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MATHEMATICAL MODEL OF NPP UNITS POWER GENERATON TO SOLVE THE PROBLEMS OF UKRAINIAN POWER SYSTEM DEVELOPMENT

Abstract: A mathematical model is offered for production processes implemented at NPPs of SE NNEGC "Energoatom", which is suitable for predicting the monthly dynamics of electricity generation volumes by power units in various scenario conditions for the development of nuclear power generation.

Keywords: system, model, NPP, long-term forecasting.

Introduction

Currently, a comprehensive analysis of various scenarios for the development of power systems is carried out using computer systems for energy modeling and an increasing number of the researchers around the world is involved in the development of them [1-2]. Sufficiently complete and adequate mapping of a set of interrelated processes in mathematical models of energy systems allows us to formulate and solve complex problems of the development of such systems by conducting computational experiments.

Modern systems of modeling of electric power industry of Ukraine are developed on the basis of mathematical models of decentralized control of interrelated processes of production, transmission, distribution and consumption of electric energy [3-4]. The completeness and adequacy of such models is achieved by reflecting in them the characteristic features of the behavior of the main participants of the electric energy market and the production processes that are under their control.

NNEGC "Energoatom" is the largest producer of electricity in Ukraine and, therefore, plays a special role in the electricity market. As an integral part of the modeling system of the electric power industry of Ukraine, the mathematical model of the generation processes implemented at the NPPs of this company should be suitable for predicting the monthly dynamics of the volumes of electricity generation by NPP units in various scenario conditions for the development of the country's nuclear power industry.

Below the model of the state enterprise NNEGC “Energoatom” is presented, which satisfies the requirement stated above. The model was developed on the basis of a comprehensive analysis of the available data on the installed capacities of power units [5], the volumes of electricity generation by them [6–9], the frequency and duration of previously completed major and intermediate maintenance of the main equipment of NPPs [10–17].

1. Model of production processes at nuclear power plants

The utilization rate of the installed capacity C_h^{UR} of the power unit h is an integral indicator of the efficiency of the safe production of electricity on it [18]. At an arbitrary time t, the value of this coefficient is determined by the ratio of the volume of electricity

$$S_h = S_h(t, \Delta t) = \int_{t-\Delta t}^{t} g_h(\tau) d\tau, \quad (1)$$

generated over the reporting period Δt, to the volume of its output by the installed capacity for the same period of time, i.e.

$$C_h^{UR} = C_h^{UR}(t, \Delta t) = S_h(t, \Delta t)/(G_h \Delta t), \quad (2)$$

where $g_h(\tau)$ and G_h are the capacities of the unit h, respectively, developed at the time $\tau \in [t - \Delta t, t]$ and installed.

From the definition (2) follows the equation

$$S_h(t, \Delta t) = C_h^{UR}(t, \Delta t) G_h \Delta t, \quad (3)$$

which can be used for predictive estimates of the volumes of electricity generation $S_h(t, \Delta t)$ if the function $C_h^{UR}(t, \Delta t) \in [0, 1)$ can be predetermined.

As a result of the research [18], it was established that the frequency and duration of preventive and predictive maintenance (hereafter referred to as PPM), i.e. the planned organizational and technical measures to check and restore the availability and service life of the systems, equipment and individual components of the power units, have a decisive influence on the behavior of functions of the type $C_h^{UR}(t, \Delta t)$. According to the reports of the current state of operational safety of nuclear power plants in Ukraine with VVER-1000, the contribution of scheduled maintenance of power units to the overall decrease in the $C_h^{UR}(t, \Delta t)$ function values reaches 84%. The rest of the decrease in the values of this function is due to unplanned outages, load reductions, violations of the units operation, accidents and other factors.

Therefore, the utilization ratio of the installed capacity $C_h^{UR}(t, \Delta t)$ of the power unit h can be decomposed into two factor multipliers and represented as

$$C_h^{UR}(t, \Delta t) = C_h^{PM}(t, \Delta t) C_h^{OS}(t, \Delta t), \quad (4)$$

where $C_h^{PM}(t, \Delta t)$ is the capacity reduction coefficient as a result of the implementation of the strategy of PPM, and $C_h^{OS}(t, \Delta t)$ is the capacity reduction ratio due to the performance of the current maintenance works and operational service.

The formation of plans for the implementation of maintenances of NPP power units is carried out on the basis of diagnostic models that implement various methods for analyzing the technical condition of equipment, as well as models for optimizing the processes of preparing and performing of PPM [18-19]. Such approaches to the formation of plans for the implementation of maintenance work are scientifically based and are regularly used in practice. As a rule, their usage has a very limited planning horizon - most often from one year to four years [20], less often up to ten years [21].

To draw up long-term maintenance plans and, as a result, determine the $C_h^{PM}(t, \Delta t)$ functions, it is suggested to use a generalized model of production processes related to the diagnostics of the state of systems, equipment and components of the power unit and optimization solutions to restore their performance. The basis for building a generalized model is the start and end dates of maintenances carried out in previous years.

Let us estimate the periods (time between the initial dates of two consecutive equipment maintenances) $T_{с}$ and $T_{к}$, as well as the duration $d_{с}$ and $d_{к}$ of intermediate and major maintenances of the main equipment of nuclear power plants in Ukraine. To do this, we use the annual schedules for such maintenances at each NPP power unit for the eight-year period from 2011 to 2018 [10–17].

The minimum, maximum and average values of the periods and durations of maintenance companies are presented in tables 1 - 2. Here, the average values of $\bar{T}_{с}$, $\bar{T}_{к}$, $\bar{d}_{с}$, $\bar{d}_{к}$ characterize the sets of values $\{T_{с}\}$, $\{T_{к}\}$, $\{d_{с}\}$, $\{d_{к}\}$, moreover, values such that are not significantly different from each other and, therefore, are representative for the corresponding sets.

Note that the alternation of intermediate and major maintenances of each NPP power unit occurs sequentially in time according to the scheme $3(с) + 1(к)$ [18]. Due to the limitedness of the analyzed set of maintenance companies conducted from 2011 to 2018, for the separately considered power unit, we have no more than two values of the periods $T_{к}$ and durations $d_{к}$ of major maintenances, which makes it difficult to estimate their average values $\bar{T}_{к}$ and $\bar{d}_{к}$. Therefore, the formal averaging of the sets of the values $\{T_{к}\}$ and $\{d_{к}\}$ is carried out in cases where such values are close. In other cases, the average values of $\bar{T}_{к}$ and $\bar{d}_{к}$ are estimated by the totality of values from the sets $\{T_{к}\}$ and $\{d_{к}\}$ and by close values from the sets from $\{T_{с}\}$ and $\{d_{с}\}$, respectively.

Table 1.

Duration of maintenance, day

Name of NPP	Unit number	Intermediate maintenance			Major maintenance		
		$d_{с}^{\min}$	$d_{с}^{\max}$	$\bar{d}_{с}$	$d_{к}^{\min}$	$d_{к}^{\max}$	$\bar{d}_{к}$
Zaporizhzhya	1	60	107	88	60	107	88
	2	76	114	95	76	114	97
	3	52	114	77	74	75	75
	4	52	86	70	72	86	79
	5	60	104	77	60	107	78
	6	52	104	69	75	96	86
South Ukraine	1	52	95	69	50	90	70
	2	64	120	86	64	120	75
	3	57	153	106	57	153	98
Rivne	1	45	78	54	55	72	64
	2	45	72	55	55	85	70
	3	62	66	64	62	85	69
	4	52	52	52	65	65	65
Khmelnytska	1	49	67	55	85	96	91
	2	52	66	58	80	80	80

Table 2.

Periods of maintenance, days

Name of NPP	Unit number	Intermediate maintenance			Major maintenance		
		$T_{с}^{\min}$	$T_{с}^{\max}$	$\bar{T}_{с}$	$T_{к}^{\min}$	$T_{к}^{\max}$	$\bar{T}_{к}$
Zaporizhzhya	1	378	414	395	378	414	403
	2	373	434	405	373	475	423
	3	389	412	398	364	373	369
	4	363	392	381	396	428	412
	5	335	454	378	335	526	403
	6	360	410	397	351	432	392
South Ukraine	1	296	565	393	296	565	387
	2	360	440	383	327	440	371
	3	358	513	430	358	513	434
Rivne	1	358	566	385	358	425	381
	2	353	401	376	353	434	386
	3	403	416	409	403	527	432
	4	316	432	389	355	412	384
Khmelnytska	1	362	507	434	395	463	429
	2	316	419	377	371	377	374

Within the average values of $\bar{T}_{с}$, $\bar{T}_{к}$, $\bar{d}_{с}$, $\bar{d}_{к}$, for each power unit h, it is possible to make the projected schedules for the implementation of intermediate and major maintenances with indication of the calendar dates of the beginning and the end of maintenance in the long term. In particular, we have compiled a sequence of schedules for the implementation of PPM under the $3(с) + 1(к)$ alternation scheme for the forecast period 2019-2040, originating from a maintenance company approved by the Ministry of Energy and Coal Industry of Ukraine in 2018 year [10].

Note that the sequence of schedules of maintenance execution must be formed with a daily step D fixing the planned events in time t. In this case, you can define integer values $C_h^{PM}(t_D, \Delta t_D) \in \{0,1\}$ of functions $C_h^{PM}(t, \Delta t)$ on a discrete set t_D of time t with an estimated period Δt_D, equal to the day.

The sets of actual values $\{T_{с}\}$, $\{T_{к}\}$, $\{d_{с}\}$, $\{d_{к}\}$, calculated from the start and end dates of maintenance companies that have already taken place, allow us to expand the domain of definition of $C_h^{PM}(t_D, \Delta t_D)$ values of functions $C_h^{PM}(t, \Delta t)$ for the corresponding periods of time in the past with the same daily detail.

In addition, daily sequences of $C_h^{PM}(t_D, \Delta t_D)$ functions of $C_h^{PM}(t, \Delta t)$ can be averaged, respectively, on monthly (M) and annual (Y) time intervals Δt_M and Δt_Y and represent the sequences of values $C_h^{PM}(t_M, \Delta t_M)$ and $C_h^{PM}(t_Y, \Delta t_Y)$, defined on the discrete sets t_M and t_Y of time t.

Using time sequences of the values of the coefficients $C_h^{PM}(t_D, \Delta t_D)$ and the values of the installed capacities G_h of the power units, in the idealized case, when the factors of capacity reduction that are not associated with PPM do not work, i.e. the values of all coefficients $C_h^{OS}(t_D, \Delta t_D)$ are equal to one, you can first estimate the dynamics of the total volumes $S_{\Sigma}(t_M, \Delta t_M)$ of the monthly electricity generation by all NPP units during the forecast period. So, following (3) - (4), we have

$$S_{\Sigma}(t_M, \Delta t_M) = \sum_h \sum_{t_D \in t_M} C_h^{PM}(t_D, \Delta t_D) G_h \Delta t_D. \quad (5)$$

Since the sequence of values of $C_h^{PM}(t_D, \Delta t_D)$ are periodic and have alternating periods T_{ch} and $T_{\kappa h}$ such that are not generally equal to the duration of the calendar year, the summation of these sequences with weights $G_h \Delta t_D$ results to the formation of a sequence of values $S_{\Sigma}(t_M, \Delta t_M)$, which does not repeat the annual seasonal fluctuations of the volumes of electricity produced by all NPPs, and the corresponding schedules of maintenance companies do not reflect the priority of summer periods for their implementation in each forecast year.

For the formation of adequate sequences of $S_{\Sigma}(t_M, \Delta t_M)$ values, the dynamics of which would be close to the dynamics of the monthly sequence of averaged values of $\bar{S}_{\Sigma}(t_M, \Delta t_M)$ calculated from the statistical data on the production volumes of nuclear power plants for a number of past years, it is necessary to solve quadratic programming problems

$$\min_{\{\Delta T_h(Y)\}} \sum_{t_M \in Y} \left[\bar{S}_{\Sigma}(t_M, \Delta t_M) - \sum_h \sum_{t_D \in t_M} C_h^{PM}(t_D + \Delta T_h(Y), \Delta t_D) G_h \Delta t_D\right]^2, (6)$$

$$\{\overline{\Delta T}^- \le \Delta T_h(Y) \le \overline{\Delta T}^+\}. \quad (7)$$

and within each forecast year Y, find the offsets $\Delta T_h(Y)$ of the argument t_D of the functions $C_h^{PM}(t_D + \Delta T_h(Y), \Delta t_D)$, which is identical to the search for the refined values of the periods $\bar{T}_{ch}$ or $\bar{T}_{\kappa h}$ maintenance companies, the implementation of which was initially planned to begin in the same forecast year. Here, the boundaries $\overline{\Delta T}^-$ and $\overline{\Delta T}^+$ of admissible changes of the desired quantities $\Delta T_h(Y)$ are set equal to the average values of the quantities from the sets $\{T_c^{\min} - \bar{T}_c\} \cup \{T_\kappa^{\min} - \bar{T}_\kappa\}$ and $\{T_c^{\max} - \bar{T}_c\} \cup \{T_\kappa^{\max} - \bar{T}_\kappa\}$, respectively. Referring to the data presented in Table 2, we determine the values $\overline{\Delta T}^- = -40$ and $\overline{\Delta T}^+ = 56$ (in days).

Problems (6) - (7) are solved sequentially for the entire set $\{Y\}$ of forecast years, starting from the first year. The values $\Delta T_h(Y)$ found allow us to form the offset sequences $\check{C}_h^{PM}(t_D, \Delta t_D) = C_h^{PM}(t_D + \Delta T_h(Y), \Delta t_D)$ and the corresponding their averaged sequences are $\check{C}_h^{PM}(t_M, \Delta t_M)$ and $\check{C}_h^{PM}(t_Y, \Delta t_Y)$.

The presence of the sequence of values of the coefficients $\check{C}_h^{PM}(t_M, \Delta t_M)$ and $\check{C}_h^{PM}(t_Y, \Delta t_Y)$, as well as data on monthly and annual electricity generation $S_h(t_M, \Delta t_M)$ and $S_h(t_Y, \Delta t_Y)$ over the past years makes it possible to retrospectively evaluate the sequence of values of the coefficients $C_h^{OS}(t_M, \Delta t_M)$ and $C_h^{OS}(t_Y, \Delta t_Y)$ for reducing capacity of the power unit h due to the performance of its current maintenance and operational service. The basis for obtaining such estimates are relations (3) and (4), with which you can determine the values

$$C_h^{OS}(t_M, \Delta t_M) = S_h(t_M, \Delta t_M) / \left[\check{C}_h^{PM}(t_M, \Delta t_M) G_h \Delta t_M\right]$$

and

$$C_h^{OS}(t_Y, \Delta t_Y) = S_h(t_Y, \Delta t_Y) / \left[\check{C}_h^{PM}(t_Y, \Delta t_Y) G_h \Delta t_Y\right]. \quad (8)$$

Analysis of the values of the coefficients $C_h^{OS}(t_M, \Delta t_M)$ and $C_h^{OS}(t_Y, \Delta t_Y)$, calculated on the basis of retrospective data, showed the impossibility of extrapolating them for the forecast period. It was also impossible to extrapolate the average estimates of the power reduction factors of a species.

$$C_H^{OS}(t_Y, \Delta t_Y) = \frac{1}{|H|} \sum_{h \in H} S_h(t_Y, \Delta t_Y) / \left[\check{C}_h^{PM}(t_Y, \Delta t_Y) G_h \Delta t_Y\right], \quad (9)$$

calculated for the set of H power units of each NPP. Graphs of changes in the values of these coefficients are presented in Figure 1.

Therefore, to perform predictive calculations, it is necessary to use the averaged values of these coefficients in the form of estimates

$$C_H^{OS}(\Delta Y) = \frac{1}{|\Delta Y|} \sum_{Y \in \Delta Y} C_H^{OS}(t_Y, \Delta t_Y), \quad (10)$$

obtained on the set ΔY of previous years.

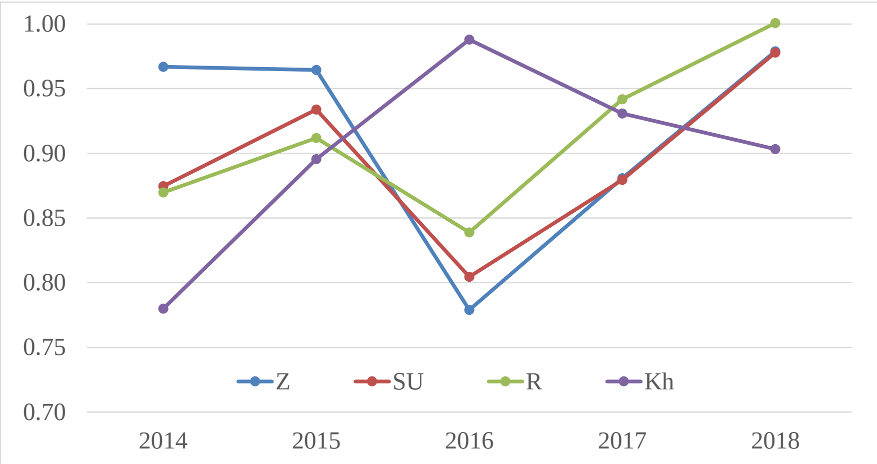

Fig. 1. The dynamics of the reduction coefficients of the annual electricity production volumes at the Zaporozhzhya NPP (Z), South-Ukraine (SU), Rivne NPP (R) and Khmelnytska (Kh) under the influence of factors not related to the implementation of PPM.

2. Algorithm for forecasting the production of electricity by NPP units

The above research results are the basis of the following algorithm for long-term forecasting of electricity production volumes by NPP units:

1. Based on the schedules for the implementation of intermedium and major maintenances of the main equipment of NPPs, we form sets $\{T_с\}$, $\{T_к\}$ and $\{d_с\}$, $\{d_к\}$ of the actual values of the periods and durations of maintenance companies carried out over a number of previous years.

2. For each power unit, we calculate the average values of $\bar{T}_с$, $\bar{T}_к$ and $\bar{d}_с$, $\bar{d}_к$ of the periods and durations of previously performed maintenances, and also determine their boundary values $T_с^{\min}$, $T_к^{\min}$, $T_с^{\max}$, $T_к^{\max}$, $d_с^{\min}$, $d_к^{\min}$, $d_с^{\max}$, $d_к^{\max}$.

3. We form sets of values $\{T_с^{\min} - \bar{T}_с\} \cup \{T_к^{\min} - \bar{T}_к\}$ and $\{T_с^{\max} - \bar{T}_с\} \cup \{T_к^{\max} - \bar{T}_к\}$ for which we calculate the average values $\overline{\Delta T}^-$ and $\overline{\Delta T}^+$.

4. Starting from the dates of the last actually performed maintenances, using average values of $\bar{T}_с$, $\bar{T}_к$, $\bar{d}_с$, $\bar{d}_к$, we form a sequence of schedules for the implementation of intermediate and major maintenances of power units according to the $3(с) + 1(к)$ alternation scheme for the forecast period.

5. Based on the formed sequence of schedules for the maintenance of power units, we determine the sequence of values $C_h^{PM}(t_D, \Delta t_D)$.

6. According to statistical data on NPP production volumes for a number of past years, we form a sequence of average values of production volumes $\bar{S}_\Sigma(t_M, \Delta t_M)$.

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7. For the entire set $\{Y\}$ of forecasting years, we sequentially, starting from the first year, solve problems (6) - (7) and find the values $\Delta T_h(Y)$.

8. Form the shifted sequences of the values of the coefficients $\check{C}_h^{PM}(t_D, \Delta t_D) = C_h^{PM}(t_D + \Delta T_h(Y), \Delta t_D)$ and the corresponding average sequences $\check{C}_h^{PM}(t_M, \Delta t_M)$ and $\check{C}_h^{PM}(t_Y, \Delta t_Y)$, respectively.

9. Using the data of previous years on the annual volumes $S_h(t_Y, \Delta t_Y)$ of electric power generation by each unit, according to the formulas (8) - (10), as well as on the found values of the coefficients $\check{C}_h^{PM}(t_Y, \Delta t_Y)$ we calculate the values of the coefficients $C_H^{OS}(\Delta Y)$.

10. Using relations (3) - (4), the found values of the coefficients $\check{C}_h^{PM}(t_M, \Delta t_M)$ and $C_H^{OS}(\Delta Y)$, as well as the data $\{G_h\}$ on the installed capacity of the set H of power units of each NPP, we calculate its monthly and annual electricity production volumes for the forecast period, respectively,

$$S_H(t_M, \Delta t_M) = C_H^{OS}(\Delta Y) \sum_{h \in H} \check{C}_h^{PM}(t_M, \Delta t_M) G_h \Delta t_M \qquad (11)$$

and

$$S_H(t_Y, \Delta t_Y) = C_H^{OS}(\Delta Y) \sum_{h \in H} \check{C}_h^{PM}(t_Y, \Delta t_Y) G_h \Delta t_Y. \qquad (12)$$

The combination of relations (6) - (7), (9) - (12) is a mathematical model of the production processes implemented at NPPs of the company NNEGC "Energoatom". This model is suitable for predicting the monthly dynamics of electricity generation by NPP units in various scenario conditions of the company's development.

According to the scenario of the planned decommissioning of NPP power units [22], presented by Y.Nedashkovsky, President of NNEGC “Energoatom”, at the Committee hearings in the Verkhovna Rada of Ukraine on July 12, 2018, model calculations of annual and monthly electricity production volumes were performed for the period forecasting 2019 - 2040 years. The simulation results are presented in Figures 2 - 4.

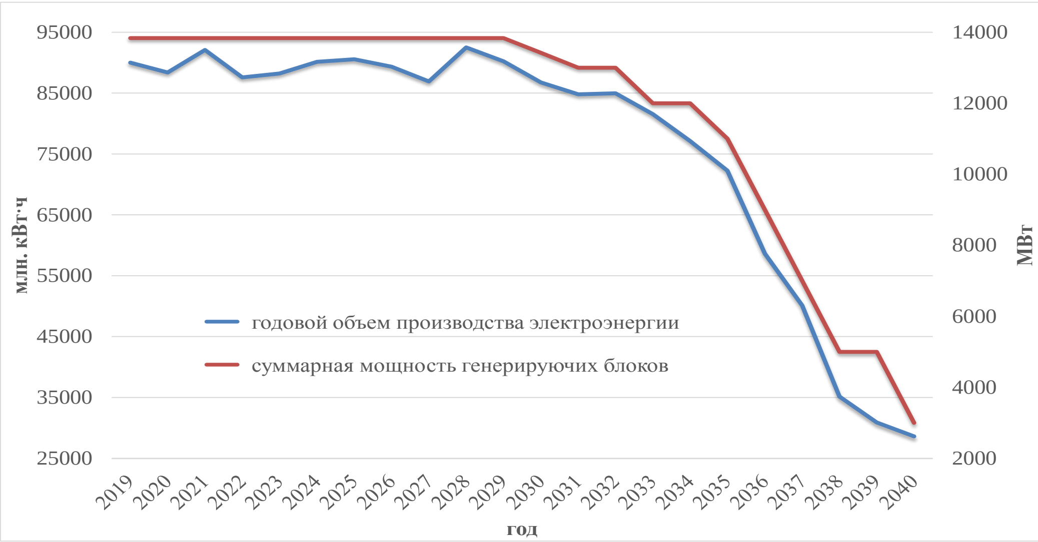

Fig. 2. Dynamics of the total capacity of power units and annual volumes of electricity production at NPPs of the company NNEGC “Energoatom”

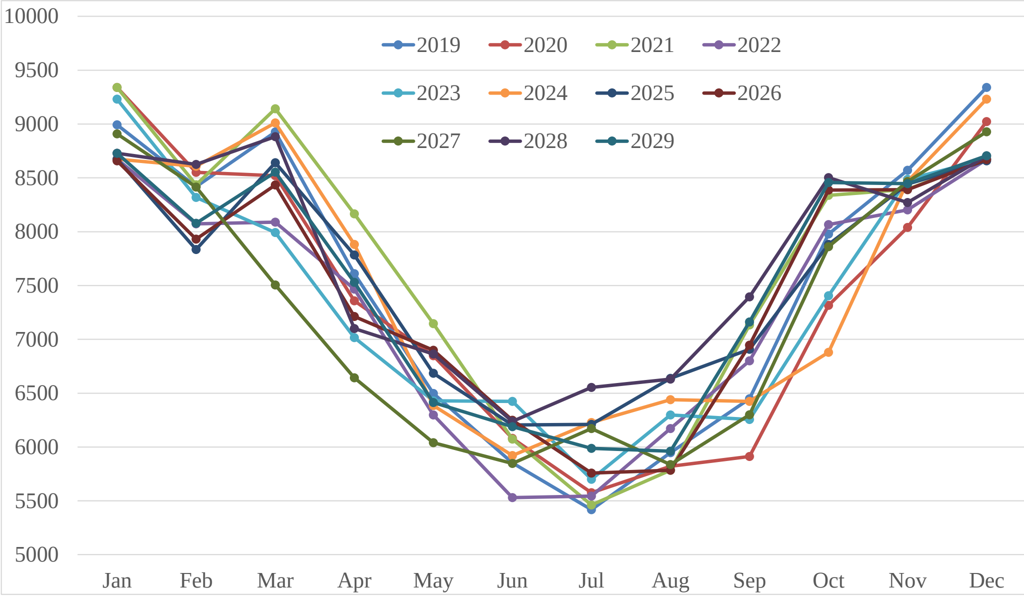

Fig. 3. Dynamics of monthly electricity production volumes at NPPs of GP NNEGC “Energoatom” (forecast for 2019-2029), mln.kWh.

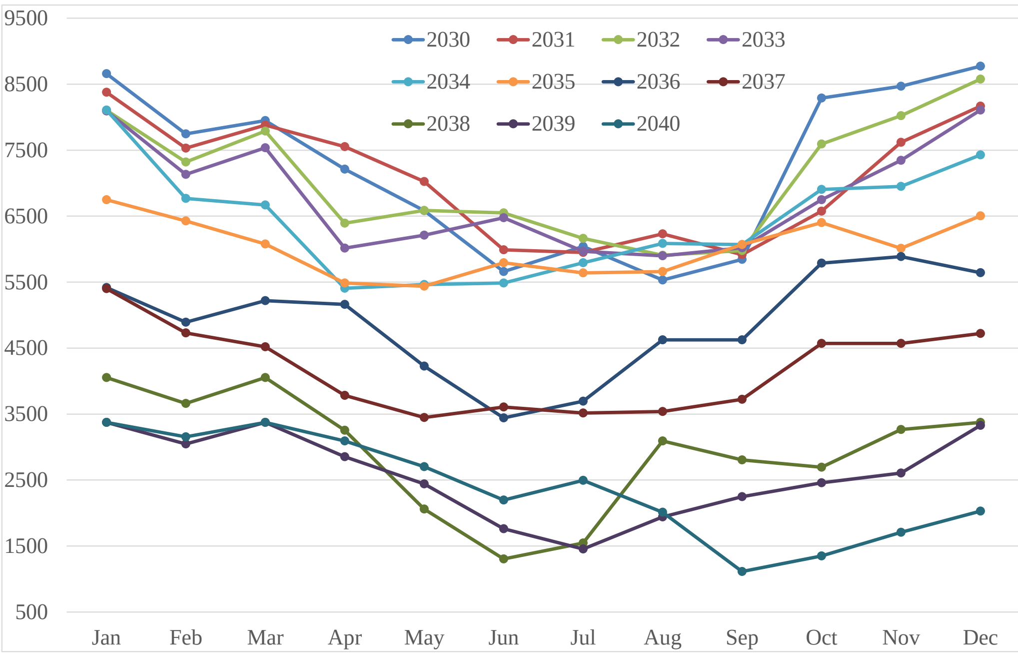

Fig. 4. Dynamics of monthly electricity production volumes at NPPs of GP NNEGC “Energoatom” (forecast for 2030-2040 years), mln.kWh

Here you can see not only the rate of decline in monthly and annual electricity production, but also the loss of the possibility of seasonal regulation of production volumes.

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Findings

1. A mathematical model of production processes implemented at NPPs of the company NNEGC "Energoatom" has been developed. The model adequately reproduces the general characteristics of the PPM of the equipment of power units, and their impact on the monthly electricity production volumes of each NPP in the medium and long term.

2. The mathematical model is focused on the use as a part of Ukrainian power industry modeling systems and makes it possible to take into account various development strategies of the company NNEGC “Energoatom” in such systems, in particular, the commissioning of new power units with regulated characteristics of periodicity and duration of preventive maintenance.

3. After the accident at the Fukushima nuclear power plant, there has been a steady increase in safety requirements for nuclear power facilities. The analysis of scenarios for increasing the duration of maintenance work and replacing the existing power units with new facilities with high reliability and safety parameters is becoming a relevant area of research. The presented model makes it possible to take into account the influence of such scenarios of the development of nuclear industry on the monthly dynamics of the volumes of electricity generation by NPP units.

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