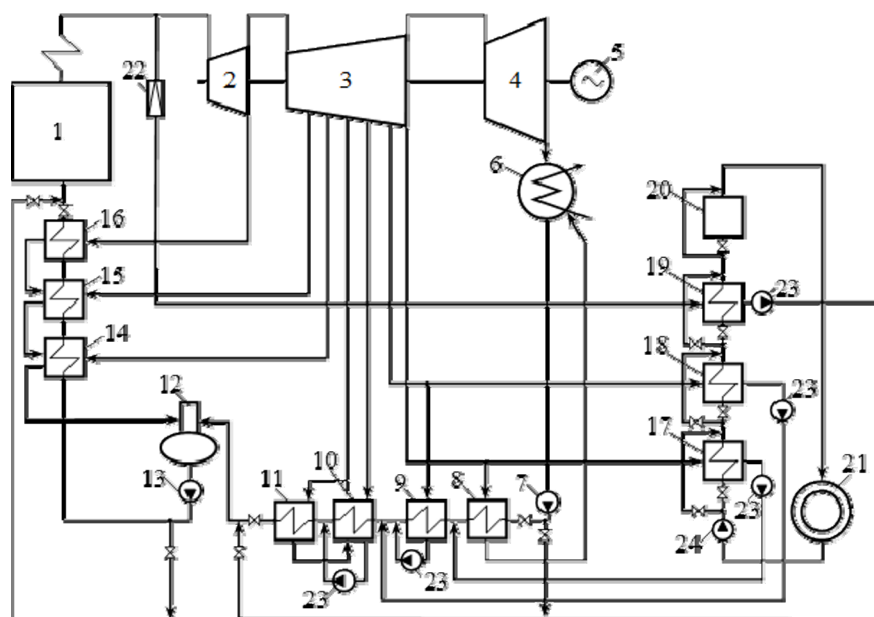
The need for electricity generated by the turbine at night decreases, during the day, on the contrary, the need for electricity increases. The papers [19–23] considered the efficiency of using thermal energy storage at night by heating networks and buildings in order to expand the regulation range of electricity generated by the turbine. To this end, only the steam needed for regeneration and minimal ventilation to the condenser was supplied to the

turbine at night. Most of the steam, after its pressure reduction in the fast-response pressure-reducing station, entered the additional boiler.

In the proposed scheme, only steam is sent to the turbine at night only for a minimum ventilation pass to the condenser. Heaters of the regeneration system and network heaters are switched off.

At night during the winter period, it is proposed to generate heat at the heat plant that exceeds what is needed for the consumer. This will allow, thanks to the storage properties of heating networks and buildings, to generate less heat during the day, increase the steam flow to the condenser and generate peak electricity. Figure 1 shows a diagram of the heat plant of the T-100-130 turbine, where network water is heated in the first network heater (NH1) by steam of the 7th selection, in NH2 – by steam of the 6th selection, in an additional boiler – by fresh steam after a fast-response steam pressure temperature reducer, then in a peak water-heating boiler and is sent to the consumer.

Three variants for the operation of a heat plant at night are considered, taking into account the accumulation of heat by heating networks and buildings. In the first variant, network water is heated in a peak water-heating boiler and sent to the consumer. In this case, the turbine operates in motor mode, and the additional boiler installation is turned off. In the second option, network water is heated in an additional boiler. This happens as follows: fresh steam after a fast-response steam pressure temperature reducer is sent to an additional boiler, gives off its heat to the network water, condenses and then, using a drain pump, is sent to the mixing point of the condensate path before the deaerator. In the third variant, network water is heated in an additional boiler, and then in a peak water-heating boiler.



**Fig. 1.** Schematic diagram of the T-100-130 turbine heat plant with an additional boiler:  
 1 – boiler; 2, 3, 4 – high, medium and low pressure cylinders; 5 – electric generator; 6 – condenser; 7 – condensate pump; 8, 9, 10, 11 – low pressure heaters LPH-7, LPH-6, LPH-5 and LPH-4; 12 – deaerator; 13 – feed pump; 14, 15, 16 – high pressure heaters HPH-3, HPH-2 and HPH-1; 17, 18 – network water heater NH1 and NH2; 19 – additional boiler; 20 – peak water-heating boiler; 21 – consumer; 22 – fast-response steam pressure temperature reducer; 23 – drainage pumps; 24 – network pump.

For the accepted initial data (table 1), technical and economic calculations were carried out in order to determine the optimal mode of operation of the heat plant at night. Calculations were made for 3 price options for night and day electricity (table 1). Price 1 is the current one for the Volga region (data from [www.atsenergo.ru](http://www.atsenergo.ru)), prices 2 and 3 are predictive. The ratio of the prices of night and day electricity for them is 0.86, 0.4 and 0.07, respectively.

In the first variant, the necessary steam flow rate for cooling the turbine and its seals is supplied from a neighboring boiler and is 0.56 kg/s, the electric power consumed by the turbine from the network is 2 MW. In all three variants, during the daytime, the steam flow from the boiler to the turbine is maximum and equals

127.78 kg/s. In the first variant, the temperature of the network water at the inlet to the peak hot water boiler at night is 48.5°C, in the third variant it is 90.3°C. In all variants during the day, the peak hot water boiler and the additional boiler are switched off, the network water is heated in the network heaters NH1 and NH2, the temperature at the inlet to NH1 is 50°C. In the second option, part of the main steam from the boiler is sent to a fast-response steam pressure temperature reducer, where its pressure is reduced to 0.12 MPa, after which it is sent to an additional boiler. In the third variant, the pressure of main steam in the fast-response steam pressure temperature reducer is reduced to 0.09 MPa, after which it is also sent to an additional boiler. Table 2 shows the results of calculations for three variants.

**Table 1.** Initial data.

Parameters		Variant 1	Variant 2	Variant 3
The amount of heat required by the consumer at night, GJ		5359.1		
Duration of night / day, h		8 / 16		
Duration of the heating period, days / year		198		
Fuel price, rubles/th. m <sup>3</sup>		5300		
Price for nighttime electricity / daytime electricity, rubles/kWh / ratio of nighttime and daytime electricity prices	price 1	1.16 / 1.35 / 0.86		
	price 2	0.64 / 1.61 / 0.4		
	price 3	0.26 / 3.73 / 0.07		
Temperature of network water at the outlet / at the inlet to the peak water-heating boiler at night, °C		100 / 48.5	– / –	100 / 90.3
Temperature of network water at the inlet to the lower network heater during the day, °C		50		
Steam consumption from the boiler to the turbine at night / day, kg/s		– / 127.78	2.79 / 127.78	2.79 / 127.78
Steam consumption for cooling the turbine and for seals in motor mode at night, kg/s		0.56	–	–
Electric capacity at night, consumed by the turbine in motor mode / generated by the turbine, MW		2 / –	– / 10	– / 10

**Table 2.** The results of calculations of the accumulation mode for three variants.

Parameters		Variant 1	Variant 2	Variant 3
Heat power of the peak water-heating boiler / additional boiler at night, MW		332.4 / –	62.5 / 269.9	– / 332.4
Share of power of an additional boiler in the heat plant at night		0	0.81	1.0
Steam consumption in the additional boiler at night, kg/s		–	87.41	123.7
Temperature of network water behind the peak hot water boiler / after the additional boiler at night, °C		100 / –	100 / 90.3	– / 100
Total fuel costs, million rubles/year		120.56	124.24	141.04
Heat power of the additional boiler at night, MW		332.39		
Excess heat generated per night, GJ		4213.6		
The required amount of night electricity per day / for the heating period, thousand kWh		16 / 3168	–	–
Costs of consumed night electricity for the heating period, million rubles/year	price 1	3.7	–	–
	price 2	2.0	–	–
	price 3	0.8	–	–

Thermal power of the lower network heater during the day, MW	112.9		
Temperature of network water during the day after the lower network heater, °C	67.5		
Steam consumption in the lower network heater / in the condenser during the day, kg/s	48.5 / 57.0		
Electric capacity at night/day, MW	- / 118.03	10 / 108.03	10 / 108.03
Electricity generated per night / per day / per 24-hour period, thousand kWh	- / 1888.4 / 1888.4	80 / 1888.5 / 1968.4	80 / 1888.5 / 1968.4
Generated amount of electricity during nights / days / total for the heating period, thousand kWh	- / 373910.3 / 373910.3	15840 / 373910.3 / 389750.3	15840 / 373910.3 / 389750.3
Adjustment range of electric power, MW	118.03	108.03	108.03
Income from the sale of electricity for the heating period: day / night / per 24-hour period / per 24-hour period, including fuel costs, million rubles/year	price 1	- / 504.8 / 504.8 / 380.6	18.4 / 504.8 / 523.2 / 398.9
	price 2	- / 602.0 / 602.0 / 479.4	10.1 / 602.0 / 612.1 / 487.9
	price 3	- / 1394.7 / 1394.7 / 1273.3	4.1 / 1394.7 / 1398.8 / 1274.6

Table 2 shows that in the first variant, the thermal power of the peak water-heating boiler (heat plant) at night is 332.4 MW. This exceeds the required amount of heat by 78.63%. Excess heat is accumulated by heating networks and buildings. This allows to generate less heat during the day, turn off the upper network heater and reduce the power of the lower NH by 13%. Due to this, the steam flow to the condenser increases by 3.67 times. Electric power generated during the day increases by 18.03%. Income from the sale of daytime electricity in tariff options 1, 2 and 3 for night and day electricity for the heating period, taking into account fuel costs, amounted to 380.55, 479.41, 1273.31 million rubles/year, respectively.

In variant 2, the thermal power of the additional boiler at night is 269.9 MW, and the power of the peak hot water boiler is 62.49 MW. The total thermal power of the heat plant is 332.4 MW. Income from the sale of daytime electricity in tariff options 1, 2 and 3 for night and day electricity for the heating period, taking into account fuel costs, amounted to 398.4, 487.38, 1274.05 million rubles/year, respectively. In variant 3, the thermal power of the additional boiler, as well as the heat plant at night, is 332.39 MW. Income from the sale of daytime electricity in tariff options 1, 2 and 3 for night and day electricity for the heating period, taking into account fuel costs, amounted to 398.91, 487.89, 1274.56 million rubles/year, respectively. It should be noted that the adjustment range for the first, second and third variants is 118.03, 108.03 and 108.03 MW, respectively.

## 2.2 Comparative analysis of the operating modes of the CCGT-450T

The thermal scheme of CCGT-450T differs from traditional schemes of thermal power plants in a number of features. In connection with the task of expanding the adjustment range limits, the main ones are three electric generators (two with gas turbines and one with a steam turbine), two heat-recovery steam generators, the ability to operate the power unit with a different composition of operating equipment (work with two or one gas turbine),

the dependence of CCGT efficiency on load (both for the power unit as a whole and for its main equipment) [24, 25].

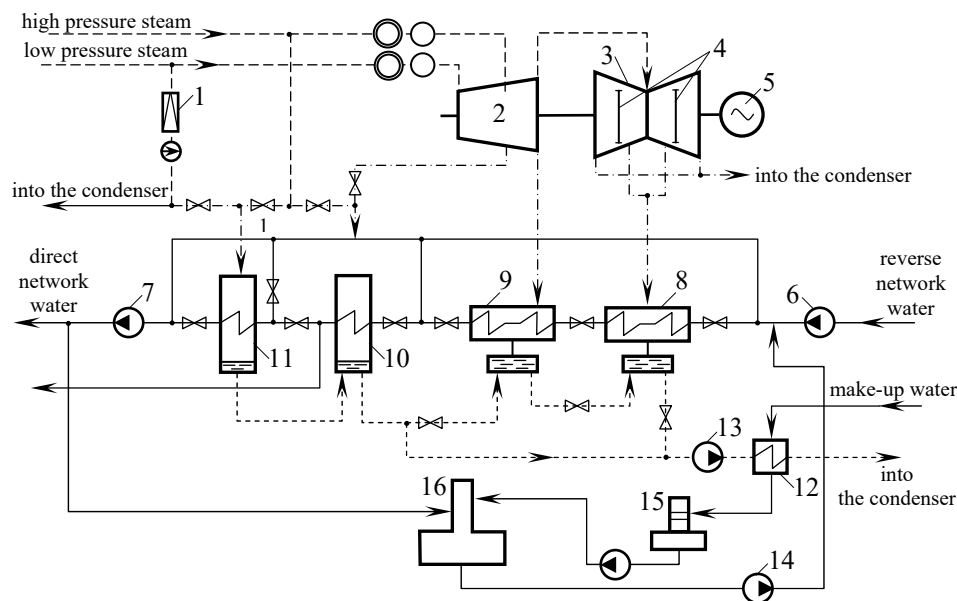
The heating equipment of CCGT-450T at Severo-Zapadnaya CHPP consists of four levels of heating of network water in two horizontal (HNWH-1 and HNWH-2) and two vertical (VNWH-3 and VNWH-4) heaters of network water, which significantly expands the temperature range of the network water after the heat plant (the maximum temperature of direct network water after VNWH-4 can reach 153°C) [26]. VNWH-3 and VNWH-4 are connected in such a way that steam can be supplied to them both from steam turbine extractions and directly from heat-recovery steam generators, figure 2 [27].

If it is necessary to ensure the rated heat supply, unloading of the electric power of the cogeneration CCGT can be ensured only by switching to the GT based CHPP mode with the steam turbine shutting down or switching it to the motor mode [28]. The disadvantage of the GT based CHPP mode, including when the steam turbine is switched to the motor mode, is the need for capital investments in the modernization of the thermal scheme of the steam turbine and the heating system [29].

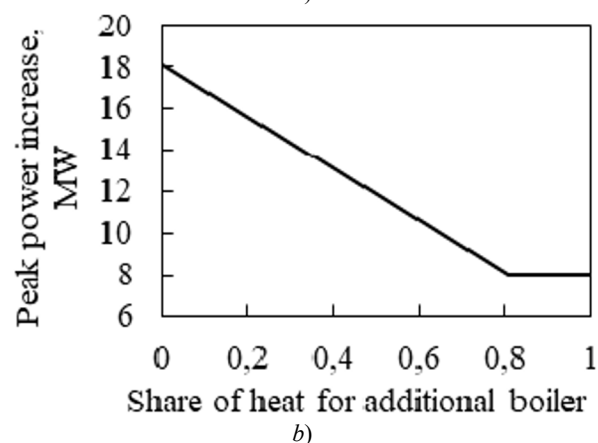
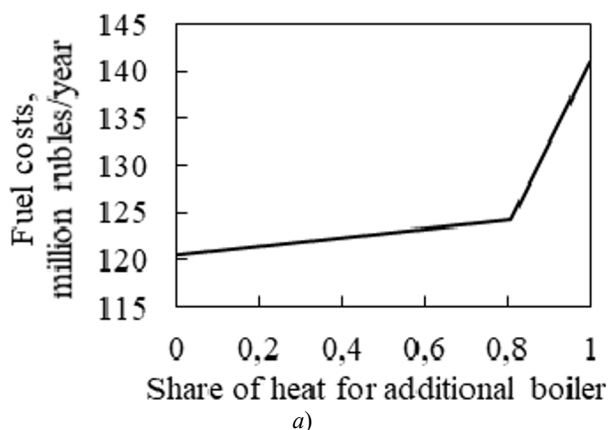
Based on the methodology [30–33], in this paper, using the example of a CCGT-450T, we compared two options for unloading at night: switching the CCGT to the GT based CHPP mode with the steam turbine shutting down and switching the steam turbine to the motor mode while providing a constant for 24-hour period of rated heat load 411.7 MW(t). CCGT in these modes is unloaded by electric power of 180.2 MW (from 450 MW to 269.8 MW).

## 3 Results

Figures 3a and 3b show the dependencies of fuel costs and additionally generated peak electricity on the share of heat produced by an additional boiler in the T-100-130 cogeneration plant.



**Fig. 2.** Schematic diagram of the CCGT-450T network water heating system at Severo-Zapadnaya CHPP: 1 – fast-response steam pressure temperature reducer; 2 – high pressure cylinder; 3 – low pressure cylinder; 4 – regulating diaphragms; 5 – electric generator; 6, 7 – network pumps; 8, 9 – horizontal network water heaters HNWH-1 and HNWH-2; 10, 11 – vertical network water heaters VNWH-3 and VNWH-4; 12 – condensate cooler; 13 – drain pump; 14 – make-up pump; 15 – decarbonator; 16 – vacuum deaerator.



**Fig. 3.** Dependences of fuel costs (a) and peak power increase (b) on the share of heat sent to the additional boiler.

Figure 3a shows that with an increase in the share of heat produced by an additional boiler in heat plant, fuel costs increase from 120.56 to 141.04 million rubles/year. From figure 3b it can be seen that the additional peak

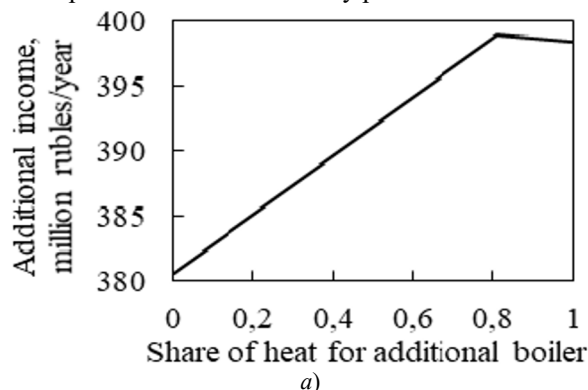
electric power with an increase in the proportion of heat produced by the additional boiler in the heat plant decreases from 18.03 to 8.03 MW.

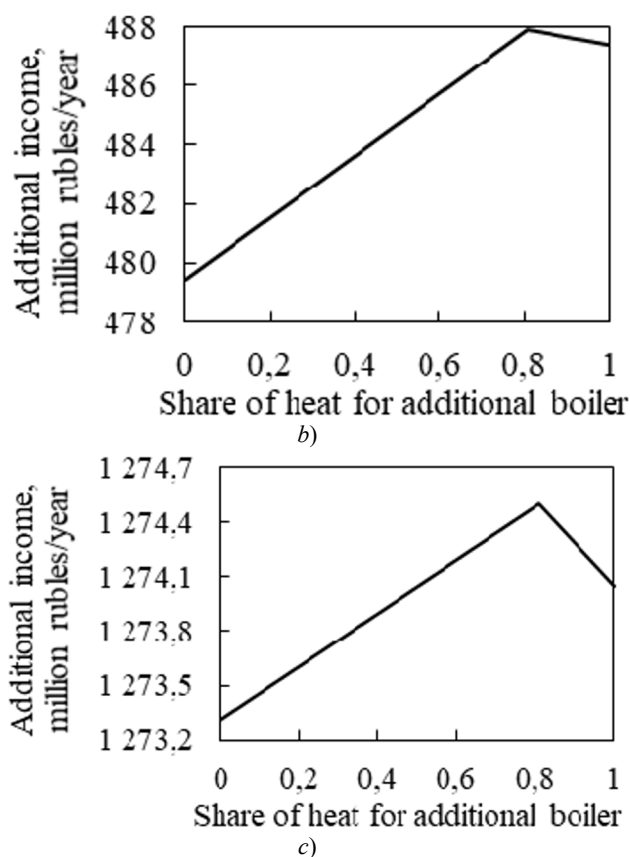
Figures 4a, b and c show the dependence of the revenue from the sale of additional peak electricity, including fuel costs, on the share of heat produced by an additional boiler in a heat plant.

Figure 4 shows that with an increase in the share of heat produced by an additional boiler in a heat plant, the income from the sale of additional peak electricity, taking into account fuel costs, increases from 380.55 to 398.4 million rubles/year at actual tariffs, from 479.41 to 487.38 million rubles/year (the ratio of the night-to-day price is 0.4) and from 1273.31 to 1274.05 (the ratio of the night-to-day price is 0.07) at forecasted prices.

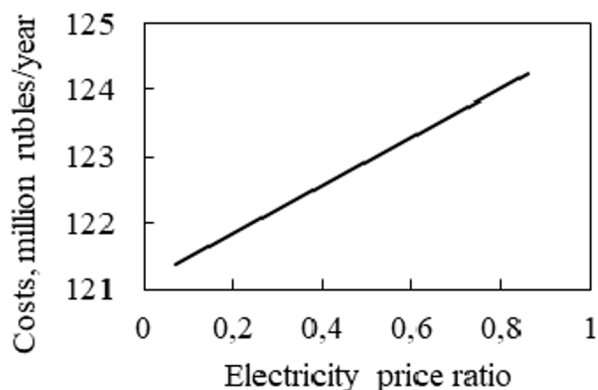
Figure 5 shows the dependence of the cost of electricity in motor mode on the ratio of prices for night and day electricity.

Figure 5 shows that with an increase in the ratio of the night to day price for electricity, the prime cost of electricity in motor mode increases from 121.4 to 124.2 million rubles/year. The highest prime cost value corresponds to current electricity prices.





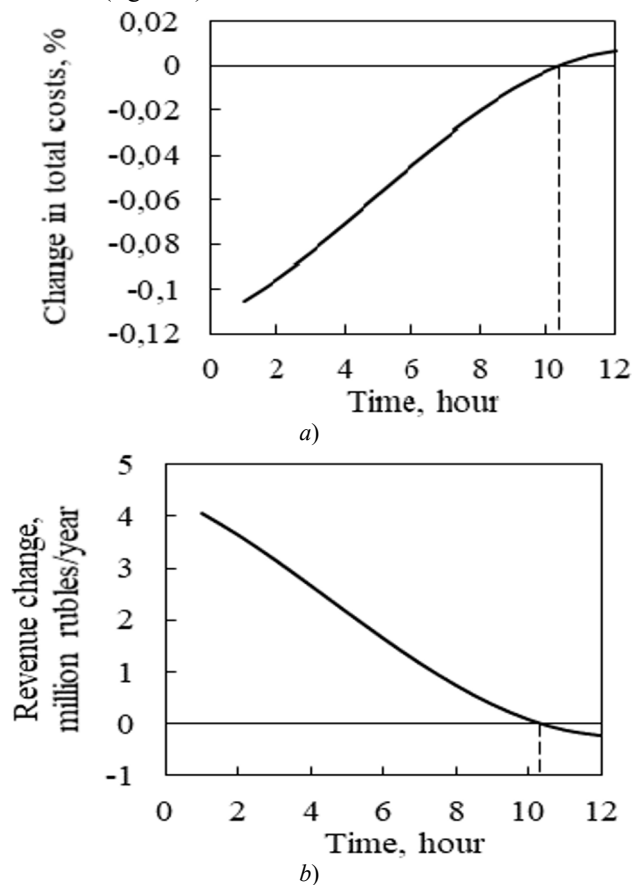
**Fig. 4.** Dependences of additional revenues on the share of heat directed to an additional boiler with different price ratios for night and day electricity: *a* – 0.86; *b* – 0.4; *c* – 0.07.



**Fig. 5.** Total costs for fuel and electricity, depending on the ratio of prices for night and day electricity, million rubles / year.

The results of calculating the costs of switching the steam turbine to the motor mode (instead of stopping), depending on the duration of unloading of the CCGT-450T, showed the following. Fuel costs are lower when unloading the CCGT with the transfer of the steam turbine to the motor mode with a duration of operation at reduced power of less than 5 hours, because in this case, less fuel consumption affects when loading the CCGT from the motor mode. With a longer duration of unloading of the CCGT, the fuel consumption for maintaining the motor mode turns out to be more than it is saved during loading. Repair costs and depreciation charges when switching a steam turbine to motor mode

are lower compared to stopping a steam turbine. The revenue from the sale of electricity is higher in the motor mode compared to the shutdown of the steam turbine only when the CCGT is operating at a reduced power level during the hours of night load reduction less than 10 hours (figure 6).



**Fig. 6.** Changes in total costs (*a*) and revenues (*b*) when the steam turbine is switched to motor mode (instead of shutdown) depending on the duration of unloading CCGT-450T.

## 4 Conclusion

Three modes of operation of the heat plant scheme based on the T-100-130 turbine are considered, taking into account the accumulating properties of heat networks and buildings: 1) in the motor mode of operation of the turbine, when the heat load is fully provided by the peak water-heating boiler; 2) in the low-flow operation of the turbine, when the heat load is provided by an additional boiler and a peak water-heating boiler; 3) in the low-flow operation of the turbine, when the heat load is provided by an additional boiler. In all modes, regenerative and network heaters are disabled. As a result of calculations, it is shown that the largest expansion of the adjustment range for the supply of electricity (18.03%) corresponds to the motor mode, in low-flow modes it is 8.03%. The lowest fuel costs also correspond to the motor mode and amount to 120.56 million rubles/year, for the second mode they amount to 124.24 million rubles/year, for the third – 141 million rubles/year. Income from the sale of electricity for the heating period, taking into account the cost of fuel, is the

highest for low-flow regimes and amounts to 398–1274 million rubles/year, depending on the price of electricity. In motor mode, it is less and amounts to 380–1273 million rubles/year, depending on the price of electricity, since in motor mode, electricity is not generated at night but is consumed from the network. Thus, in the motor mode of operation of the turbine, the mode of operation of the heat plant is optimal only in the case of a zero price of electricity. At modern prices for the supplied electricity, the modes of operation of the heat plant with low-flow turbine operation are preferable.

An analysis was made of ways to expand the adjustment range for the supply of electricity from combined heat and power plants. Using the example of a CCGT-450T, an assessment was made of the reduction in the service life of the main equipment and the economic efficiency of the combined-cycle cogeneration plant during unloading during the hours of the nighttime failure of the electrical load due to the transfer to the GT based CHP mode with the steam turbine turned off and with the transfer of the steam turbine to the motor mode at a constant (nominal) release of thermal energy. It is shown that if it is necessary to ensure the nominal heat supply, it is advisable to unload the CCGT-450T at night in terms of electric power for up to 10 hours by unloading gas turbines with the transfer of the steam turbine to the motor mode, with a longer unloading time – with the shutdown of the steam turbine.

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