NUCLEAR POWER PLANTS

Evaluation of NPP Efficiency Using Phase-Transition Batteries

R. Z. Aminov[a], * and M. V. Garievsky[a]

[a] Gagarin Saratov State Technical University, Saratov 410054 Russia

*e-mail: oepran@inbox.ru

Abstract—In the context of the growing share of nuclear power plants in the energy systems of the European part of Russia and the shortage of flexible generating capacities, it becomes necessary to involve nuclear power plants in covering the variable part of the load schedule. With relatively low prices for nuclear fuel (at present, the equivalent cost of a uranium fuel load is five to six times lower than the cost of natural gas inside the country) and high specific capital investments in nuclear power plants, it is not economically efficient to unload them. Therefore, the combination of nuclear power plants with latent heat thermal energy storage (LHTES) and an additional steam turbine makes it possible to accumulate thermal energy generated at night and use it during peak hours to generate electricity with the maximum use of nuclear fuel, i.e., without changing the power of the nuclear reactor. In addition, the presence of an additional turbogenerator in emergency situations with a complete blackout of the NPP makes it possible to ensure the operation of the cooling systems by using the residual heat of the reactor to drive the turbine and, thereby, increase the safety level of the NPP. The analysis of prices for electricity in the wholesale electricity and capacity market of the Unified Energy System of Russia (WECM UES) and in the energy system of France (with the highest share of nuclear power plants) was carried out. The impact of the operation of the NPP power unit with a thermal energy storage system was assessed in addition to the alternative option: the construction of a pumped storage power plant (PSPP) at the WECM. Calculations of technical and economic indicators of the use of LHTES-based thermal energy accumulators at NPPs are carried out depending on the level of thermal power of the latter as well as the increase in the regulation range for electricity supply. It is shown that if we do not take into account the multifunctional properties of the energy complex based on LHTES and an additional turbine (increased safety, NPP participation in primary frequency control) with the existing difference in prices for electricity generated during peak and night periods on the day-ahead market, the payback of the NPP energy complex for LHTES-based is not provided. The return on investment in phase-change batteries and an additional turbine in the considered example can be achieved provided that the difference between the average prices for electricity generated during peak and night hours over a billing period of 25 years is 3400 rubles/(MW h) and the charging time/LHTES discharge exceeds 7 h per day.

Keywords: nuclear power plant, thermal storage, phase change accumulator, wholesale electricity and capacity market, uneven power consumption curves

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The most important feature of electricity consumption in power systems is the uneven daily, weekly, and seasonal schedules of electrical loads, while large generating sources, such as nuclear power plants, are most efficient when operating at maximum power levels for a long period.

In the UES of Russia, there is a shortage of maneuverable capacities that can reduce the load (or stop) during hours of reduced power consumption and provide the energy system with electricity during hours of increased load. Most thermal power plants operating on fossil fuels are transferred to the semipeak zone of the electrical load schedule, which negatively affects their efficiency and reliability. The aging of thermal power plants' equipment, the constant increase in prices for fossil fuels, and the requirements for environmental safety lead to the need to increase the share

of nuclear power plants in the UES [1, 2]. The active growth of the share of nuclear power plants leads to an increase in the volume of nonflexible generation in the wholesale electricity and capacity market, which forces nuclear power plants to participate in covering the irregularities in the electrical load schedule.

When operating in maneuvering modes, economic indicators decrease and, as a result, the competitiveness of nuclear power plants and the technical capabilities of regulating the power of reactors of modern nuclear power plants depend on the period of the fuel campaign and do not always meet the requirements of power systems. Due to the objective difficulties in creating and mastering the necessary maneuverable capacity of a pumped-storage power plant (PSPP) and semipeak power units, it is necessary to have alternative technical solutions that will make it possible to

unload nuclear power plants at night and produce additional energy during periods of its increased consumption.

The above reasons make it expedient to search for ways to organize the maneuvering mode of nuclear power plants while maintaining the same basic mode of reactor installations [3–6]. One of these ways can be the deployment of systems that allow for accumulating the thermal energy of reactors during night hours of reduced power consumption and use it to generate additional electricity during hours of increased power consumption [7, 8]. Through the use of storage units, such as phase change heat accumulators, in combination with hot water tanks capable of storing the thermal energy of reactor plants during the hours of load decline in the power system, together with an additional steam turbine, it is possible to increase the system efficiency of a nuclear power plant. The presence of an additional turbine unit in emergency situations with a complete blackout of a nuclear power plant makes it possible to ensure the operation of cooling systems by using steam generated by the residual heat of the reactor to drive the turbine. This provides an increase in the NPP safety level and makes it possible to abandon expensive additional passive heat removal systems (PHRS), which leads to a full payback of the costs of the storage system [9, 10]. As a result of additional electricity generation during hours of increased electrical load, additional profit is provided for the nuclear power plant and, thus, the maneuverability and competitiveness of nuclear power plants are significantly increased [11–15].

In addition, due to the tightening of requirements for improving the quality of frequency regulation in the UES of Russia, power units of all types, with the exception of power units with high power channel-type reactors (RBMK) and fast neutron reactors (FNR), should participate in frequency control. Taking into account the difficulties of fulfilling the requirement for the participation of NPPs with water-water energy reactors (VVER) in frequency control due to the low maneuverability of NPP power units (especially the core), leading to the depletion of the resource of the main equipment under variable loads, the authors of [16, 17] proposed a thermal energy storage system (TESS) at NPPs. As a storage medium, a high-temperature coolant (oil) is used, which is heated by the heat released during the condensation of part of the fresh steam during the hours of the night load failure. Heat recovery is carried out by heating the main condensate and feed water during peak hours in special discharge heat exchangers instead of regenerative heating with selective steam, which is directed at this time to increase the turbine power. Such a thermal energy storage system at a nuclear power plant with VVER ensures the participation of the NPP power unit in regulating the frequency of the current in the power system without changing the power of the nuclear reactor [16].

In [18], a technical and economic comparison of the participation of NPPs with alternative options in the regulation of daily electrical load schedules was carried out and the economic efficiency of using thermal energy accumulators at NPPs was shown. It is noted that the given annual costs in the options with heat storage at nuclear power plants and pumped storage power plants are approximately equal, while a comparison of TESS with a pumped storage power plant in terms of material consumption shows a significant advantage of the heat-storage system [18].

Previously, the economic efficiency of projected pumped storage power plants was estimated by the cost of displaced fuel in the power system in comparison with alternative thermal peak power plants and the reduction in annual operating costs. The economic situation of flexible capacities in the energy system, such as a pumped storage power plant, is now determined by market conditions, and, along with the planned supply of electric power and energy to the WECM, technological (system) services have begun to be used as a commodity: frequency and voltage regulation, operational and emergency backup of active power, etc. [19].

In recent decades, due to a change in the structure of generating capacities, the urgency of passing night load dips has increased. In addition, with an increase in the share of power plants operating on renewable energy sources (RES), the problem of coordinating the schedule of electricity consumption and stochastic generation of RES is transferred to traditional energy facilities, which leads to an aggravation of their modes (the time of forced unloading of power units increases, the number of start-stop cycles increases) [20]. In most energy systems, there are no opportunities for both increasing the capacity of existing and building new hydraulic and pumped storage power plants. In this situation, the available highly flexible (regulating) power maintains a balance between consumption and generation, which indirectly affects the quality (frequency) of electricity. High reliability of power supply can only be ensured due to the presence in the power pool of a sufficient reserve of maneuverable power.

It is important to note that a pumped storage power plant with a capacity of approximately 1000 MW or more (namely, such projects are usually considered in the UES of Russia) is a concentrated source of highly flexible power, and its integration into the power system will require a fair amount of network construction. The use of LHTES at nuclear power plants will allow more distributed deployment of flexible capacities in the power system with potential savings in investments in strengthening the network. If LHTES provides additional power of 30–50 MW per power unit, i.e., up to 200 MW for a four-unit nuclear power plant, then the commissioning of five nuclear power plants will make it possible to achieve the same 1000 MW of maneuverable power. However, the increase in maneuverable capac-

ity due to LHTES is limited by the volumes of commissioning of new NPPs. When implementing scenarios for the development of a UES with a high share of RES, additional needs for flexible capacities can reach several gigawatts, and both pumped storage power plants and other electric energy storage systems will be needed to meet such needs.

PRICE ANALYSIS IN THE WHOLESALE MARKET OF ELECTRICITY AND CAPACITY

The price parameters of the wholesale electricity and capacity market have a significant impact on the payback of the thermal-storage system at nuclear power plants. The revenue of the energy complex based on nuclear power plants with heat accumulators at the WECM is formed from the sale of electricity and capacity with a two-part tariff for all zones of the electric load schedule.

Electricity within the price zones of the wholesale electricity and capacity market can be sold at regulated prices under regulated contracts (RC) and at competitive (nonregulated) prices: on the day ahead market (DAM) (1 day before the expected trading), on the balancing market (per day of trading) and within the framework of free bilateral agreements.

Competitive selection of price bids from suppliers and buyers 1 day before the actual supply of electricity with the determination of prices and supply volumes for each hour of the coming day takes place on the market for the day ahead. The competitive selection of price bids and the determination of planned volumes and prices for DAM is based on the solution of the optimization problem according to the criterion of minimizing the cost of electric energy, while the variables to be optimized are the planned volumes of consumed or produced electricity in each node of the calculation model at each hour of the operating day. At the same time, all changes in the level of consumption, network restrictions, and the state of generating equipment cannot be predicted in advance with absolute accuracy. Trading by the volumes of electricity in order to balance the difference between the actual volumes of production or consumption from the planned ones is carried out on the balancing market.

The WECM participant, as a rule, sells the main volume of purchase and sale of electricity on the day-ahead market (74.6% in 2021) [21]. The equilibrium prices obtained as a result of competitive selection in the day-ahead market are determined by a number of factors, including the composition of the generating equipment selected by the system operator to cover the declared energy consumption, including the technical characteristics of the generating equipment, the composition of generating equipment in hot or cold standby, the pricing strategies of wholesale market participants, the structure of energy consumption, and the ratio of supply and demand.

In general, in the UES of Russia, the volume of electricity sold (purchased) under regulated contracts in 2020 amounted to 175.49 billion/(kWh) in the amount of 113.17 billion rubles, the volume of sold (purchased) capacity under these contracts was 559 790 MW in the amount of RUB 94.61 billion. The market volume for the day ahead in 2020 amounted to 818.22 billion/(kW h), and the cost of sold (purchased) electric energy was 868.01 billion rubles. In the balancing market, the volume of sold (purchased) electric energy in 2020 amounted to 55.12 billion/(kW h) in the amount of 54.15 billion rubles [22].

The average annual DAM index in the first price zone in 2020 was set at 1212.13 rubles/(MWh), which is 5.84% lower than in 2019 [1287.32 rubles/(MWh)]. The decrease in the DAM index is due to a decrease in demand (due to the impact of the coronavirus pandemic on the country's economy) as well as an increase in the planned generation of hydroelectric power plants (due to the relatively high water content of rivers) and nuclear power plants (due to the commissioning of new power units). In 2021, the DAM index amounted to 1403.6 rubles/(MW h), an increase of 15.8% due to the recovery of economic activity after the easing of restrictions, as well as an increase in electricity consumption in the central and southern regions of the country in summer 2021 at abnormally high atmospheric air temperatures [21]. In the long term, an increase in the average annual equilibrium price index will be mainly due to an increase in fuel prices (for the first price zone—gas), which is used by thermal power plants (in 2008, the DAM index in the first price zone amounted to 708.28 rubles/(MW h)) [22].

During 2020, the DAM index changed in a wide range. The minimum value of the DAM index for the year was recorded on May 3, 738.87 rubles/(MW h), and the maximum on July 16: 1444.74 rubles/(MW h). Such price dynamics is primarily due to the unevenness of the energy consumption schedule during not only a day but also a year, i.e., cyclical uneven demand with recessions relative to the general trend on weekends and holidays and with a decrease in volumes in the summer months caused by climatic factors as well as selected composition of generating equipment. During the heating period, due to the high proportion of CHPPs, the minimum active power increases, which entails an increase in the price-taking offer, while network and generating equipment is put into repair with the end of the heating season, including hydroelectric power plants and nuclear power plants, which forms a significant part of the price-taking offer. In 2020, the formation of the price annual minimum was also affected by the relatively high level of planned generation of HPPs in the second quarter [22].
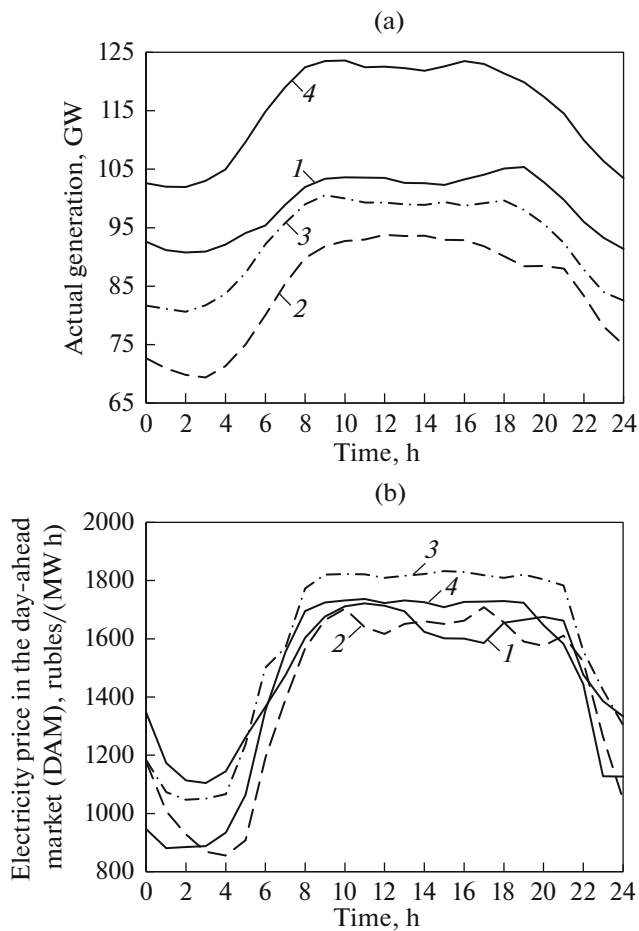
Fig. 1. (a) Actual generation (total for all sectors of the WECM) and (b) electricity price on the day ahead market in the first price zone of the UES (territories of the European part of Russia and the Urals) on characteristic days of 2021 city (data from SO UES): *1*—spring (March 20, 2021); *2*—summer (June 21, 2021); *3*—autumn (September 22, 2021); *4*—winter (December 24, 2021, annual maximum power consumption of the UES)

PRICE DYNAMICS IN THE MARKET FOR THE DAY AHEAD

The price of electricity in the WECM varies depending on the dynamics of consumption during the day and season and other factors. A very high correlation between actual generation and electricity prices on the day-ahead market in the first UES price zone is reflected by the correlation coefficient, which was in the range from 0.940 to 0.967 on typical days in 2021 (Fig. 1).

The coefficient of daily unevenness of generation schedules in the first price zone of the UES on the characteristic days of 2021 varied from 0.740 to 0.862, and that of the density of load schedules varied from 0.901 to 0.938. The minimum price for electricity on the day-ahead market in the first price zone of the UES on typical days in 2021 was 855.9–

1105.0 rubles/(MW h), the maximum was 1708.4–1832.5 rubles/(MW h) (see Fig. 1). The ratio of the maximum to the minimum price for electricity was in the range of 1.56–2.00.

Of particular interest in the light of the topic under consideration is the power system of France with the highest level of installed NPP capacity in the structure of generating capacities. The total installed generating capacity of the French power system in 2021 was 139.1 GW, and the total generation was 522.9 TWh. The structure of installed capacity in France at the end of 2021 is presented below [23]

Total power, GW:	
NPP	61.4
TPP	17.9
Including:	
on gas	12.7
on fuel oil	3.4
on the corner	1.8
HPP	25.7
WPP	18.8
SES	13.1
Share of electricity generation (in 2021), %:	
NPP	69.0
TPP	7.4
HPP	12.0
WPP	7.0
SES	2.7
others	1.9

For the stable operation of the power system, some of the French nuclear power plants operate in base load mode, while others operate in variable mode. An important role in the French energy system is played by gas-fired thermal power plants, hydroelectric power plants, including pumped storage power plants, which provide nuclear power plants with the proper level of load-bearing flexibility. In addition, cross-border electricity supplies contribute to balancing the system. France has been the EU's largest electricity exporter for several years. In 2021, the volume of exports amounted to 86.5 TW h and imports were 42.2 TW h. For example, Swiss pumped storage power plants actively buy electricity from France at night at a low price, after which they sell it during peak hours.

Figure 2 shows graphs of electricity production (total) and spot prices on the day ahead market in France on characteristic days in 2021. The relationship between the price of electricity on the day ahead market and actual generation in France is moderate—the correlation coefficient on characteristic days in 2021 was from 0.333 to 0.726, which is explained by the

influence of stochastic generation based on renewable energy sources on the price of electricity.

The coefficient of daily unevenness of generation schedules in the power system of France on typical days in 2021 varied from 0.763 to 0.890, the density of load schedules varied from 0.910 to 0.947. The minimum price for electricity on the day-ahead market in France on typical days in 2021 was 43.1−108.8 euros/(MW h) and the maximum was 77.7−307.7 euros/(MW h) (see Fig. 2). The ratio of the maximum price of electricity to the minimum was in the range of 1.5−1.8.

Since the second half of 2021, prices for fossil fuels (gas, oil) in Europe have risen sharply, which has led to higher electricity prices. At the same time, European electricity prices are strongly correlated with its production at wind farms. In [24], the price consequences of implementing the policy of stimulating generation based on renewable energy sources in the countries of the European Union are considered. It is shown that the intensive introduction of RES, characterized by extremely low variable costs, has led to a decrease in spot (wholesale) electricity prices in most European countries and exacerbated the problem of "negative" spot prices. Moreover, there are more and more periods of negative prices, regardless of the main price dynamics. For example, in France, historical price increases in 2021 were accompanied by a large number of hourly intervals during which the spot electricity price turned negative: 64 h in 2021 (compared to 27 h in 2019) [23]. These factors have led to the fact that the ratio of the maximum price of electricity to the minimum in France on some days could be 3.5.

ASSESSING THE IMPACT OF THE OPERATION OF AN NPP POWER UNIT WITH A THERMAL ENERGY STORAGE SYSTEM ON THE WHOLESALE ELECTRICITY AND CAPACITY MARKET

Introduction into the wholesale market of electricity and capacity of an energy complex based on nuclear power plants with systemic thermal storage, along with obvious advantages for both the WECM participants and the operating organization (compliance with the requirements of SO UES on the operating modes of power plants, expanding the range of NPP maneuvering while maintaining the basic operating mode of the reactor plant, increasing the reliability and safety of the functioning of the electric power system, etc.), will lead to the following technical and economic consequences: the main volume of NPP electricity under existing conditions will be sold on the market a day ahead, commissioning of a new NPP power unit in conditions of practically unchanged consumption and supply on the wholesale electricity and capacity market will lead to a decrease in the sale price of electricity. The use of the maneuverability of nuclear power plants with a thermal-storage system will cause a change in electricity prices in the WECM
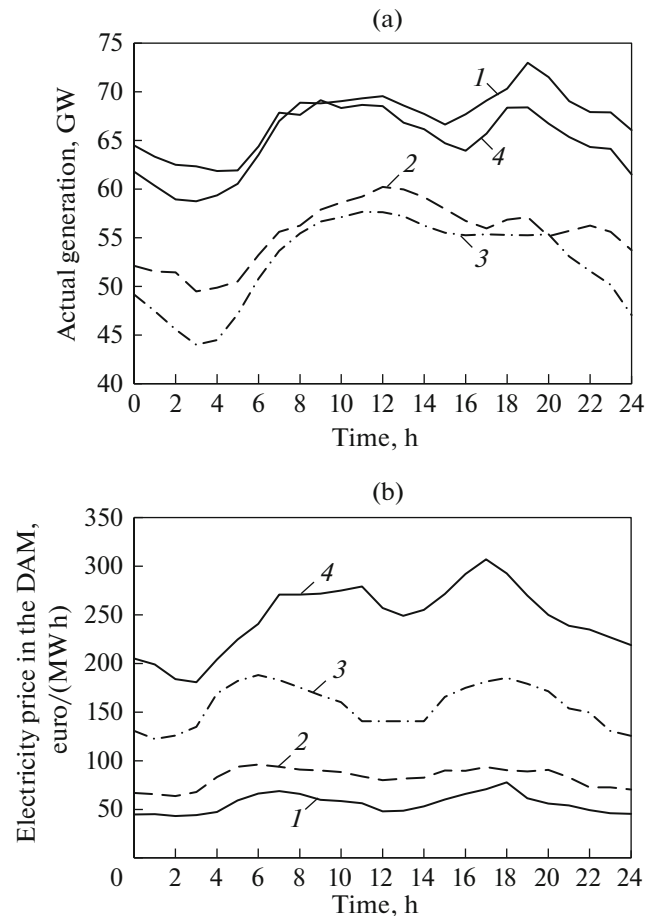
Fig. 2. (a) Power generation and (b) spot prices for electricity in the day-ahead market in France in 2021 (data from Energy-Charts): *1*—spring (March 16, 2021); *2*—summer (June 22, 2021); *3*—autumn (September 17, 2021); *4*—winter (December 8, 2021)

during the day: the price of electricity will decrease during the day, while it will increase at night [25].

In [26], using the example of the project of power unit no. 1 of Novovoronezh NPP-2 with the TESS option, it was shown that the commissioning of a new NPP power unit with VVER-1200 (excluding TESS) under conditions of almost unchanged consumption and supply at the WECM led to a decrease in the sale price of electricity in the day-ahead market in the group of NVNPP supply points in September 2015 by 16.51 rubles/(MW h) and in the first price zone by 10.28 rubles/(MW h). The use of the maneuverability of the power unit with STS (load-carrying mode: 75% at night, 110% peak hours of the rated power, 80% storage efficiency) will entail an increase in the price of electricity in the region by 1.35 rubles/(MW h) and in the first price zone by 0.31 rubles/(MW h) (i.e., it will partially "win back" the reduction in electricity prices). The increase in the price of electricity in the region when using the maneuvering capabilities of NPP + STS (compared to the operation of NPPs
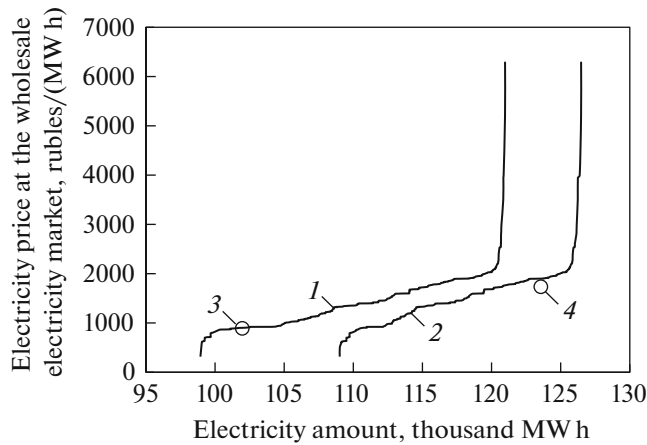
Fig. 3. Price bids for the sale of electricity on the WECM in the first price zone on December 24, 2021 at (*1*) 2:00 a.m., minimum daily generation and at (*2*) 10:00 a.m., maximum daily generation (data from ATS-Energo) and (*3, 4*) actual DAM indices for actual generation in all sectors of the WECM (data from SO UES).

without STS) at night will be 2.29 rubles/(MW h), and its decrease in the daytime is 0.93 rubles/(MW h).

In 2015, the equilibrium price index on the day-ahead market in the Voronezh region amounted to 1213 rubles/(MW h), and the DAM index in the first price zone was 1153.29 rubles/(MW h). Thus, the commissioning of a new nuclear power unit with a VVER-1200 led to a decrease in the price of electricity by 1.36% in the region and by 0.89% in the first price zone (relative to the average annual price), and the use of a nuclear power plant with a heat-storage system led to an increase in the price by 0.11% in the region (up 0.19% overnight and down 0.08% during the day) and 0.03% in the first price zone.

In addition, the operation of the NPP power unit with a thermal energy storage system ensures the participation of the nuclear power plant in the primary and secondary frequency control and also helps to reduce costs in the power system with the maximum demand for electricity [27–29].

The use of consumers-regulators in the power system, which include the pumped storage power plant, leads to the alignment of the power consumption schedule in the power system, a decrease in the night dip in electrical loads, which directly contributes to an increase in night tariffs. At the same time, the level of increase in night tariffs will be determined by the growth in the relative share of night power consumption. Such conditions for the proportion of pumped storage power plants using "night" electricity during the charging period will lead to a decrease in their efficiency.

It is possible to estimate the change in prices on the day-ahead market with an alternative option—the construction of a pumped storage power plant—based on price bids for the sale of electricity in the WECM

(Fig. 3). During the hours of minimum load, the PSP works in pumping mode, storing energy, the generation of power plants in the energy system increases and, accordingly, the sale price of electricity increases. During peak hours when the pumped storage power plant operates in generator mode, the total generation of the remaining power plants decreases and the sale price of electricity decreases. As a result of the calculations, it was determined that with a power plant capacity of 300 MW in pumping mode and 225 MW in turbine mode, the increase in the price on the day-ahead market in the first price zone on December 24, 2021, during the hours of minimum daily generation (at 2:00 a.m.) was 3.98 rubles/(MW h), and the decrease in the price of the DAM during the hours of maximum daily generation (at 10:00 a.m.) was 1.23 rubles/(MW h). With the DAM index in 2021 1403.6 rubles/(MW h), such operation of the pumped storage power plant will lead to an increase in the price of electricity by 0.28% at night and its decrease by 0.09% during peak hours.

Unlike consumers-regulators, thermal accumulation only leads to a decrease in the electric power of the NPP during the passage of the night minimum and does not have any effect on the configuration of the electric load schedule. The increase in the night tariff in this case can only be caused by the redistribution of the load between the power generators and will depend on the structure of the generating capacities for each power system.

EVALUATING THE OPTIMAL MODE OF OPERATION OF THE NPP POWER COMPLEX BASED ON PHASE-TRANSITION BATTERIES IN THE POWER SYSTEM

The efficiency of using a storage system with LHTES at NPPs depends on a large number of factors, including external ones. It is of particular interest to evaluate their efficiency and payback under conditions when, for some reason, it is difficult or impossible to implement their multifunctional properties (improving safety, NPP participation in primary frequency control). The determining factor in this case will be the difference in prices for electricity supplied from a generating source during periods of high and low demand. Based on the data presented in Fig. 1b, the difference between the average (during the LHTES discharge time) price for "peak" electricity and the average (during the LHTES charging time) price for "failure" (night) electricity on the day-ahead market in the first price zone of the UES on typical days of 2021 is calculated (Fig. 4).

In [30], as applied to an existing nuclear power plant with a capacity of 670 MW in the United Kingdom, an energy-management system was proposed for the operation of a nuclear power plant in variable mode, based on a thermal energy storage device with a phase change accumulator and an additional installa-

tion with an organic Rankine cycle. The economic viability of the proposed energy complex was analyzed taking into account hourly prices in the United Kingdom on the wholesale electricity market in 2019 and 2021. It was concluded that such an energy complex can be economically profitable if the fluctuations in the average "peak" and "night" electricity prices are at least two times greater than those that took place in the United Kingdom market in 2019 (data for 2021 are close to this ratio) and the duration of the heat-storage discharge exceeds 2 h or the charge or discharge cycle is performed more than once a day.

With the participation of one of the authors of this article, a scheme was developed and patented for combining a thermal-storage system with a double-circuit nuclear power plant based on phase-change batteries and an additional low-power turbine [31]. During the night hours when the electrical load falls, part of the fresh steam from the steam generators is sent to the LHTES charging, and the fresh steam condensate after the LHTES enters the feed water path of the main steam turbine. In the peak load mode, when the battery is discharged, part of the feed water after the high-pressure heaters is supplied to the LHTES and then mixed with the feed water in the main path. Due to the increase in the temperature of the feed water at the inlet to the steam generators at the same reactor power, an excess of live steam is generated, which is directed to an additional steam turbine plant (STP).

For these purposes, LHTES with phase-change material (PCM) 59% $NaOH$ + 41% $NaNO_3$ can be used. PCM melting point is 266°C, heat of phase transition is 278 kJ/kg, density is 1910 and 2150 kg/m^3, and heat capacity is 1.85 and 1.65 kJ/(kg K) in liquid and solid state, respectively. To ensure the possibility of operation of the multifunctional thermal-storage system in the VVER-1000 thermal scheme with the participation of the author of this article, the design of a heat accumulator with a phase-transition material was developed and patented [32]. A bundle of metal heat-exchange tubes is located vertically inside the battery case, through which the coolant flows (condensate from fresh steam during charging or a steam-water mixture formed during battery discharge). The staggered arrangement of the LHTES tube bundle and the longitudinal finning of the heat-exchange tubes are chosen. It should be noted that since the volume of the material changes when the aggregate state changes, a cavity filled with air is provided in the body of the phase-transition accumulator. In the lower part of the case, there is a lower collector designed for uniform distribution of the main coolant flow through the heat-exchange metal tubes during discharge hours and for collecting condensate during battery charging. Installing a separator drum in the upper part of the heat-accumulator structure allows one to dry the accumulated steam generated in the heat-exchange tubes (if it is only necessary to heat the coolant, it is
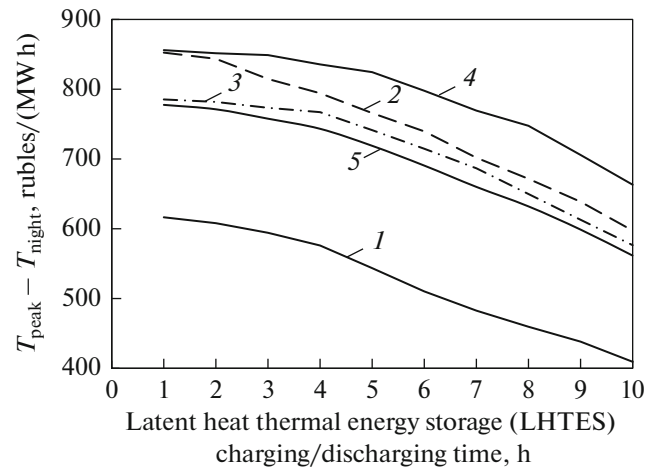
Fig. 4. Peak difference T_{peak} and night T_{nights} of electricity tariffs (average value for the time of discharging and charging LHTES) on the day-ahead market in the first price zone of the UES, depending on the time of LHTES charging on typical days in 2021: *1*—spring (March 20, 2021); *2*—summer (June 21, 2021); *3*—autumn (September 22, 2021); *4*—winter (December 24, 2021); *5*—average in 2021 (by 4 days).

rational to replace the separator drum with an upper distribution manifold).

The cost of PCM is \$1.8/kg (135 rubles/kg), including the cost of the material itself, delivery, customs payments, etc., and the weight is 1586 t [9]. In the calculations, the aging of the phase change material was taken into account as an annual decrease in additional generation by 0.3%. The estimate of the full cost of the LHTES included the cost of the metal structure of the body with thermal insulation (3.749 million rubles), the heat-exchange surface with distribution manifolds (63.750 million rubles), additional auxiliary equipment (such as process equipment, measuring devices, shut-off valves, etc.), delivery of components to the place of operation, installation of all technical units with subsequent start-up (accepted as + 100% of the cost of the body and heat exchangers: 67.500 million rubles), and PCM (214.110 million rubles) [9].

The power of the additional steam turbine is determined depending on the discharge time of the LHTES during the hours of peak electrical loads in the power system (the shorter the discharge time, the higher the power of the STP should be with the same energy stored in the LHTES). The calculation of specific capital investments (thousand rubles/kW) in an additional steam turbine of various capacities was carried out based on the approximation of data on the cost of typical equipment using a power law $k_{sp} = 45.082N^{-0.11}$, where N is the turbine power, MW [14]. The cost of the turbine condenser was taken as equal to 7% of the cost of the turbine, the cost of delivery and installation
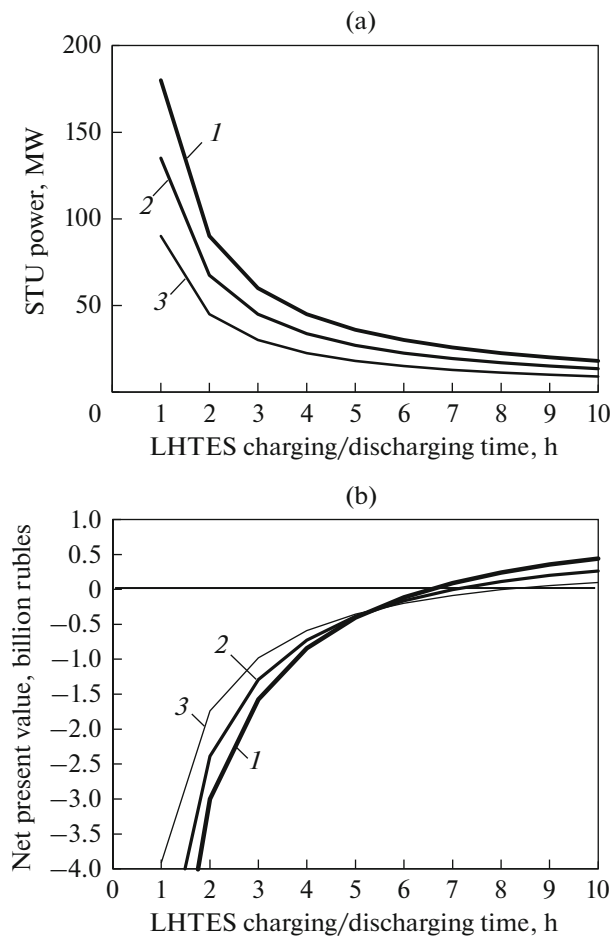
Fig. 5. Required power of the (a) additional steam turbine plant and (b) accumulated net present value depending on the LHTES charging or discharging time when implementing an accumulation system of various capacities. Energy generated during peak hours, MW h: *1*—180; *2*—135; *3*—90.

was 25%, the cost of modernizing the electrical economy and the automatic control system was $87/kW (6.525 thousand rubles/kW), and capital investments in the construction of the premises was 20% of the total costs on the thermal-storage system [9].

The calculations were carried out in real terms, the discount rate was assumed to be 10%. The calculation horizon is 25 years. The annual semifixed costs for the thermal-storage system are assumed to be 15 million rubles/year. Efficiency of the thermal-storage system, equal to the ratio of the amount of electricity released when the battery is discharged to the amount of electricity not generated due to steam extraction for battery charging, for the adopted system was 0.9. The decrease in NPP power during LHTES charging, for example, for 5 h during the night load failure in the power system will be 40 MW, and the increase in power complex power (due to an additional steam turbine) during the peak period for 5 h will be 36 MW. At the same time, the installed capacity utilization factor of NPPs (in all considered options) will decrease from

83.89% (in the calculations of the capacity factor of the NPP, it is taken as the average for the UES of Russia in 2021) to 83.73%.

Calculations of technical and economic indicators of the use of LHTES-based thermal energy accumulators at NPPs showed the following: with the existing difference in electricity prices during peak and night periods at DAM (see Fig. 4), the payback of the technical solution is not ensured (net present value is negative in all options). For both LHTESs and other capital-intensive types of batteries (e.g., pumped storage power plants), the difference in electricity prices during night and peak hours should be more significant in order to recoup investments in measures to increase the flexibility of the power system through storage systems.

The results of calculations of the technical and economic indicators of the use of LHTES-based thermal energy accumulators at NPPs with an increase in the difference in prices (averaged over a billing period of 25 years) for electricity in peak and night periods up to 3400 rubles/(MW h) are given in Table 1. In this case, the return on investment will be achieved with an LHTES charge or discharge time of more than 7 h per day. It follows from Table 1 that, despite the fact that the largest additional revenue from the sale of electricity will be at the time of charging or discharging LHTES 1 h (the maximum difference in electricity prices during peak and night hours)—due to the high capital investment in an additional steam turbine—this option is the least efficient. The most efficient option is with LHTES charging or discharging for 10 h and the power of an additional STP of 18 MW.

Figure 5 presents the results of calculating the technical and economic indicators of the use of LHTES at nuclear power plants with a change in the capacity of thermal energy accumulators. Calculation results for option one (curve *1*) with a mass of PCM of 1586 t and electricity generated during peak hours of 180 MW h are presented in Table 1, in options two and three (curves *2* and *3*), LHTES capacity is reduced by 25 and 50%, respectively. At the same time, the mass of PCM is 1189.5 and 793 t, capital investments in the LHTES are 264.520 and 178.995 million rubles, and the peak energy generated is 135 and 90 MW h. The capacity factor of nuclear power plants in options two and three will decrease to 83.84 and 83.86%, respectively. It can be seen in Fig. 5 that the largest net discounted income in options two and three will also be obtained with a charge or discharge time of 10 h.

The economic efficiency of an energy complex based on a nuclear power plant with phase-change batteries depends on the duration of LHTES charging or discharging: with a longer LHTES charging or discharging time, it becomes possible to install an additional steam turbine with less power and, accordingly, a lower price; with shorter charging/discharging cycles of the phase change heat accumulators, a large differ-

Table 1. Results of calculations of technical and economic indicators of the use of thermal energy accumulators based on phase-transition accumulators at nuclear power plants

Index	LHTES charging or discharging time, h									
	1	2	3	4	5	6	7	8	9	10
Power of additional STP, MW	180	90	60	45	36	30	25.7	22.5	20	18
Specific capital investments in additional STU, thousand rubles/kW	25.5	27.5	28.7	29.7	30.4	31.0	31.5	32.0	32.4	32.8
NPP power reduction at night to charge LHTES, MW	200	100	66.7	50	40	33.3	28.6	25	22.2	20
Capital investments in the thermal-storage system (total), billion rubles	9.185	5.094	3.656	2.914	2.458	2.147	1.923	1.751	1.617	1.508
Including:										
in LHTES	0.349	0.349	0.349	0.349	0.349	0.349	0.349	0.349	0.349	0.349
in vocational schools	6.130	3.308	2.306	1.785	1.464	1.244	1.085	0.963	0.867	0.790
in the modernization of electrical facilities and control system	1.175	0.587	0.392	0.294	0.235	0.196	0.168	0.147	0.131	0.117
in the construction of premises	1.531	0.849	0.609	0.486	0.410	0.358	0.320	0.292	0.269	0.251
Decrease in revenue from the sale of overnight (failed) electricity, million rubles/year	60	60	60	61	62	64	66	67	69	71
Revenue from the sale of additional peak electricity, million rubles/year	232	232	231	231	230	230	229	229	229	228
Additional revenue, million rubles/year	172	172	171	170	168	166	163	162	160	157
Net present value, billion rubles	−7.086	−3.000	−1.575	−0.844	−0.405	−0.114	0.090	0.242	0.355	0.438

ence in electricity prices during peak and night hours can be used. The results obtained indicate the need to determine the rational power of an additional steam turbine for a given PCM mass as well as the optimal duration of battery charge or discharge cycles that provide the highest economic effect at current electricity prices in the power system.

CONCLUSIONS

(1) With an increase in the share of nuclear power plants in the energy systems of the European part of Russia and the current shortage of maneuverable capacities, it becomes necessary to involve nuclear power plants in covering the uneven part of the load schedule. Combining nuclear power plants with phase-change batteries makes it possible to accumulate thermal energy generated at night and use it during peak hours to generate electricity with the maximum use of nuclear fuel, i.e., without changing the power of the nuclear reactor.

(2) The impact of the operation of a nuclear power plant with a thermal energy storage system on the WECM was assessed. Thermal storage, unlike con-

sumers-regulators, leads only to a decrease in the electric power of the NPP during the passage of the night minimum and does not have any effect on the configuration of the electric load schedule. An increase in the night tariff can only be caused by a redistribution of the load between power generators and in each power system will depend on the structure of its generating capacities.

(3) It has been established that, with the existing difference in prices for electricity generated during peak and night periods, on the day-ahead market, the payback of the NPP energy complex based on phase-change batteries is not ensured. The return on investment in the latent heat thermal energy storage and an additional turbine in the considered example can be achieved if the difference between the average—for the 25-year period considered in the analysis—prices for electricity generated during peak and night hours [3400 rubles/(MW h)] and the charging or discharging time of the LHTES is more than 7 h per day.

(4) As a result of technical and economic calculations, the optimal mode of operation of the NPP power complex based on phase-change batteries in the power system was determined. It is shown that for the

accepted initial conditions, the highest net discounted income when implementing the accumulation system in the first price zone of the UES is achieved when the phase-transition accumulator charging or discharging time is at least 10 h.

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REFERENCES

1. F. V. Veselov and A. A. Khorshev, "Optimal scale of development of nuclear energy in the UES of Russia to 2050," At. Energy **128**, 259−264 (2020).

2. E. O. Adamov, D. A. Tolstoukhov, S. A. Panov, F. V. Veselov, A. A. Khorshev, and A. I. Solyanik, "Role of NPPs in the Russian electricity industry taking into account carbon emissions limits," At. Energy **130**, 127−135 (2021).

3. A. A. Al Kindi, M.Aunedi, A. M. Pantaleo, G. Strbac, and C. N. Markides, "Thermo-economic assessment of flexible nuclear power plants in future low-carbon electricity systems: Role of thermal energy storage," Energy Convers. Manage. **258**, 115484 (2022).
https://doi.org/10.1016/j.enconman.2022.115484

4. C. W. Forsberg, "Variable and assured peak electricity production from base-load light-water reactors with heat storage and auxiliary combustible fuels," Nucl. Technol. **205**, 377−396 (2019).
https://doi.org/10.1080/00295450.2018.1518555

5. C. Forsberg, S. Brick, and G. Haratyk, "Coupling heat storage to nuclear reactors for variable electricity output with baseload reactor operation," Electricity **31** (3), 23−31 (2018).
https://doi.org/10.1016/j.tej.2018.03.008

6. V. M. Borovkov and A. V. Kushakov, "Improvement of NPP flexibility by means of energy accumulators," Izv. Vyssh. Uchebn. Zaved., Probl. Energ., No. 5−6, 135−139 (2010).

7. F. Carlson and J. H. Davidson, "On the use of thermal energy storage for flexible baseload power plants: Thermodynamic analysis of options for a nuclear Rankine cycle," J. Heat Transfer **142**, 052904 (2020).
https://doi.org/10.1115/1.4045230

8. F. Carlson, J. H. Davidson, N. Tran, and A. Stein, "Model of the impact of use of thermal energy storage on operation of a nuclear power plant Rankine cycle," Energy Convers. Manage. **181**, 36−47 (2019).
https://doi.org/10.1016/j.enconman.2018.11.058

9. R. Aminov, V. Yurin, and M. Murtazov, "Efficiency and economic assessment of combining nuclear power plants with multifunctional heat accumulation systems," Int. J. Energy Res. **45**, 12464−12473 (2021).
https://doi.org/10.1002/er.6580

10. R. Z. Aminov, "Application of multifunctional systems with latent heat thermal energy storages: A way to improve NPP safety and efficiency," Therm. Eng. **69**, 555−562 (2022).
https://doi.org/10.1134/S0040601522080018

11. F. Carlson and J. H. Davidson, "Nuclear power coupled with thermal energy storage: Impact of technical performance on economics in an exemplary electricity grid," ASME Open J. Eng. **1**, 011006 (2022).
https://doi.org/10.1115/1.4053419

12. F. Carlson and J. H. Davidson, "Parametric study of thermodynamic and cost performance of thermal energy storage coupled with nuclear power," Energy Convers. Manage. **236**, 114054 (2021).
https://doi.org/10.1016/j.enconman.2021.114054

13. M. Ali, A. K. Alkaabi, S. A. Alameri, and Y. Addad, "Overall efficiency analysis of an innovative load-following nuclear power plant-thermal energy storage coupled cycle," Int. J. Exergy **36**, 98−122 (2021).
https://doi.org/10.1504/IJEX.2021.117606

14. M. A. Murtazov, *High-Potential Thermal Energy Storage-Based Improvement of NPP System Efficiency*, Candidate's Dissertation in Engineering (Saratov State Technical Univ., Saratov, 2022).

15. N. I. Abrosimova and M. M. Kaverznev, "About the competitiveness of a thermal energy storage system as a way of setting up the NPP load following mode," Vestn. MEI, No. 5, 57−62 (2016).

16. V. V. Bazhanov, I. I. Loshchakov, and A. P. Shchuklinov, "Investigation of the possibility of using thermal energy accumulators at nuclear power plants in current frequency regulation in the power network," Izv. Vyssh. Uchebn. Zaved., Yad. Energ., No. 4, 29−36 (2013).

17. V. V. Bazhanov, I. I. Loshchakov, and A. P. Shchuklinov, "Study of NPP operation with thermal energy accumulators in turbine power regulation at discharge mode," Nauchno-Tekh. Vedomosti SPbGPU, No. 4 (231), 47−58 (2015).

18. A. E. Vlasov, M. E. Voronkov, M. Z. Krivoshei, Yu. A. Mostovoi, and V. M. Chakhovskii, "Design of the first cycling nuclear power station with heat storage," At. Energ. **62**, 343−350 (1987).

19. V. Yu. Sinyugin, V. I. Magruk, and V. G. Rodionov, *Pump-Storage Power Plants in State of the Art Power Engineering* (ENAS, Moscow, 2008) [in Russian].

20. S. A. Nekrasov, "Reducing costs for integration of renewable energy sources: A way to making renewable energy more accessible," Therm. Eng. **68**, 593−603 (2021).
https://doi.org/10.1134/S00406015521070077

21. 2021 Year Report of "NP Market Council" Association.
https://www.np-sr.ru/sites/default/files/1_go_.pdf

22. 2020 Year Report of SC "Admistrator of the Trade System of the Wholesale Market of Electricity".
https://www.atsenergo.ru/sites/default/files/reportdocs/2021/06/go_ats_2020.pdf

23. Le Fonctionnement du Système Électrique en 2021.
https://bilan-electrique-2021.rte-france.com/wp-content/uploads/2022/06/Note-BILAN-ELECTRIQUE-Vfinale.pdf

24. F. V. Veselov, A. A. Khorshev, and A. I. Solyanik, "Impact of renewable generation on the level of wholesale and retail prices on electricity in European countries," Energ. Rubezhom, No. 2, 20−30 (2021).

25. N. I. Abrosimova, *Optimization of Parameters and Operating Regimes of a "Nuclear Power Plant + Thermal Energy Accumulation System" Energy Complex*, Candi-

date's Dissertation in Engineering (Moscow Power Engineering Inst., Moscow, 2016).

26. N. I. Abrosimova, "Assessment of the impact of the commissioning of power unit VVER-1200 with the system of accumulation of thermal energy on the wholesale market of electricity and capacity," Vestn. MEI, No. 3, 16−22 (2016).

27. B. Flamm, A. Eichler, R. S. Smith, and J. Lygeros, "Price arbitrage using variable-efficiency energy storage," J. Phys.: Conf. Ser. **1343**, 012060 (2019).
https://doi.org/10.1088/1742-6596/1343/1/012060

28. D. Connolly, H. Lund, P. Finn, B. V. Mathiesen, and M. Leahy, "Practical operation strategies for pumped hydroelectric energy storage (PHES) utilizing electricity price arbitrage," Energy Policy **39**, 4189−4196 (2011).
https://doi.org/10.1016/j.enpol.2011.04.032

29. B. Zakeri and S. Syri, "Value of energy storage in the Nordic Power market — Benefits from price arbitrage and ancillary services," in *Proc. 13th Int. Conf. on the European Energy Market (EEM), Porto, Portugal, June 6−9, 2016* (IEEE, Piscataway, N.J., 2016), pp. 1−5.
https://doi.org/10.1109/EEM.2016.7521275

30. P. Romanos, A. A. A. Kindi, A. M. Pantaleo, and C. N. Markides, "Flexible nuclear plants with thermal energy storage and secondary power cycles: Virtual power plant integration in a UK energy system case study," e-Prime - Adv. Electr. Eng., Electron. Energy **2**, 100027 (2022).
https://doi.org/10.1016/j.prime.2021.100027

31. R. Z. Aminov, V. E. Yurin, and M. A. Murtazov, "A method of increasing power and improving safety of a power unit of a NPP with a VVER-type reactor based on thermal energy accumulation," RF Patent No. 2680380, MPK G21D 5/00, Byull. Izobret. No. 5 (2019).

32. R. Z. Aminov, V. E. Yurin, and M. A. Murtazov, "Thermal energy accumulator with phase-transient material," RF Patent No. 179855, MPK F24H 7/00, Byull. Izobret. No. 16 (2018).