Efficiency of flexible operation of cogeneration nuclear power plants

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Abstract. The purpose of the study is to estimate the efficiency of long-distance heat supply from nuclear power plants with the ability to vary the production of heat and electricity. The method of multi-factor system analysis taking into account the real cost of products produced: electricity, network water for heating and hot water supply were used. Differences in revenue from sales of heat and electricity in different months of the heating period, day and night, and also taking into account the forecast for the future, were taken into account. It is shown that only the price method of accounting for production at nuclear power plants by products can really assess the effectiveness of the multi-product production of NPPs.

1. Introduction
Increasing the capacity of nuclear power plants in power systems, reduction in the share of maneuverable fossil-fueled power plants, increasing share of renewable energy, increasing prices for fossil fuels and growing restrictions on its use in the electric power industry for environmental reasons necessitate the use of nuclear power plants in a variable mode [1–3]. One way to increase the efficiency of nuclear power plants and operate in a variable mode without reducing the installed capacity utilization factor is to use cogeneration with the ability to vary the production of heat and electricity [4–6].

Considerable attention is paid to the use of turbines of nuclear power plants with uncontrolled steam extraction for the combined generation of electric energy and heat, both at plants producing steam turbines and among university specialists [7–10]. So, for example, extreme combinations of electrical and thermal loads causing high stresses in the elements of the turbine flow part are taken into account. For example, design changes were made in the chambers of unregulated steam extraction to increase the allowable steam flow through them. This made it possible to remove to some extent the limitations on the power reduction with a large steam extraction from turbine offsets. This is especially important for the mid-latitude location of Russian nuclear power plants with heat supply functions when the need for a large heat production appears precisely in the winter at low temperatures of cooling water and minimum pressure values in the condensers [11–14].

In some papers, including [15], it is proposed to reserve heating equipment by supplying reduced steam through an auxiliary collector to the upper exchanger in case of insufficient productivity of peak heat sources or due to their absence. Reputedly, in the presence of such sources, their inclusion in the work is required only during the coincidence of the failure of the turbine with the coldest period of the heating season, i.e. most likely impractical. Moreover, it is logistically better to have a reserve of heating capacity with the consumer.
The paper [16] of the “Kharkiv Turbogenerator Plant” is devoted to regulating the heating load of condensing turbines with large steam extraction at unregulated pressure, and three- and four-stage heating equipment are considered. In [16] it was noted that in the condensation turbine the extraction steam pressure is not regulated, but nevertheless it is strictly determined by the capacity of the steam generators (at a given electrical load) and the heat output of unregulated steam extraction. Accordingly, with a constant heat supply, the steam pressure in the unregulated extraction section of the turbine will fall with a decrease in the electrical capacity of the turbine during a decrease in power consumption in the power system. In such modes, during operation of all stages of the cogeneration plant, the set temperature of the network water is first provided by a decrease, and then by a complete stopping of the supply of network water through the bypass line of the upper heater. When the electrical load of the power unit is further reduced, the supply of the network water heater is switched to steam extraction 3 (if until that moment the heater was fed with steam extraction 4) or to reduced fresh steam [17].

The use of nuclear power plants with VVER reactors (VVER – pressurized water reactors developed in Russia) in long-distance heat supply systems is the subject of a paper by the “VNIPIenergoprom” Institute [18]. The analysis of district heat loads performed by this Institute in the 90s of the last century showed that almost all Russian nuclear power plants were located in centers with a heat consumption of 1200–1500 MW(t) (1035–1290 Gcal/h). At that the length of transit pipelines ranged from 20 to 60 km, which determined the possibility of heat supply only with hot water [18]. Over the past time (35–40 years), the number of sites with newly commissioned NPPs with VVER-1000, VVER-1200 (Volgograd, Kursk, Leningrad NPPs and others) has increased significantly, moreover, in urbanized areas [19]. Therefore, the dependence of the justified branch lengths on the main heating main (for consumers near the pipeline) at additional heat loads, determined earlier in [18], and today confirms the advisability of connecting loads of 116–580 MW(t) (100–500 Gcal/h), respectively, at distances up to 5–25 km from the main transit highways. This increases the possible scale of the use of nuclear power plants in long-distance heat supply systems. At that time, the Loviisa NPP with VVER-440 reactors was launched, which connected the heat collectors of the NPP with Helsinki, the capital of Finland, located 80 km from the station using an indoor underground heat pipe with polyurethane foam insulation. This is one of the first examples of long-distance heat supply from nuclear power plants [20, 21].

It should be noted that scientists at the Saratov scientific center of the Russian Academy of Sciences also studied issues of improving the efficiency of nuclear power plants. These issues are discussed in the papers of prof. R. Z. Aminov [22–28], and even earlier in the monograph of professors of the Saratov State Technical University: A. I. Andryushenko, R. Z. Aminov, Yu. M. Khlebalin [29]. At the same time, changes in nuclear fuel prices and the evolution of scientific points of view on heat supply from nuclear power plants in Russia and in the world require further research on this important issue [30, 31].

For the technological cycle of multi-purpose NPPs, for example, with the production of heat energy (heat supply and hot water supply), desalination of large volumes of water, and other low-temperature technologies, for the implementation of which the temperature level of modern NPPs with VVER is sufficient, a systematic approach is necessary [32–35]. For example, an assessment of the cost of electricity and heat (or any other product) at nuclear power plants with uncontrolled heat extraction (for heating or any other available technology) using any method of fuel division distorts the real picture of profitability of multi-product production (hydrogen, heavy water, brackish clarification and desalination of marine water and, of course, traditional heating and hot water). And, first of all, because the rigid division of fuel between the products of such power plant does not allow a flexible response to changes in the economic situation and the ratio of prices for products, it does not allow comparing prices for products produced in an alternative way, taking into account the location of consumers [36–38].

In the case of multi-product production at nuclear power plants, the last two criteria are of particular interest, since, in fact, they assess the economic stability (efficiency) of electricity production according to a certain consumption schedule in the conditions of associated production (heat supply, hot water and cold supply, desalination plants). But the closest to the criterion of the thermoeconomic index [39] proposed earlier in the Saratov Scientific Center of the Russian Academy of Sciences and the Saratov State Technical University is SNWC. Given the set ratio of profit to revenue NPM (in the given tax
law), this criterion directly speaks of the expediency and payback periods of the organization of the production of additional products based on nuclear power plants. Without questioning the importance and significance of the NPV, IRR, PP, P, PI criteria, it should be noted that the SNWC indicator (the ratio of revenue from sales of manufactured products to net working capital) is also useful for already operating power plants, especially with current changes in market conditions and price dynamics for individual products. Note that the proposed thermoeconomic index in structure is very close to this indicator.

2. Theoretical positions

For long-distance heat supply (including hot water supply), the use of nuclear power plants with VVER can have a certain advantage (even if their capacity is slightly reduced) if we take into account the totality of factors. We represent the general cost function as follows

\[ \Delta R_{ele} + \Delta C_{pump} + \Delta C_{repl} + \Delta R_{heat} + \Delta C_{fuel} + 0.5 \Delta \gamma_{export} + \Delta C_{eco} + \Delta C_{reliab}, \]  

where \( \Delta R_{ele} \) is the decrease in profit with a decrease in electricity generation; \( \Delta C_{pump} \) is additional costs for network water pumps; \( \Delta C_{repl} \) is costs of operation of feed pumps for network water; \( \Delta R_{heat} \) is additional profit from the sale of heat energy; \( \Delta C_{fuel} \) is annual savings in fuel costs for the operation of long-distance heat supply in comparison with the use of gas in the boiler room at Russian prices; \( 0.5 \Delta \gamma_{export} \) is additional profit in case of 50% reinvestment in nuclear energy from revenue for gas in the export market; \( \Delta C_{eco} \) is reduction of environmental costs due to the reduction of NO\textsubscript{x} emissions into the atmosphere when replacing gas with nuclear fuel; \( \Delta C_{reliab} \) is the cost of providing higher reliability of heat supply from a cogeneration plant.

We write in detail the first term of formula (1):

\[ \Delta R_{ele} = \sum_{j=1}^{4} \sum_{i=1}^{n} \Delta P_j \tau_{ij} T_{ij}^{ele}, \]

where \( \Delta P_j \) is power reduction, MW; \( \tau_{ij} \) is electricity tariff, taking into account the number of hours per day, the tariff \( \tau_{ij} \) is valid for the \( j \) season US dollar / MWh.

In the calculations, the heating period of 4380 hours (6 months) was adopted. The flow of network water is 2500 t/h for the K-1000-60/1500 turbine unit, the heat supply is 232 MW (200 Gcal/h) with a heat network schedule of 150/70°C. Heat loads are set by season and the duration of the daily period (day, night). To more accurately determine the decrease in revenue for electricity, electricity tariffs during the day are taken into account, and different amounts of heat released day and night, and as a result, higher reduced production of electricity at night throughout the heating period, are also taken into account.

The energy consumption for pumping network water is calculated using the formula [40]

\[ E_{pump} = \frac{G \Delta p n}{\rho \eta_{m, p} \times 10^{-3}}, \]

where \( G \) is water flow in the heating network (pump supply), kg/s; \( \Delta p \) is the pressure drop developed by the pumps, Pa; \( \rho \) is the density of water, kg/m\textsuperscript{3}; \( n \) is the number of pump hours per year; \( \eta_{m, p} \) is motor pump efficiency (product of pump efficiency \( \eta_{pump} \) and electric motor efficiency \( \eta_{motor} \)).

The additional profit from the sale of heat energy is determined by the formula:

\[ \Delta R_{heat} = \sum_{j=1}^{4} \sum_{i=1}^{n} Q_j \tau_{ij} T_{ij}^{heat}, \]  

where \( Q_j \) is the amount of heat released by the plant, Gcal.
where \( Q_{ij} \) is the heat supplied for \( \tau_{ij} \) hours per day in \( j \) season at the tariff \( T_{ij} \), dollars/kWh(t).

It is known that the price of nuclear fuel in conventional fuel equivalent is much lower than the price of natural gas. The reduction in fuel costs due to a decrease in the consumption of natural gas in boiler houses due to heat supply from nuclear power plants is determined by the formula:

\[
\Delta C_{fuel} = \sum_{j=1}^{4} \sum_{t=1}^{n} Q_{ij} \left( \frac{C_{gas}}{LHV_{gas} \eta_{boiler}} - \frac{C_{nuclear}}{24B} \right),
\]

where \( C_{gas}, C_{nuclear} \) are the prices of natural gas and nuclear fuel, dollars/kg; \( LHV_{gas} \) is lower heating value of natural gas, MWh/kg; \( B \) is average depth of fuel burnup (\( \text{UO}_2 \) – uranium dioxide of a given enrichment in modern reactors), MWh/kg; \( \eta_{boiler} \) is the average efficiency of a natural gas boiler.

Additional profit in case of 50% reinvestment in nuclear energy power from the sale of saved natural gas abroad is determined by the formula:

\[
0.5\Delta R_{gas}^{exp} = 0.5 \sum_{j=1}^{4} \sum_{t=1}^{n} Q_{ij} \left( C_{gas}^{exp} - C_{gas}^{Russia} \right),
\]

where \( C_{gas}^{exp}, C_{gas}^{Russia} \) are average gas prices in the export market and Russia.

According to the data [17], figure 1 shows the dependence of the decrease of NPP electrical capacity per unit of heat output on the temperatures of the direct and reverse network water for the K-1000-60/1500 turbine with a capacity of 1000 MW (manufactured by Kharkov turbogenerator plant). The curves are plotted at full steam flow to the turbine and a constant flow of network water corresponding to a nominal heat output of 232 MW(t) (200 Gcal/h) according to a heat network schedule of 150/70°C. With a decrease in the heat load (flow rate of network water), the specific under production at any ratio of the temperatures of the direct and return water slightly decreases. The relatively low level of specific reduction in electricity production is explained by the fact that the main part (over 85%) of the heat generated by the turbine unit is obtained not due to the underutilization of the possible operability of steam in the turbine, but due to the utilization of energy, which is discharged into the condenser in the condensation mode.

Figure 1. Dependence of the decrease of NPP electrical capacity per unit of heat output from the temperature of the network water in supply \( t_{supply} \) and return \( t_{return} \) pipelines at its flow rate of about 2500 t/h for the K-1000-60/1500 turbine:
1 – \( t_{supply} = 140°C \); 2 – \( t_{supply} = 130°C \) (three-stage water heating); 3 – \( t_{supply} = 120 °C \); 4 – \( t_{supply} = 110°C \) (two-stage water heating); 5 – \( t_{supply} = 80°C \) [17]

The high efficiency of multi-stage heating of network water by the steam of uncontrolled steam extraction allows us to raise the question of increasing the extraction factor (the ratio of a load of turbine extraction to the maximum heat supply from the combined heat and power plant) in comparison with the value adopted for existing CHP plants. This is especially true for nuclear power plants, for which the fuel component in the cost of generated energy is relatively low, while an increase in the share of
nuclear power plants in covering heat needs allows saving a significant amount of scarce expensive fossil fuels, including natural gas. Today, natural gas is considered a valuable export resource for the nearest foreseeable period of development of the Russian economy.

Multi-stage heating of network water in the condensing turbine unit allows to increase the heat-end mode electricity production, facilitates the regulation of the temperature of the network water, and reduces the associated underproduction of electricity. The change in the network water temperature can be achieved by gradually increasing the bypass of the last (in the course of the network water) operating heat exchanger or by throttling the steam supplied to it until this heat exchanger stops, after which similar operations can be performed with the previous one in the course of the water of the heat exchanger. In any case, we are talking about partial underutilization of the potential of a relatively small amount of steam going to the heat exchanger in question, and this amount is less the greater the difference between the saturation temperatures of steam in extraction section and the network water at the outlet of the heating plant. If the bypass is not permissible (for example, the use of a nuclear power plant for desalination of water), the Kharkiv turbogenerator plant provides throttle valves on steam pipelines [15, 17].

3. Results

If we assume that with sufficiently small consumption of extraction steam, a change (some decrease) in the efficiency ratio of turbine can be neglected, then the production of thermal power of 232 MW(t) (200 Gcal/h) leads to a relative under-production (-dP/dQ) by 0.155 relative units or by 36.1 MW(e), i.e. only 3.6% of nominal capacity. However, in subsequent publications by specialists of the Kharkiv turbogenerator plant, it was shown that with modernization of the turbine, the actual allowable thermal power of uncontrolled steam extraction of turbine units can be increased to 290–348 MW(t) (250–300 Gcal/h). With the same value of -dP/dQ, the decrease in electric power during off-peak periods will be 44.95 and 53.9 MW(e), respectively, which is significantly higher and amounts to 4.5% and 5.4% of nominal capacity.

For calculations in this paper, the calendar year is conditionally divided into 4 main periods: I – heat supply (with hot water supply) with the highest network water temperature of 150/70°C and a duration of 2 months; II – heat supply with hot water supply according to the schedule 140/70°C for 2 months; III – the same as scheduled 130/70°C for 2 months; IV – non-heating period, only hot water supply 6 months. The decrease in the capacity of NPP (1000 MW) at nighttime was determined for the heat supply temperature schedule: 150/70°C – 36.1 MW; 140/70°C – 30.3 MW; 130/70°C – 24.8 MW; only hot water supply – 2.7 MW (daytime – 5.3 MW), table 1.

For the data used in the calculation, the specific pressure drop, i.e. the pressure drop per unit length of the pipeline at a flow rate of 2500 t/h (694.4 kg/s) and a pipeline diameter of 650 mm is 70 Pa/m [40]. With a pipeline length of 100 km this will be 7 MPa (713.8 m).

According to Wilo, the cost of an SCP-200-460-HA-200-4 pump (flow rate 2500 m3 / h, 60 m head) with an electric motor with a rated power of 200 kW is 23215 euros, a control cabinet for 4 pumps – 56,544 euros. The cost of 4 pumps (according to the 3+1 scheme) with a control cabinet is 149,404 euros (169,894 dollars). The number of SCP-200-460-HA-200-4 pumps with a pressure of 60 m for the pipelines under consideration (supply and return) is defined as 24 (taking into account the reserve 3+1 – 32) with a total required power of 4.8 MW. The total costs for pumps and control cabinets will be 1.359 million dollars, table 2.

The cost function according to formula (1) is compared with the cost of a pipeline (double-pipe scheme) 100 km long with a diameter of 650 mm with polyurethane foam insulation in a polyethylene shell with a lining in an underground passage and the cost of 8 pumphouses (4 pumps of SCP-200-460-HA-200-4 type with a pressure of 60 m). At this stage of the calculation, costs in the branches from the heat pipeline to the consumers near the pipeline were not taken into account.

Using the forecast for fuel prices and tariffs for heat and electricity shown in table 3, the economic effect of heat supply from nuclear power plants was calculated (figure 2).
Table 1. The results of the calculation of technical and economic indicators of the heat supply system from the nuclear power plant.

| Indicators                                      | Heating period | Non-heating period (IV) |
|------------------------------------------------|----------------|-------------------------|
|                                                | I             | II                      | III                     |
| Number of hours of operation, h / year         | 1460          | 1460                    | 1460                    | 4380                    |
| Temperature of direct / return network water, °C: |               |                         |                         |                         |
| day                                            | 140/70        | 130/70                  | 120/70                  | HW                      |
| night                                          | 150/70        | 140/70                  | 130/70                  | HW                      |
| Heat output, MW(t):                            |               |                         |                         |                         |
| day                                            | 203.5         | 174.5                   | 145.4                   | 46.5                    |
| night                                          | 232.6         | 203.5                   | 174.5                   | 23.3                    |
| Relative heat output:                          |               |                         |                         |                         |
| day                                            | 0.88          | 0.75                    | 0.63                    | 0.2                     |
| night                                          | 1.0           | 0.88                    | 0.75                    | 0.1                     |
| Decrease of NPP electrical capacity per unit of heat output dp/dQ: |   |                         |                         |                         |
| day                                            | 0.149         | 0.142                   | 0.134                   | 0.115                   |
| night                                          | 0.155         | 0.149                   | 0.142                   | 0.115                   |
| Decrease of NPP electrical capacity, MW(e)     |               |                         |                         |                         |
| day                                            | 30.3          | 24.8                    | 19.5                    | 5.3                     |
| night                                          | 36.1          | 30.3                    | 24.8                    | 2.7                     |
| Revenue from the sale of thermal energy, million dollars a | 6.471       | 5.586                   | 4.700                   | 3.529                   |
| Decrease in revenue from electricity sales, million dollars b | 0.800       | 0.657                   | 0.529                   | 0.343                   |

a The heat tariff from the power plant is 20.8 dollars / MWh (1454 rubles / MWh)

b The daytime and nighttime electricity tariffs are 18.6 and 14.3 dollars / MWh (1300 and 1000 rubles / MWh) duration 16 and 8 hours, respectively

Table 2. Annual technical and economic indicators of the heat supply system from NPP.

| Indicators                                      | Value          |
|------------------------------------------------|----------------|
| Annual heat generation, MWh(t)                  | 976 339        |
| Annual decrease in electricity output, MWh(e)   | 136 646        |
| Electric power of all network pumps, MW         | 4.8            |
| Electricity costs for network pumps, million dollars / year c | 0.514 |
| Annual increase in revenue, million dollars / year | 17.443 |
| Capital investments in network pumps, million dollars | 1.359         |
| Capital investments in heating networks, million dollars | 14.286 |
| Payback period, years                          | 0.9            |
| Annual fuel cost savings due to reduced natural gas consumption in the power system, million dollars / year | 7.186         |
| Additional profit when reinvesting in NPPs50% of the sale of saved natural gas abroad, million dollars / year | 11.900         |

a The cost of electricity for pumps is 12.1 dollars / MWh (850 rubles / MWh)

Table 3. Fuel price and heat and electricity tariff forecast.

| Indicators                                      | Years          |
|------------------------------------------------|----------------|
|                                                | 2020  | 2022  | 2024  | 2026  | 2028  | 2030  |
| Price of natural gas in Russia, dollars / thousand m³ | 50    | 55    | 60    | 65    | 70    | 75    |
| Export price of natural gas, dollars / thousand m³ | 200   | 210   | 220   | 230   | 240   | 250   |
| Nuclear fuel price, dollars / kg UO₂             | 1071  | 1125  | 1179  | 1232  | 1286  | 1339  |
| Heat tariff, dollars / MWh(t) a                  | 20.8  | 22.4  | 24.1  | 25.8  | 27.4  | 29.1  |
| Electricity tariff, dollars / MWh(e): b          |       |       |       |       |       |       |
| daytime                                        | 18.6  | 20.1  | 21.7  | 23.3  | 24.8  | 26.4  |
| nighttime                                      | 14.3  | 15.5  | 16.7  | 17.9  | 19.1  | 20.3  |

a Annual increase of 4%

b Annual increase of 4.2%
Figure 2. Annual increase in revenue of nuclear power plants during heat supply (1), the same with saving more expensive fuel (natural gas) (2), the same with 50% reinvestment from the sale of saved natural gas abroad

4. Calculation of the reliability of district heating pump

Let the failure rate of each of the pumps $\lambda^{(j)}$, h\(^{-1}\), where $i$ is the sequential number of the pump in the $j$ group along the length of the heat pipeline, and $\mu^{(j)}$ is the corresponding repair rate, h\(^{-1}\). If the pump fails in its $j$ group ($j$ pumphouse), the mathematical expectation of the probability of a partial failure (reduction in flow from the maximum value to a value of about 0.86–0.88) can be determined using the following algorithm.

According to statistics, medium and high-power network pumps operate for 3 to 5 years without stopping, so the failure rate is $2.3 \times 10^{-5} \leq \lambda \leq 3.8 \times 10^{-5}$ h\(^{-1}\). The average pump recovery time is 4–5 hours, taking into account spare parts and remote failure detection in the pump using electronic sensors and telemetry with transmission to the monitor house, and the pump recovery flow rate is $\mu \leq 0.25$ h\(^{-1}\). Therefore, we can accept the range of reliability coefficients $\rho = \lambda/\mu = 10^{-4}$; $1.5 \times 10^{-4}$, as optimistic and pessimistic, respectively, at $\lambda = 2.5 \times 10^{-5}$ and $3.75 \times 10^{-5}$.

Consider the scheme of the network water pipeline with similar pump houses, characterized by complex reliability indicators $\rho^{(j)} = \lambda^{(j)}/\mu^{(j)}$. Using the provisions of graph theory, we write in the form of Chapman–Kolmogorov equations the relationship between events in the initial node of the state graph of the heat pipeline for the first pump house.

$$-P_{e1}\lambda^{(1)} + P_{e1}\mu^{(1)} = 0$$

where $P_{e1}$ is the initial state with all pumps in the first pump house; $P_{e1}$ is the final state with one failed pump in the same pump house.

This is the same state can be identified as the input state to the second pumping station, etc., if we do not take into account accidents of pipelines of the underground installation itself.

In the overall assessment of the reliability of all pumps in each group, it should be taken into account that when all pumps are running, the following equation is valid $\lambda^{(1+4)} = 4\lambda^{(1)}$. From the system of equations (7) it follows

$$P_{e1} = \frac{\mu^{(1)}}{\mu^{(1)} + 4\lambda^{(1)}} = \frac{1}{1 + 4\rho^{(1)}}$$

Thus, $P_{e1} = 0.9996$ at $\rho = 10^{-4}$ and $P_{e1} = 0.9994$ at $\rho = 1.5 \times 10^{-4}$. Similarly, the reliability of the remaining pump houses is calculated, which leads to an overall system reliability in the range from 0.9968 to 0.9952, which is quite sufficient.
5. Conclusions

Thus, the operation of nuclear power plants in the cogeneration mode makes it possible to increase the economic efficiency of nuclear energy sources, maximize profits when electricity prices change in the energy market, and operate nuclear plants in a variable mode due to the ability to vary heat and electricity production in accordance with the ratio of prices for manufactured products. Also, heat supply from nuclear power plants reduces the use of fossil fuels and allows the use of a valuable export resource – natural gas for sale abroad. Reliability indices of heating network pumps make it possible to recommend long-distance heat supply from nuclear power plants as one of the auxiliary ways to expand the NPP market and increase flexibility, and also to improve the environmental improvement.

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