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IMPROVING THE MODEL OF LONG-TERM TECHNOLOGICAL UPDATE OF POWER SYSTEM COMPONENTS

Abstract. *An improved model of mathematical programming is proposed for the study of directions and optimal parameters of the technological renewal of energy system elements operating in energy associations, for the distant perspective and taking into account the perspectives of these elements. The model is a combination and, at the same time, a separate case of two models: a model of a hierarchical controlled quasi-dynamic system and a stochastic quasi-dynamic model of the economic and technological impact of the life cycle of innovative technologies. The main difference of the proposed improved model is the explicit consideration of the influence of economic and technological indicators of the development of the national economy and production, presented in the form of stochastic quasi-dynamic functions. The conducted test calculations confirm the adequacy of the proposed model, the perspective of applying this approach and further development of the model to achieve the necessary levels of detail in the forecast scenarios of the development of energy systems of Ukraine. The performed test calculations made it possible to obtain numerical estimates of the potential that can be achieved by improving the model of long-term technological renewal of power system components. Consideration of the influence of economic and technological indicators of the development of the national economy and production in the form of stochastic quasi-dynamic functions expands the tools and possibilities of obtaining high-quality predictive scenarios of the development of energy systems in Ukraine. The use of efficiency coefficients LCOE, LCOS and LACE, which are widely used in modeling the development of energy systems, increases the quality of the conclusions obtained. Examples of calculations of values of parameters of power system components under different modes of use are given.*

Keywords: long-term technological renewal of power system components.

ACRONYMS

SS	Battery Electric Storage System
IPS	Integrated Power System
NPP	Nuclear Power Plant

1. Introduction

The study of the development and improvement of energy systems is an urgent scientific problem, which is given considerable attention [1]–[3]. An improvement of the model of mathematical programming is proposed, which is based on the modification and development of a family of hierarchical models of step-by-step optimization of trajectories of sustainable development of energy systems [4] and a stochastic quasi-dynamic model of the economic and technological impact of the life cycle of innovative technologies [5]. The main difference of the proposed model is the explicit consideration of the influence of economic and technological indicators of the development of the national economy and production, presented in the form of stochastic quasi-dynamic functions. The calculations used the actual and predicted values of these functions at the corresponding step of the modeling horizon. The modification and development of these models is aimed at adapting the latter to study on their basis the directions and optimal parameters of technological renewal of the components of energy systems operating within the framework of energy associations in the long term, and taking into account their prospects.

Estimating the relative costs of upgrading energy systems that use different technologies is a difficult task. The results of this assessment are critically dependent on location. For example, coal, given the current situation, is and is likely to remain economically attractive in countries, where carbon emissions are taxed low or not at all. Gas is also able to compete with base generation capacity, especially when combined cycle plants are used. Nuclear power plants are expensive to build, but relatively cheap to operate. Waste disposal and decommissioning costs are usually fully included in operating costs. In many places, nuclear energy successfully competes with fossil fuels as a means of generating electricity. Accounting for the social, health and environmental costs of using fossil fuels increases the competitiveness of nuclear power. Technology life cycle assessments show that nuclear power is an economically viable source of electricity generation, combining the benefits of safety, reliability and very low greenhouse gas emissions. Existing NPPs operate reliably with a high degree of predictability. The operating costs of nuclear power plants are lower than those of all fossil fuel competitors and also have a very low risk of operating cost inflation. Experience shows that the life cycle of nuclear power plants is 60 years and may be extended in the future. The main economic risks for existing nuclear power plants lie in competition both with subsidized renewable energy, whose generation volumes are difficult to predict, and with low-cost gas generation, especially given the political risks of increased specific taxation of nuclear power.

2. Methods and materials

At the moment, the following two performance factors are widely used in modeling scenarios for the development of energy systems.

Levelized Cost of Electricity (LCOE)

Currently, the evaluation of the effectiveness of decisions made is often based on the calculation of the levelized cost of electricity produced – LCOE, which is used as a convenient generalizing indicator of the overall competitiveness of various generating technologies [6]. It represents the cost per kilowatt-hour (with currency discounts) to build and operate a generating set over its expected life cycle, including decommissioning. The main inputs for the calculation are: capital costs, fuel prices, fixed and variable operating costs, maintenance costs, financing costs and the estimated utilization rate for each type of generating plant. The weight of the factors varies depending on the technology. For technologies such as solar and wind that have no fuel consumption and relatively small operating costs, the LCOE is roughly proportional to the estimated cost of capital for generating capacity. For technologies with significant fuel costs, fuel consumption and operating costs have a significant impact on LCOE. The presence of various incentives, including state or federal tax credits, may also affect the LCOE calculation. As with any design, there is uncertainty about all of these factors and their importance may vary regionally and over time as technology advances and fuel prices change. It is important to consider that the actual investment costs depend on the specific technological and regional features of the project, which are influenced by many other factors.

Levelized Avoided Cost of Electricity (LACE) as an additional indicator

Because projected utilization rates, existing resource mixes, and the amount of capacity required can vary greatly in different regions where new generation capacity may be required, direct comparison of LCOE technologies as a method of assessing the economic competitiveness of various generation project alternatives is often problematic and misleading. Conceptually, a better estimate of economic competitiveness can be achieved by taking into account cost avoidance, namely the cost of generating resources that already exist, the electricity that is supposed to be generated by a new generation project, as well as its LCOE. Cost savings, providing a proxy for the annual economic value of a candidate project, can be estimated over the horizon of its financial life cycle by dividing on the project's average annual generation to determine the unit cost of electricity avoided (LACE) [7]–[8]. Then, the LACE value of the candidate project can be compared with the LCOE value, and thus determine whether the benefit received from the project exceeds its cost. If several competing technologies are considered, a comparison of each project's LACE with its LCOE can be used to select the most efficient project. A LACE estimate is more complex than an LCOE estimate because it requires information about how the system would perform without the modification. The LACE calculation is based on forecasting the marginal cost of energy and capacity, as a result of the use of existing technology or the technology being developed, for a certain future date and allows the investor to estimate the potential value of the project implementation. Long-term forecasts use both LACE and LCOE indicators, which is generally more representative than using LCOE alone. However, it should be noted that LACE and LCOE estimates are simplifications of modeled decisions and cannot fully account for all decision-making factors or comparisons of simulation results. Calculations based on LACE and LCOE estimates, which are usually performed using an assumed set of capital and operating costs, are subject to uncertainty due to the use of projected values of fuel prices and possible administrative acts. This should be taken into account when analyzing technology choices in the electricity sector based on estimated LCOE and LACE.

Model formulation

The main difference of the proposed step-by-step optimization model is taking into account explicitly the impact of economic and technological indicators of the development of the national economy and production, presented in the form of stochastic quasi-dynamic functions. Therefore, the model allows the study of the optimum volume of technological renovation of combined power systems. The model is represented as a hierarchy of scenarios. On the top-level of the hierarchy involved aggregated technology of energy provision. For example, aggregated technology *k = 1,* is an aggregation of several coal technologies. Aggregated technology *k = 2,* is the aggregation of gas technologies, etc. The matrix of the system state $\Omega_{\tau k}$ reflects the structure of the volumes of generation, delivery and consumption of energy at $\tau\tau$ step of the modeling horizon. All $k = 1, \dots, K$ used technologies are involved in ensuring the balance of energy supplied $E^{\Sigma}_{S\tau}$ and consumed $E^{\Sigma}_{C\tau}$ at each τ step. The main limitations of the model – keeping the right balance of the total power P^{Σ}_{τ}, maneuverable power $P^{\Sigma}_{m\tau}$ and the volumes of generated $E^{\Sigma}_{G\tau}$, supplied $E^{\Sigma}_{S\tau}$ and consumed $E^{\Sigma}_{C\tau}$ energy, when restrictions, that all parameters belong to the set of possible states performed. The measure $\mu_{\tau k}$ of the inconsistency of supplied and consumed energy vectors is introduced.

The initial information for modeling are:

- target sequence of annual total energy consumption $E^{\Sigma}_{C\tau} = \sum_{k=1}^{K} E^{Consum}_{k\tau}$, at time τ, $\tau = 0, 1, 2, \dots, T$;
- the initial state of the vector of total supply E^{Σ}_{S0};
- the vector of integral parameter differences $L_k(LACE_k - LCOE_k$ for each of the aggregated technologies involved in the calculation;
- functional of economic and technological influence *F[PPF(τ),ET(k,τ),FCF(k,τ),EGR(τ)],* where *PPF(τ)* – regional purchasing power factor, *ET(k,τ)* – efficiency of technology, *FCF(k,τ)* – final cost factor, *EGR(τ)* – economy growth rate;
- forecast cost of technology components: $C^{cap}_{k\tau}$ – investment, $/kW, $C^{co}_{k\tau}$ – constant operating expenses, $/kW, $C^{vo}_{k\tau}$ – variable operational costs, $/kWh.

The set of admissible states $\Phi_{\tau k}\left\{L_k\left(LACE_k-LCOE_k\right),F\left[PPF\left(\tau\right),ET\left(k,\tau\right),FCF\left(k,\tau\right),EGR\left(\tau\right)\right]\right\}$ for the development trajectory of the aggregated technology k is calculated. Solved the problem of calculating the development scenario of the such supply vector

$$E_{S\tau}^{\Sigma}\left\{\Phi_{\tau k}\left\{L_k\left(LACE_k-LCOE_k\right),F\left[PPF\left(\tau\right),ET\left(k,\tau\right),FCF\left(k,\tau\right),EGR\left(\tau\right)\right]\right\}\right\},$$

that the measure μ^{Σ} of the total inconsistency of the supplied and consumed energy vectors minimized. The objective function of minimizing the total inconsistency of supplied and consumed energy vectors during the forecast period with the observance of mandatory restrictions is as follows:

$$\mu^{\Sigma}=\sum_{\tau=1}^{\mathrm{T}}\left(E_{S\tau}^{\Sigma}-E_{C\tau}^{\Sigma}\right)\forall u\left(\tau,k\right),\xi\left(\tau,k\right))\rightarrow min,$$

where: $E_{S\tau}^{\Sigma}$, $E_{C\tau}^{\Sigma}$ – total volumes of supplied and consumed energy; $u(\tau,k)$ – vector of control actions for aggregated technology k at the time τ; $\xi(\tau,k)$ – vector of random external actions for aggregated technology k at the time τ. Optimal target trajectory for supply vector

$$E_{S\tau}^{\Sigma}\left\{\Phi_{\tau k}\left\{L_k\left(LACE_k-LCOE_k\right),F\left[PPF\left(\tau\right),ET\left(k,\tau\right),FCF\left(k,\tau\right),EGR\left(\tau\right)\right]\right\}\right\}, \tau=1,2,...,T$$

determined on the basis of forecasts of the overall development of the economy and related forecasts of consumption structure $E_{C\tau}^{\Sigma}=\sum_{k=1}^{K}E_{C\tau}^{k}$. The values of the total supply obtained at the upper level and the component value of the vector $E_{S\tau}^{\Sigma}=\sum_{k=1}^{K}E_{S\tau}^{k}$ for each of the aggregated technologies are the source data for the following calculations: the required balance of total power P_{τ}^{Σ}; the necessary structure of maneuver capacities $P_{m\tau}^{\Sigma}$; volumes of total and component generation $E_{G\tau}^{\Sigma}=\sum_{k=1}^{K}E_{G\tau}^{k}$; volume of necessary investments $C_{k\tau}^{\Sigma cap}=\sum_{k=1}^{K}C_{k\tau}^{cap}$, \$/kW; volumes of constant operating expenses, $C_{k\tau}^{\Sigma co}=\sum_{k=1}^{K}C_{k\tau}^{co}$ \$/kW; amounts of variable operating costs, $C_{k\tau}^{\Sigma vo}=\sum_{k=1}^{K}C_{k\tau}^{vo}$ \$/kWh.

At the following simulation levels, similar calculations are performed within each of the aggregated technologies, that is, the components of the development scenarios for the respective vectors of each of the aggregated technologies are calculated. Returning to the above examples of coal and gas technology, all the calculations listed above, which include the components of the aggregated coal and gas technology components, are fulfilled. Further application of this approach ends with the achievement of required or specified by the developer level of the simulation detail. Perhaps the use of the model in the opposite (bottom-up) direction. The performed test calculations confirm the adequacy of the proposed model, the promising application of this approach and the further development of the model to achieve the necessary levels of detail of forecast scenarios for the development of energy systems in Ukraine.

As described above, aggregate technologies were used at the top level of the hierarchical model for stepwise optimization of the sustainable development of the power system. At the following levels of modeling are performed similarly calculations for each of the aggregated technology, that is, the components of the scenarios for the corresponding vectors for each of the aggregated technologies are calculated. The disaggregated (detailed in modeling) technology k of electricity production with a battery electric storage system described below, is considered as a set (combination) of several technologies that reflect the functions of its components. The purpose of this combination is the reduction of the cost of maintaining the balance of the network peak loads and the risk of overload in current mode and emergency modes. The set is equipped with the necessary control device, which monitors voltage and frequency in the network, converts

AC to DC and Vice versa, stores the electric energy received from the system in batteries and uses it if necessary, correcting poor frequency, voltage and other, to increase energy efficiency. The operation is in automatic mode or at the command of the dispatcher, using:

- frequency controller (FC), which in real time changes the frequency of electricity in the network and issues commands to the charging or discharging of the battery;
- system of energy conversion, which receives signals from the FC, calculates the necessary degree of charge or discharge of the battery and converts the direct current of batteries into alternating current network, and vice versa;
- battery management system, which in real time monitors the state of charge in the system, makes a decision and gives commands to the charge/discharge/holding and monitors the temperature of the batteries.

In the simulation, a battery electric storage system (SS) is submitted in the form of two power generating technologies, one primary and one that models the energy from SS at the stage when it is discharged. In addition, the SS included the technology of consumption, which reflects energy consumption at the stage of charge of the SS. For each of these technologies are calculated target sequence of annual total volumes consumed and supplied energy and the initial state of the volume of electricity. To calculate the vector of differences of integral parameters $L_k\left(LACE_k - LCOE_k\right)$, pre-calculates $LCOS_{SS}$ – reduced cost of storage [9] according to the formula:

$$LCOS_{SS} = \frac{\sum_{\tau}^{T} \frac{\left(C_{SS\tau}^{cap} + C_{SS\tau}^{co} + C_{SS\tau}^{vo}\right)}{\left(1+i\right)^{\tau}}}{\sum_{\tau}^{T} \frac{E_{SS\tau}}{\left(1+i\right)^{\tau}}},$$

where: $E_{SS\tau}$ – stored energy in each year, kWh; i – discounted rate (%); $C_{SS\tau}^{cap}$ – capital investment, $/kW, $C_{SS\tau}^{co}$ – constant operating expenses, $/kW, $C_{SS\tau}^{vo}$ – variable operational costs, $/kWh.

Further, calculations are made similar to the aggregated top-level technologies.

Calculations

Considering the foregoing, below are examples of calculations comparative assessment NPPs parameters in modes of basic generation – $LCOE_{NPP}^{base}$, load following – $LCOE_{NPP}^{LF}$ and with ESS – set of several storage system – $LCOE_{NPP+ESS}^{\Sigma}$. The results of all subsequent test calculations are summarized in Table 1.

The base generation $LCOE_{NPP}^{base}$ was calculated by the formula (1) [3]:

$$LCOE_{NPP}^{base} = \frac{\sum_{\tau}^{T_{NPP}} \frac{\left(C_{NPP\tau}^{cc} + C_{NPP\tau}^{FO\&M} + C_{NPP\tau}^{VO\&M}\right)}{\left(1+i\right)^{\tau}}}{\sum_{\tau}^{T_{NPP}} \frac{E_{NPP\tau}^{An\_base}}{\left(1+i\right)^{\tau}}}, \qquad (1)$$

where: $E_{NPP\tau}^{An\_base}$ – annual NPP generation in base mode, kWh; i – discounted rate (WACC), %; $C_{NPP\tau}^{cc}$ – capital costs, $/kW; $C_{NPP\tau}^{FO\&M}$ – annual fixed costs, $/kW-yr; $C_{NPP\tau}^{VO\&M}$ – variable costs, $/kWh; T_{NPP} – NPP life cycle, years. Test calculations for WACC 3, 5, 7 and 10% confirm the model adequacy.

In load following (LF) mode, $LCOE_{NPP}^{LF}$ calculated using the formula similar to (1). Based on the hourly load distribution of the IPS of Ukraine components [10], the model hourly power balance and the annual generation of NPP in the LF mode – E_{NPP}^{LF} were calculated. The results of the test calculations of $LCOE_{NPP}^{LF}$ and the ratio of $LCOE_{NPP}^{LF} / LCOE_{NPP}^{base}$ are also given in Table 1.

Table 1. Results of the test calculations

WACC	%	3	5	7	10
$LCOE^{base}_{NPP}$	$/kWh	0,058	0,071	0,084	0,105
$LCOE^{LF}_{NPP}$	$/kWh	0,066	0,080	0,096	0,120
LF/BASE		1,138	1,127	1,143	1,143
$LCOS^{T_{ESS}}_{ESS}$	$/kWh	0,279	0,279	0,280	0,280
$LCOE^{\Sigma}_{NPP+1\ ESS-100}$	$/kWh	0,061	0,073	0,087	0,107
$LCOE^{\Sigma}_{NPP+3\ ESS-100}$	$/kWh	0,066	0,078	0,092	0,112
$LCOE^{\Sigma}_{NPP+5\ ESS-100}$	$/kWh	0,071	0,083	0,097	0,117
$LCOE^{\Sigma}_{NPP+7\ ESS-100}$	$/kWh	0,075	0,087	0,101	0,122

The NPP with a set of several storage systems (ESS) $LCOE^{\Sigma}_{NPP+ESS}$ is calculated according to the formula (2), which is a development of the formula (1):

$$LCOE^{\Sigma}_{NPP+ESS} = \frac{\sum_{\tau}^{T} \frac{\left(C^{cc}_{NPP\tau} + C^{FO\&M}_{NPP\tau} + C^{VO\&M}_{NPP\tau} + C^{IIc}_{ESS\tau} + C^{O\&M}_{ESS\tau} + C^{Charg}_{ESS\tau}\right)}{\left(1+i\right)^{\tau}}}{\sum_{\tau}^{T_{NPP}} \frac{E^{An\_base}_{NPP\tau}}{\left(1+i\right)^{\tau}}}, \qquad (2)$$

where: $C^{IIc}_{ESS\tau}$ – total initial installed costs, $/kWh; $C^{O\&M}_{ESS\tau}$ – operating costs, $/kW-yr; $C^{Charg}_{ESS\tau}$ – charging cost, $/kWh.

In the first phase, it was performed a test calculation of levelized cost $LCOS^{T_{ESS}}_{ESS}$ for a storage system ESS-100 with power of 100 MW and capacity of 400 MWh, throughout the life cycle T_{ESS} = 20 years [11]. The results of these calculations confirm the adequacy of the model. In the second phase $LCOE^{\Sigma}_{NPP+1\,ESS-100}$ for a two advanced nuclear power unit AP1000 with a total capacity of 2200 MW (NPP-2200) and one ESS–100 during the life cycle of 40 years was calculated. Next, the model hourly balance of NPP-2200 is calculated, which, with the required amount N_{ESS} of ESS-100, will allow leveling the daily energy consumption schedule. The required N_{ESS} is determined taking into account the limit on the maximum annual permissible charge / discharge power, which, according to passport data, should not exceed 140 000 MWh. Accordingly, the charge / discharge energy required to completely equalize the load schedule and the NPP's operation in the base generation mode is 936 437 MWh and N_{ESS} = 7.

Calculations of the comparative cost of a system consisting of NPP-2200 and several (3, 5, 7) ESS-100 are performed. The results are shown in Table 1 and Figure 1. Calculations showed, that for this particular configuration, the system is economical until N_{ESS} does not exceed 3, and total ESS power does not exceed 15% of NPP power.

3. Results and discussion

The results obtained during test calculations made it possible to obtain numerical estimates of the potential for improving the model of long-term technological renewal of power system components. The use for obtaining estimates, of efficiency coefficients LCOE, LCOS and LACE, which are widely used in modeling the development of energy systems, provides an opportunity to develop high-quality development scenarios. Consideration of the influence of economic and technological indicators of the development of the national economy and production, presented in the form of stochastic quasi-dynamic functions, to study on their basis the directions and optimal parameters of the technological renewal of the energy systems components, that operate as part of energy associations, in the long term and taking into account their prospects, expands tools and possibilities of qualitative forecasting.

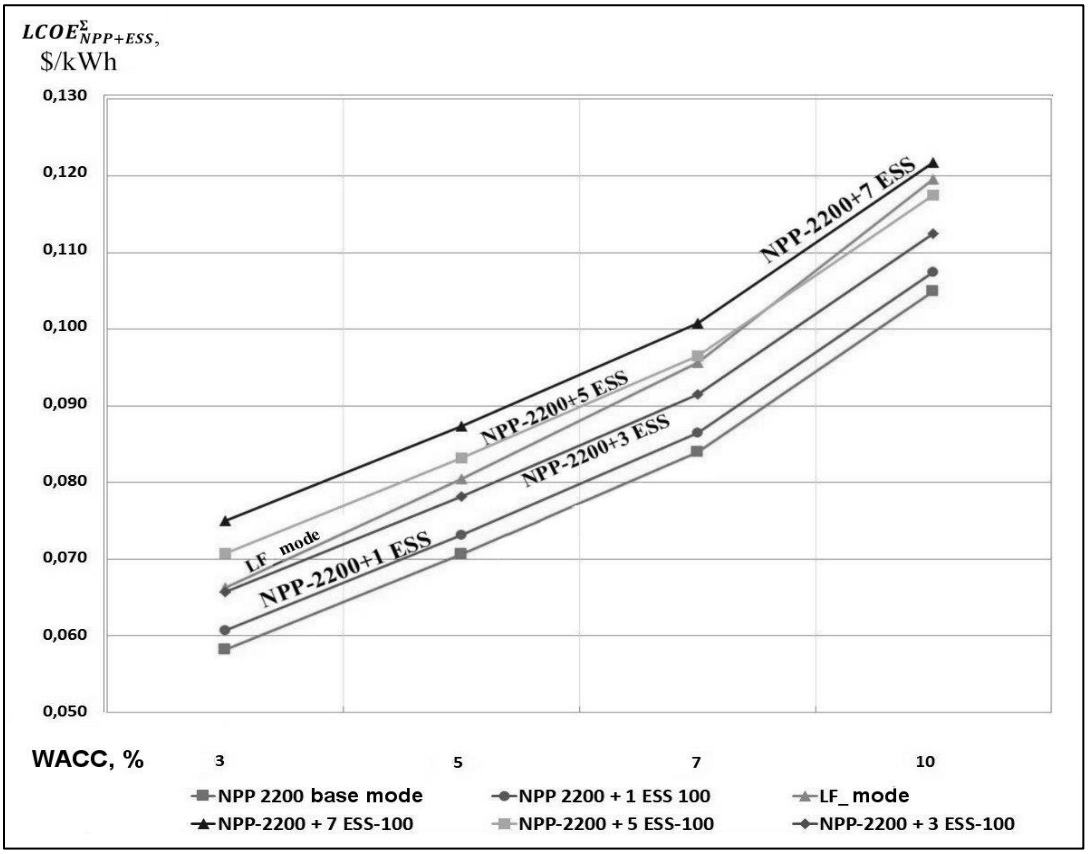

Fig. 1. The generation system comparative cost

4. Conclusions

In order to adapt mathematical programming models to study the directions and optimal parameters of technological renewal of power system components operating in power interconnections, in the long term and taking into account their prospects, an improved model is proposed. It is based on the modification and development of the family of hierarchical models of step-by-step optimization of trajectories of sustainable development of energy systems and of the stochastic quasi-dynamic model of economic and technological impact of the life cycle of innovative technologies. The main difference of the proposed model is the explicit consideration of the influence of economic and technological indicators of the development of the national economy and production, presented in the form of stochastic quasi-dynamic functions. The use of efficiency factors LCOE, LCOS and LACE, widely used in modeling the development of power systems, improve the quality of the resulting development scenarios. The simulation results can be used to study the prospects for the short-term and long-term development of the energy system of Ukraine, which is relevant in these conditions.

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УДОСКОНАЛЕННЯ МОДЕЛІ ДОВГОСТРОКОВОГО ТЕХНОЛОГІЧНОГО ОНОВЛЕННЯ КОМПОНЕНТНИХ ЕНЕРГОСИСТЕМ

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Анотація. *Запропоновано удосконалену модель математичного програмування для дослідження напрямів та оптимальних параметрів технологічного оновлення елементів енергосистем, що працюють в енергооб’єднаннях, на віддалену перспективу та з урахуванням перспектив цих елементів. Модель є об’єднанням і в той же час окремим випадком двох моделей: моделі ієрархічної керованої квазідинамічної системи та стохастичної квазідинамічної моделі економіко-технологічного впливу життєвого циклу інноваційних технологій. Основною відмінністю запропонованої удосконаленої моделі є явне врахування впливу економіко-технологічних показників розвитку національної економіки та виробництва, представлених у вигляді стохастичних квазідинамічних функцій. Проведені тестові розрахунки підтверджують адекватність запропонованої моделі, перспективність застосування даного підходу та подальшого розвитку моделі для досягнення необхідних рівнів деталізації прогнозних сценаріїв розвитку енергосистем України. Виконані тестові розрахунки дозволили отримати числові оцінки потенціалу, що може бути досягнутим за рахунок вдосконалення моделі довгострокового технологічного оновлення компонентів енергосистем. Розгляд впливу економіко-технологічних показників розвитку національної економіки та виробництва у вигляді стохастичних квазідинамічних функцій розширює інструменти та можливості одержання якісних прогнозних сценаріїв розвитку енергосистем України. Використання коефіцієнтів ефективності LCOE, LCOS і LACE, широко використовуваних при моделюванні розвитку енергосистем, підвищує якість одержуваних висновків. Наведено приклади розрахунків значень параметрів компонентів енергосистем при різних режимах використання.*

Ключові слова: довгострокове технологічне оновлення компонент енергосистем.

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