Evaluation of the Comparative Efficiency of CCGT in Variable Modes

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Abstract. The purpose of the research is to select the priorities for the development of various types of power plants and to substantiate the structure of generating capacities. An improved method has been developed for the selection of priorities for the development of various types of power plants, taking into account the service life and economic performance of the main equipment of power plants in variable modes based on equivalent operating hours. The influence of variable modes of combined-cycle gas installations on the service life of the main equipment (steam and gas turbines) is studied. The comparative efficiency of CCGT-450 in variable modes is calculated, taking into account the wear of the main equipment. As a result of calculations, it was found that with the minimum forecast prices for natural gas, the most efficient power plant (among those considered) is combined cycle power plant, which provides the lowest prime cost of electricity when operating in the base mode and the least increase in the prime cost of electricity when operating in an alternating mode.

1. Introduction

The increasing demand for electric energy necessitates the development of electric power systems. In this case, many complex technical and economic problems arise, the most important of which is the need to select priorities for the development of various types of power plants and substantiate the structure of generating capacities. As a rule, any type of power plant does not have an absolute economic advantage, therefore, it is necessary to justify the choice of types of power plants to cover the base and variable parts of the electrical load schedule.

The transition to low-carbon energy requires careful analysis. The rapid development of renewable energy without taking into account systemic effects can have significant negative economic consequences. With a share in the power system of more than 15–20% of solar and wind power plants characterized by stochastic energy output, thermal power plants are pushed out of the base part of the electric load schedule into the half-peak and even peak zone. This worsens their working conditions, increases fuel consumption, reduces the service life of the main equipment, and increases the cost of electricity.

The problem of choosing priorities for the development of various types of power plants is complicated by the influence of many factors. The most important of them are the technical and economic performance of the power plant, the maneuverable characteristics of the main equipment of power plants, the schedule of power consumption, environmental, economic, and other factors. The modes of operation of thermal and nuclear power plants, the consumption and maneuverability
characteristics of the installations participating in the process of energy production, and their starting characteristics have a significant impact. The task under consideration is further complicated by the fact that it is expedient to consider the operation of power plants over a long period, over the entire service life of power plants. For this, it is necessary to study the patterns and trends of development in the long term, the impact of scientific and technological progress, as well as take into account various scenarios of the fuel and energy balance and higher requirements for reliability and safety of power plants.

2. Expected operating conditions of power plants

In the coming years, the electric power sector will become the center of transformations taking place in global power engineering [1, 2]. In the forecast of the Energy Research Institute of the Russian Academy of Sciences [3], seven technological innovations are considered, the application of which may entail organizational and technological changes in the functioning and management of electric power systems and contribute to the transition of energy to a new technological basis: increasing energy efficiency, electrification, reducing the cost of electricity production and heat based on renewable energy sources, the development of energy storage and storage technologies, the development of hydrogen energy, increasing controllability – the introduction of digital and intelligent systems in the electric power industry, the development of distributed energy.

There is a transition in the era of active competition of technologies that can offer a large number of options for energy supply using various energy sources [4, 5]. One of the key sectors of inter-fuel competition will be the electric power industry, which is especially important in the context of an increasing share of electricity in the structure of final consumption of energy resources.

Modern changes in the energy markets are largely due to the growing competitiveness of production from renewable energy sources, stimulated by an active energy policy aimed at decarbonizing the energy sector. In the period 2000–2018 capacity of renewable energy sources (solar, wind, and biomass energy, excluding traditional hydropower) increased by 21 times from 56 GW in 2000 to 1179 GW in 2018. The share of renewable energy sources (excluding hydropower) in the final world primary energy consumption has more than tripled, and in electricity generation from 3.4% in 2006 to 10.5% in 2018 [3]. Today, the most common renewable energy technologies are wind energy (5.6% of total generation), bioenergy (2.2%), and solar energy (1.9%).

The development of renewable energy sources negatively affects the economic efficiency of traditional power plants and reduces their competitiveness in comparison with electricity generation based on renewable energy sources. A paradoxical situation arises: the competitiveness of power plants based on renewable energy sources is growing not only due to their technical and economic improvement but also due to the deterioration of the operational performance of traditional power plants caused by them.

In Russia, the capacities of solar and wind power plants are still small, their total share in the installed capacity of the country's power plants is about 0.3%, and in electricity generation – 0.1%. It is expected that thanks to government support, this share will gradually increase [6]. According to the order of the Government of the Russian Federation No 354-r dated February 28, 2017, the target values for the volumes of commissioning of the installed capacity of generating facilities based on renewable energy sources until 2024 should be: wind power plants 3.35 GW, solar power plants 1.76 GW. Experts of the State Corporation Rosatom (which entered the wind energy market in 2018) estimate the possibility of introducing wind power plants in Russia even higher – 3.6 GW until 2024 [7].

Taking into account the inevitability of the appearance of negative systemic effects with an increase in the share of renewable energy sources in power systems, it is necessary to provide timely measures to compensate for these effects [8]. At the same time, it is necessary to take into account the peculiarities of the Russian electric power industry: the rather low cost of organic fuels and their availability (large reserves and production volumes in the country), a high degree of centralization, a high degree of concentration of energy production (a large share of powerful power plants), the
important role of district heating, a significant share of nuclear power. It is important to achieve the consistent introduction of renewable energy sources and compensation measures of possible negative consequences.

At the same time, taking into account the significant inertia of the energy sector, expressed in the high capital and resource intensity of investment projects and their long-term nature, in Russia in the future until 2035, fossil fuels will continue to form the basis of energy with a gradual increase in the share of renewable energy sources in the national fuel and energy balance [9, 10].

Now the main focus in the strategy for the development of the electric power industry is made on the technological upgrade of about 60 GW of gas-fired thermal power plants, which will reach their maximum operating life in the next 10–20 years. According to the priorities of the Energy Strategy to improve energy efficiency and environmental friendliness of the energy sector, traditional gas-fired thermal power plants should be replaced by new, low-carbon technologies, primarily combined cycle gas turbines (CCGT), which reduce specific fuel consumption by up to 1.5 times.

Initially, CCGT units were intended for operation in the basic part of the load schedule with a limited number of starts-stops (about 30 starts per year with a service life of 30 years). With the massive introduction of solar and wind power plants into the energy system, the number of start-stop cycles of CCGT will increase many times over. In this case, thermal power plants, including powerful CCGTs, will be pushed into the half-peak, and then into the peak zone of the electric load schedule.

3. Theoretical positions

High competition among power plants and the projected increase in the share of renewable energy sources (which for environmental reasons are considered a priority in electricity generation) necessitate a change in the strategy of operating thermal power plants: extremely irregular and intermittent operation is necessary to meet consumer demand and energy production, mainly during hours when the electricity price is higher to maximize profits [11–13]. This operating strategy is generally required for all power plants, not only those traditionally designed for load regulation but also those originally designed to cover the base load. As a result, in the short term, more income is provided for power plants, but due to low-cycle metal fatigue, the service life of the main equipment will decrease. This will lead to additional costs for preventive and emergency repairs, as well as an increase in costs for reserve capacity [14–16]. Thus, it is necessary to optimize the entire life of the main equipment of power plants. The influence of operating modes on the life of the main equipment is taken into account using equivalent operating hours (EOHs) [17–19].

As a criterion for assessing the efficiency of power plants operation, the cost of the supplied electricity is taken: $S = C_{\Sigma} / E_{\text{sup}}$, where $C_{\Sigma}$ is the total annual cost of generating electricity associated with the variable operating mode of the power plant, USD/year; $E_{\text{sup}}$ is the annual electricity supply from the power plant, kWh/year. This indicator reflects well the production costs associated with the operating modes of the power plant. The total costs include the following values

$$C_{\Sigma} = C_{\text{fuel}} + C_{\text{rep}} + C_{\text{renew}} + C_{\text{salary}} + C_{\text{other}},$$  \hspace{1cm} (1)

where $C_{\text{fuel}}$ is fuel costs, USD/year; $C_{\text{rep}}$ is repair and maintenance costs, USD/year; $C_{\text{renew}}$ is depreciation deductions for full restoration – renovation of fixed assets, USD/year; $C_{\text{salary}}$ is salary costs, USD/year; $C_{\text{other}}$ is other costs, USD/year.

The total annual operating costs for electricity production, taking into account the operating modes of the power plant, were determined by the following equation [20]:

$$C_{\Sigma} = \left( \sum_{t=1}^{t} P_{t} \cdot h_{t} + B_{\Sigma} \right) F + \left( \frac{c_{\text{rep}} \cdot c_{\text{main}} \cdot \alpha_{\text{rep}}} {t_{\text{life}} (1 - k_{a})} + c_{\text{ex}} \cdot \alpha_{\text{ex}} \cdot \Omega_{\text{ex}} + c_{\text{spare}} \cdot \Omega_{\text{ex}} + c_{\text{spare}} \cdot \Omega_{\text{ex}}^{2} \right) \frac{P_{\text{nom}}}{t_{\text{life}}} + \frac{t_{\text{eq}}}{t_{\text{life}}},$$  \hspace{1cm} (2)

$$+ \frac{c_{\text{person}} \cdot n_{\text{shift}} \cdot P_{\text{nom}} \cdot (1 + \alpha_{\text{pay}}) \cdot 10^{-3} + \alpha_{\text{pp}} \cdot k_{\text{pp}} \cdot P_{\text{nom}}}{t_{\text{life}}}.$$
where \( I \) is number of i-modes of the power unit operation, units; \( P_i \) is i-mode unit loading, kW; \( t_i \) is time of operation in i-mode, h/year; \( b_i \) is specific consumption of fuel for electric power production in i-mode, tons of reference fuel/kWh; \( B_2 \) is total annual fuel consumption for all startups of the power plant, tons of reference fuel/year; \( F \) is the fuel costs, USD/tons of reference fuel; \( \alpha_{\text{repair}} \) is the share of funds invested in the main equipment of the power unit, spent on mid-life, and current repair costs; \( c_{\text{main}} \) is specific funds invested in the main equipment of the power unit, USD/kW; \( c_{\text{spare}} \) is specific annual costs of spare capacity associated with the standby of equipment, USD/kW; \( t_{\text{pr}} \) is the average annual duration of proactive maintenance, h; \( t_{\text{cal}} \) is the calendar time in the year, h/year; \( k_{\text{st}} \) is the coefficient of the scheduled standby; \( c_{\text{em}} \) is specific costs of emergency recovery, USD/(kWh); \( \omega \) is the frequency of emergency failures of the power unit, 1/year; and \( t_{\text{em}} \) is the average annual time of recovery after emergency repair, h/year; \( P_{\text{nom}} \) is the nominal capacity of the power plant, kW; \( \tau_{\text{eq}} \) is equivalent operating hours, h; \( \tau_{\text{life}} \) is lifespan of the main equipment, h; \( \alpha_{\text{renew}} \) is the share of funds invested in the main equipment of the power unit, spent on renewal at the estimated lifespan \( \tau_{\text{life}} \) of the power unit; \( c_{\text{person}} \) is the annual salary of one employee, USD/(person·year); \( n_{\text{staff}} \) is staffing factor, person/MW; \( \alpha_{\text{soc}} \) is payroll – social tax; \( \alpha_{\text{pp}} \) is the weighted average rate of deductions from capital investments for general station costs; \( k_{\text{pp}} \) is specific capital investment in the power plant, USD/kW.

To evaluate the comparative efficiency and the choice of priority ways of using thermal and nuclear power plants for the future, the most advanced and relatively well mastered power plants were adopted: condensing CCGT unit with a capacity of 450 MW with two gas turbines GTE-160 (V94.2) and one steam turbine K-150-7.5; TPP 300 MW with a K-300-240 turbine; TPP 500 MW with a K-500-240 turbine; TPP 800 MW with K-800-240 turbine. Separately, the near-nominal operating mode of a 1200 MW NPP power unit with VVER-1200 is considered.

The technical and economic indicators of these power plants and their operating conditions are used as initial information to evaluate their comparative efficiency, table 1 [21–25].

**Table 1. Initial indicators of the considered power plants.**

| Indicators                        | CCGT 450 MW | TPP 300 MW | TPP 800 MW | TPP 500 MW | NPP 1200 MW |
|-----------------------------------|-------------|------------|------------|------------|-------------|
| Installed capacity, MW            | 450         | 300        | 800        | 500        | 1200        |
| Specific capital investments, USD/kW | 1100           | 1300       | 1200       | 1500       | 2500        |
| Type of fuel                      | natural gas | natural gas| natural gas| coal       | nuclear fuel|
| Average discounted fuel price,    | 98–139      | 98–139     | 98–139     | 49–64      | 14.5–24     |
| USD/ton of fuel equivalent        | 0.246       | 0.326      | 0.325      | 0.340      | 0.384       |

Variable operating costs, depending on the modes of use of power plants, are the specific fuel consumption for electricity generation and the share of electricity consumed for the plant's own needs. Variable operating modes of power plant equipment significantly increase fuel consumption for power generation. The dependences of the specific fuel consumption on the power of power plants are shown in figure 1 [23].
4. Results

The CCGT calculation was carried out according to the presented method, taking into account the equivalent operating hours of gas and steam turbines, as well as waste heat boilers [26, 27]. In the calculations of thermal power plants of 300, 500, and 800 MW, additional costs associated with a decrease in the service life of the main equipment were taken into account – the equivalent operating hours of the steam turbine rotor under variable conditions were calculated [28]. At the NPP, only the near-nominal operating mode was considered and these costs were not taken into account. The results of calculating the comparative efficiency of power plants when operating at a constant power level for the adopted initial information are shown in Figure 2. Figure 2 shows that when operating at a nominal power level, the most efficient source of electrical energy is a combined cycle plant, a 500 MW coal-fired thermal power plant, and a nuclear power plant.

The mode of operation of power plants with a change in power is considered: operation at 100% capacity during the day and unloading to $P$ for 8 hours at night. Taking into account the peculiarities of the CCGT operation, the equivalent operating hours of the main equipment of the CCGT-450 (steam and gas turbines, waste heat boiler) are determined. In the area of high loads, when the variable inlet guide vanes of the compressor participate in the regulation of the gas turbine, a decrease in the power of the CCGT-450 to $P$≈(0,6÷0,65)$ \cdot P_{\text{nominal}}$ is accompanied by a decrease in gas consumption at a constant or slightly changing temperature behind the gas turbine (≈535°C) and therefore the equivalent operating hours of the steam turbine and heat recovery boilers in this load range are zero. Table 2 shows the results of calculations of the technical and economic indicators of CCGT-450 under variable...
modes – overnight unloading of all equipment of the power unit (2 gas turbines + 2 waste heat boilers + steam turbine) to capacity $P$.

**Table 2.** Calculation results of technical and economic indicators of CCGT-450 under variable modes (operation at 100% power and unloading for 8 hours at night to power $P$).

| CCGT capacity at unloading $P$ | Equivalent operating hours of a gas turbine per cycle of power change, eq. h | Increase in costs for CCGT repair, % | Increase in the cost of electricity, % |
|--------------------------------|---------------------------------|-----------------------------------|------------------------------------|
| MW                             | %                               | per hour of operation at $P$       |                                    |
| 425                            | 94.4                            | 0.003                             | 0.9                                |
| 400                            | 88.9                            | 0.005                             | 3.7                                |
| 375                            | 83.3                            | 0.008                             | 5.7                                |
| 350                            | 77.8                            | 0.015                             | 7.7                                |
| 325                            | 72.2                            | 0.030                             | 9.9                                |
| 300                            | 66.7                            | 0.055                             | 12.1                               |
| 275                            | 61.1                            | 0.091                             | 14.5                               |
| 250                            | 55.6                            | 0.241                             | 16.9                               |
| 225                            | 50.0                            | 0.526                             | 19.7                               |

Figure 3 shows the results of calculations of the comparative efficiency of all the above power plants when operating in variable mode, depending on the degree of their participation in load regulation (i.e., for different levels of night unloading $P$ and, accordingly, different hours of installed capacity use).

**Figure 3.** The prime cost of electricity (average for the billing period) of power plants depending on the degree of participation in load regulation (from the level of unloading for 8 hours at night) for the minimum (lower line) and maximum (upper line) forecast fuel prices: 1 – gas-fired CCGT 450 MW ($1'$ – one gas turbine is running; $1''$ – two gas turbines are running); 2 – gas-fired TPP 300 MW; 3 – coal-fired TPP 500 MW; 4 – gas-fired TPP 800 MW; 5 – NPP 1200 MW

Figure 3 shows that for the accepted initial data at the minimum forecast prices for natural gas, one of the most efficient power plants (among those considered) is the CCGT-450 condensing combined-cycle gas plant, which has a low prime cost of electricity (average for the calculated period) when operating in base mode (4.12 and 5.16 cents/kWh at the minimum and maximum forecast prices for natural gas, respectively) and the smallest increase in the prime cost of electricity when operating in variable mode (9.5% when unloading at night for 8 hours to 50% $P_{nominal}$, see table 2). Taking into account the reduction in the service life of the main CCGT equipment under variable loads, it is advisable to unload CCGT-450 by unloading two gas turbines (and, accordingly, unloading a steam turbine), without stopping down the gas turbine (figure 3).

NPP with VVER-1200 has the lowest prime cost of electricity among the considered power plants at maximum prices for natural gas and coal (4.1–4.48 cents/kWh at the minimum and maximum forecast prices for nuclear fuel, respectively) (figure 3). The operation of a nuclear power plant in a variable mode leads to the greatest increase in the prime cost of electricity.
Condensing TPPs of 300 and 800 MW have a higher prime cost of electricity (average for the billing period): 5.2–6.6 cents/kWh when operating a 300 MW power plant with a K-300-240 turbine in the base mode and 5.1–6.4 cents/kWh – 800 MW power plants with a K-800-240 turbine (at the minimum and maximum forecast prices for natural gas, respectively) (figure 3).

5. Conclusions
The systemic factors influencing the choice of the structure of power plants in the power system and the forecast conditions for the development of generating capacities are analyzed. In the coming years, the electric power sector will become the center of changes taking place in the global energy sector, such as increased inter-fuel competition, intensified scientific and technological progress, increased energy efficiency, and an increase in the share of renewable energy sources.

An improved method has been developed for the selection of priorities for the development of various types of power plants, taking into account the service life and economic performance of the main equipment of power plants in variable modes based on equivalent operating hours. This will allow optimizing the operating modes of power equipment, taking into account wear and tear throughout its entire service life, as well as adjusting the operating modes of power units in response to changes in the electricity market, for example, changes in fuel prices.

The economic efficiency of the condensing CCGT-450 is studied in comparison with the 300 MW TPP with the K-300-240 turbine, the 800 MW TPP with the K-800-240 turbine, the 500 MW TPP with the K-500-240 turbine, and the 1200 MW NPP with the VVER-1200 for the future in relation to the European part of Russia, taking into account the service life. As a result of calculations, it was found that with the minimum forecast prices for natural gas, the most efficient power plant (among those considered) is CCGT-450, which provides the lowest prime cost of electricity when operating in the base mode and the least increase in the prime cost of electricity when operating in an alternating mode.

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