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DYNAMIC MODELS FOR DEVELOPING REFERENCE SCENARIOS OF ENERGY SYSTEM IN THE LOW-CARBON TRANSITION

Abstract. *The proposed study is aimed at the development of dynamic input-output models in relation to energy development systems. The main task is to find optimal scenarios, defined as sequences of optimal balances between production and capital investment. These models are rooted in Leontief's conceptual concept of input-output, which emphasizes the timing of the introduction of new production systems. The article discusses the economic interpretation and mathematical conditions of intersectoral models, and examines their application to problems related to energy. The model uses the concept of balanced equilibrium growth, in which the ratio of consumption to net release is the same for all resources, and the reserve of at least one resource is fully utilized. The growth rate of the system is the most important parameter that determines the trajectory of balanced growth. Solving the system of inequalities yields balanced growth trajectories in which the dominant root and the associated vector of characteristics plays a key role. A balanced equilibrium growth rate has the properties of a minimax with the presence of a saddle point, which indicates its importance in achieving market equilibrium while preventing a reduction in inventories. The practical application of the model is described. The results of calculations of pessimistic, reference and optimistic scenarios of electricity production in the IPS of Ukraine are presented. Official statistical information and economic forecasts are used, and various restrictions are taken into account. The model aims to minimize the total cost of electricity generation while respecting environmental and operational constraints. The proposed model provides a comprehensive basis for understanding the dynamics of resource reserves, consumption and growth of electricity production of the IPS of Ukraine. It offers decision-makers a valuable tool to optimize electricity generation strategies, taking into account a range of scenarios and constraints, for the sustainable and cost-effective operation of the energy system.*
Keywords: Dynamic input-output models, optimal scenarios, balanced equilibrium growth, growth rate of the system.

ACRONYMS

GDP	Gross domestic product
HPP	Hydro Power Plant
IPS	Integrated Power System
NPP	Nuclear Power Plant
RES	Renewable Energy Sources
SPP	Solar Photovoltaic Station
TPP	Thermal Power Plant
WPP	Wind Power Plant

1. Introduction

Dynamic input-output models are designed to analyze the time-varying relationships between capital expenditures and property, plant and equipment, providing a balance of continuity between different periods of the technology life cycle [1]. Thus, we get a description of the cycle of reproduction, usually for a period of implementation – from the creation of funds to identify increased as a result of their use of production capacity.

The main types of dynamic models [1]:

1. The model of reverse recursion, which balances production and distribution of products combined with equations, needs capital investments for the entire planning period. In the second stage of solving a model, production rates and capital investments are allocated to all the years of the planning period in the direction from the first to the last year;

2. The models for the calculation of production and capital investments for each stage of the planning period. They are usually represented as a set of balance of production and capital investments, demand for which is set for future steps by rationing under construction;

3. The models with a clear view of investments lag, which shows their forward and backward linkages in time with the indicators of production.

This work focuses on the application of models corresponding to item 2 of the above list to energy development systems. Namely, the tasks of finding the optimal scenario, which is understood as a sequence of optimal balances – combinations of the balance of production and capital investments, the need for which is set for subsequent steps by rationing resources. The primary source of such models can be considered the Leontief's models – "investments - production - supplies - consumption", which take into account the timing of the introduction of new and modernized systems of production, release and delivery, including taking into account the necessary stocks of material and production resources.

Work [2] introduces Leontief’s conceptual input–output framework and explains how to develop the fundamental mathematical relationships from the interindustry transactions table. The key assumptions associated with the basic Leontief model and implications of those assumptions are recounted and the economic interpretation of the basic framework is explored. To illustrate the basic structure, a highly aggregated model of the US economy is used. To study the influence of the price component in input-output models, the concept of a "price model" of structure is introduced. A fundamental set of mathematical conditions for input-output models, known as Hawkins-Simon conditions, is presented.

The paper [3] discusses a class of problems of forecasting the production of products, services and demand for them, for which the key problem is the discrepancy between the sum of indicators of the lower hierarchical levels and the upper ones. The discrepancy problem was solved in [3] by combining the TD–BU methodology with the analytical apparatus of the general risk theory, thanks to which analytical dependencies were obtained that provide a solution to the problem of non-conformity. Based on these dependencies, in combination with the apparatus of risk theory, solutions for both levels with zero risks were identified. As a risk function, the functionality of the classical least squares method is used, which gives the best results compared to others.

Energy [4] is a disciplinary core idea and a cross-cutting concept in the K-121 Science Education Framework and the Next Generation Science Standards (NGSS) [5]. As many authors have noted [6, 7], the energy model in these standards emphasizes the connections between energy and systems. Using energy ideas to interpret or make sense of phenomena means tracking the transfer of energy between systems (including objects and fields) as phenomena evolve.

In [8] examines the extension of the input-output system for a more detailed analysis of the energy consumption associated with industrial production, including some of the difficulties that may arise when measuring cross-industry transactions in terms of physical units of production rather than in monetary terms of the value of output. An analysis of the costs of energy production is considered, taking into account modern approaches, as well as the strengths and weaknesses of alternatives widely used today. Special methodological considerations, such as adjustments to energy conversion efficiency, are being developed, as well as several illustrative applications, including estimating the energy costs of goods and services, the impact of new energy technologies, and energy taxes. Energy input and output analyses are increasingly being applied to global issues, such as energy embodied in international trade in goods and services. Finally, the role of structural changes in the cross-sectoral economy, associated with changes in energy use patterns, is illustrated on the basis of more general approaches.

Object-oriented approach and general architecture of intellectual software for mathematical modelling of dynamic energy systems proposed [9].

In work [10] presents a unified method based on convex optimization to control over time the power produced and consumed by a network of devices. Starting with a simple setup for optimizing power flows in a static network, then the case of optimizing dynamic power flows, i.e., power flows that change over time looked. The method is used to develop a real-time control strategy of predictive control, which at each time step solves the problem of dynamic optimization of the power flow, using forecasts of future quantities, such as demand, capacity, or prices, to select current power flow values. The problem of predictive model management, which explicitly takes into account uncertainty in forecasts, is considered. Examples of implementation are given. Some methods of making forecasts based on historical data are described.

The problem of distributing the customer's requirements for the load on the existing power units in order to ensure reliable and safe operation of the system is analyzed [11]. In this way, a generation schedule is determined for the existing generating units to meet the projected load demand over a period of time at lower production costs, taking into account the rate of ramp-up and capacity reduction and other necessary constraints.

Typical problems of the power distribution system include [12]: differences in generation and demand, power outages and undervoltages, environmental problems due to the burning of natural resources in power plants, and reliability problems. This study [12] aims to improve the performance and mitigate the power quality problems associated with the distribution system. Voltage fluctuations in the grid are among those problems of electricity distribution that make it difficult to solve the problem of ensuring the load schedule of the power system. A power quality compensation strategy is needed to ensure reliable operation and reduce power surges [12]. The paper proposes a complex device of the third generation to ensure the flexibility of the control system, which ensures the reliability of the local load distribution system, the absence of voltage dips and spikes. The results of the simulation in MATLAB/Simulink [12] confirmed the performance of the presented control approach and the efficiency of load distribution.

Forecasting the energy consumption of energy-intensive buildings [13] is one of the objectives of improving the efficiency of energy saving and provides an opportunity to improve the strategy of building management. Reliable forecasting methods can identify the most significant factors influencing a building's energy consumption. Study [13] proposed two approaches to predicting and estimating a building's daily energy consumption. The first is based on multiple regression, while the second is based on the use of an artificial neural network. The analysis, made by comparing the projected consumption with the actual data set of the same building, showed that both models performed reasonably well. The mean absolute percentage error of the multiple regression model is 3.34 % and 2.44 % for business days and 5.12 % and 4.59 % for non-working days, respectively. The results of the neural network are estimated to be slightly better than multiple regression models [13]. The authors believe that the proposed approach to energy forecasting can be easily adapted to predict the energy consumption of different buildings.

The book [14] discusses technologies and models for optimizing the use of renewable energy sources and integrating power systems. The studies presented in [14] cover smart grid technologies, global management of solar radiation forecasting, and econometric models. The results of the assessment of the efficiency of photovoltaic systems are also presented. Various models and approaches to improving power generation systems in the context of a rapid increase in the capacity of renewable energy sources are described.

To predict the availability of solar generation in work [15], which is part of the book [14], a fuzzy regression model is proposed. According to the authors, it is a good alternative to the standard regression model. It is planned to use the model to predict the efficiency of a solar power plant at Universiti Teknologi PETRONAS (UTP), Malaysia.

The efficiency of energy saving, particularly in the cooling of buildings, is discussed in chapter [16] of the book [14]. As the increase in the amount of energy required for cooling leads to an increase in electricity consumption, the task of improving intelligent methods for estimating energy consumption becomes urgent [16]. Chapter [16] proposes a method for predicting energy consumption based on an adaptive fuzzy inference model.

In this era of Internet of Thing (IoT) and Big Data [17], observations are collected not as daily, weekly, monthly, quarterly or yearly, but are taken at a finer timescale. These observations [17] are in hourly, minutely, second and then divide into fractions of second have become available mainly due to the advancement in data acquisition and processing techniques. In this chapter [17], high frequency time series data of solar radiation of every 30 s gathered and model using Box and Jenkins methodology. The important advantages of the methodology used [17] include the ability to identify, verify and assess the adequacy of the model.

Paper [18] provides a general description of models of energy systems. Various approaches to energy demand modeling are described. The most widely used approaches in energy system models are discussed: optimization using linear programming and simulation modeling. Economic approaches to energy modeling: partial and general equilibrium modeling are discussed. The scenario approach used in the modeling of power systems is briefly discussed, taking into account information on climate change and the facts of rapid increase in renewable energy capacity.

Papers [19, 20] propose simulation models, the purpose of which is to assess the energy demand of countries and regions of the world in the medium and long term. The models are based on a scenario-based approach, which gives a consistent description of a country's long-term development. The main purpose of using the presented models [20] is to assess the feasibility of meeting a given demand for energy consumption. The following levels are considered: demand, after distribution, after transmission, energy resources and others.

Long-term models of energy systems [21] are widely used in planning, technology assessment, and decision-making analysis. The stated decarbonization goals in the context of rapid technological change increase the importance of taking into account the economic characteristics and technical details of energy system resources, including renewable energy sources, energy storage technologies, carbon capture capacity and nuclear power. Long-term energy models [21], in addition to studies of renewable energy and energy storage prospects, address the future of nuclear power. The study [21] focused on long-term modeling of national energy systems with the goal of developing tools for more in-depth analysis and evaluation of method performance.

Energy storage technologies [22] are aimed at solving grid stability problems associated with the integration of renewable energy sources. The task of matching generating capacity with instantaneous fluctuations in demand remains relevant. Incorporating the high power energy storages into an integrated energy system [22] is seen as one effective way to address this issue. In [22] compiles the economics of energy storage technologies to enable an assessment of the cost-effectiveness of integrating energy storage into IPS. Taking into account the low levelized cost of storing thermal energy and, especially, the possibilities of its long-term storage, the storage devices are an important tool for increasing the reliability of power supply. Since the assessment of the total life cycle cost and profitability of new technologies is widely used, models of the economic efficiency of thermal energy storage are studied in [22].

A review of the above works confirms the expediency of using mathematical models for the development of the pessimistic, reference and optimistic scenarios for the development of energy systems in the context of a low-carbon transition.

2. Model formulation

The proposed model is based on the following considerations and assumptions [1].

It is assumed [1] that the stock of each i-resource multiplied by the k_i factor should not be less than that used in the system per unit of time. A set of coefficients needs for inventories k_i, $i = 1,...,n$ expressed as a diagonal matrix *K*. Vector, which determines the total cost of resources, is *Ax*. Thus, the need for system reserves needed to generate gross issue *x* are given by the vector *KAx*. So, if at step τ it is necessary to ensure gross output $x(\tau)$, then the reserves $s(\tau)$ at the transition to this step must be sufficient to ensure this level of release, i.e. the next inequality is satisfied:

$$KAx(\tau) \le s(\tau).$$

Let $c(\tau)$ – arbitrary assortment set of consumption. To ensure this is necessary to provide a set of gross output *x*, defined by equality:

$$x(\tau) = (I - A)^{-1} c(\tau).$$

So, for this set of consumption $c(\tau)$ at step τ the inequality:

$$KA(I - A)^{-1} c(\tau) \le s(\tau). \tag{1}$$

Restriction (1) is a fundamental limitation of the model with the reserves.

The dynamic modeling is based on the following considerations. Since stocks are limited, growth is possible only if stocks increase. In turn, growth stocks should be provided by production. We can assume that any set of production assortment consists of two parts. The first part of $c'(\tau)$ is the consumption vector at step τ. The second part of the set $\Delta s(\tau)$ is the value of the growth of the reserve. Thus, we have two connections:

$$c(\tau) = c'(\tau) + \Delta s(\tau), \tag{2}$$

$$s(\tau + 1) = s(\tau) + \Delta s(\tau). \tag{3}$$

If current consumption $c'(\tau)$ is set, the system of equations (2) establishes a link between growth stocks and the current stocks. System (3) fixes the relationship between stocks corresponding to two, consecutive, periods of time.

If we denote the ratio of consumption to net release of *i*-resource – as propensity to consume of *i*-resource, we can form a diagonal matrix *D* of propensity to consume.

$$c'(\tau) = Dc(\tau),$$

$$\Delta s(\tau) = (I - D)c(\tau),$$

$$c(\tau) = (I - D)^{-1} \Delta s(\tau). \tag{4}$$

Substituting (4) into (1) we obtain:

$$KA(I - A)^{-1} (I - D)^{-1} \Delta s(\tau) \le s(\tau).$$

If we denote: $K^* = KA(I - A)^{-1}(I - D)^{-1}$ obtain:

$$K^* \Delta s(\tau) \le s(\tau).$$

Growth, in which the ratio $\mu = \Delta s_i(\tau) / s_i(\tau)$ the same for all resources and reserve at least of one resource is used completely (i.e. fundamental restriction (1) there is equality, at least for one resource) is called ***balanced equilibrium growth***. The value of μ is called the growth rate of the system.

Thus, the problem reduces to the solution of a special system of inequalities:

$$K^{*}\Delta s(\tau) \le \frac{1}{\mu}\Delta s(\tau). \qquad (5)$$

As shown in [1], the only solution of (5) are:

$$\frac{1}{\mu^{*}} = \lambda^{*}, \quad \Delta s(\tau) = x^{*},$$

where λ^* – are the dominant root, and x^* – associated characteristic vector of the semipositive indecomposable matrix K^*. This balance is achieved for all resources as a solution of the resulting system becomes an equality all the relations of the fundamental limitations. The above solution system determines $\Delta s(\tau)$ and $s(\tau)$ to all τ.

$$s(\tau) = \left(1+\mu^{*}\right)^{i} s(\varnothing),$$

where $s(\varnothing)$– initial stock levels. Thus, the trajectory of balanced growth can be obtained only if the initial vector of stocks is proportional to their own vector x^*. If the initial stocks not represented in the appropriate proportions, the trajectory of growth is significantly different from the balanced equilibrium growth.

Since K^* has characteristic vectors other than λ^*, there are other balanced growth paths with equalities in constraints. The characteristic root λ^* – is the root with largest modulus. Therefore, the growth rate, which is inverse of root, is smallest for λ^*. However, no other growth paths for this type of characteristic roots other than λ^* have associated nonnegative stock vectors. You can get a balanced growth without equilibrium, if the surplus stocks are presence. However, the rate of balanced growth in that case less than at the balanced. The balanced equilibrium growth rate μ^* has properties of minimax and saddle-point. It is the lowest rate of balanced growth in the market equilibrium, but the largest that does not allow the reduction of stocks.

3. Calculations

In the calculation of pessimistic, reference and optimistic scenarios for the generation and capacities of electricity of IPS of Ukraine, used the following initial information [23–31]:

- official statistical information on the scope and structure of consumption in previous years $E^{cons}_{\tau=0}$;
- projections of consumption scenario obtained on the basis of forecasts for the economy – $E^{cons}_{\tau}, \tau = 1,\ldots,T$;
- forecasts for the cost of power generation – C^{J}_{τ}, $J = TPP, HPP, NPP, WPP, SPP;\ \tau = 1,\ldots,T$;
- forecasts of vectors restrictions required for sustainable operation and development of energy systems:
  1. shunting capacities – $P^{shunt}_{\tau}, \tau = 1,\ldots,T$;
  2. the losses in distribution networks – $E^{losses}_{\tau}, \tau = 1,\ldots,T$;
  3. the specific fuel consumption for electricity supplied – $p^{spec}_{\tau}, \tau = 1,\ldots,T$;
  4. the share of renewable energy in gross final energy consumption – $K^{RES}_{\tau}, \tau = 1,\ldots,T$;
  5. the energy intensity of GDP – $e^{GDP}_{\tau}, \tau = 1,\ldots,T$;
  6. the maximum amounts of generation – $E^{J}_{\max,\tau}$, $J = TPP, HPP, NPP, WPP, SPP;\ \tau = 1,\ldots,T$;
  7. environmental restrictions on emissions, etc..

In the process of the scenarios calculating the problem of minimum total cost Q^{gen} of generating electric power for the period of simulation solved:

$$Q^{gen} = \sum_{\tau}^{T}\sum_{J} Q^{J}_{\tau} \Rightarrow \min,\ J = TPP, HPP, NPP, WPP, SPP;\ \tau = 1,\ldots,T,$$

subject to the limitations mentioned above.

The calculated pessimistic, reference and optimistic scenarios of generation and capacities are given in Table 1 and on Fig. 1, 2 and 3.

Table 1. Pessimistic, reference and optimistic scenarios of generation and capacities

	2020	**2025**	**2030**	**2035**	**2040**	**2020**	**2025**	**2030**	**2035**	**2040**	**2020**	**2025**	**2030**	**2035**	**2040**
	Pessimistic scenario					**Reference scenario**					**Optimistic scenario**				
Generation	**GWh**														
Total	137	140	190	212	217	137	140	202	230	237	137	140	213	249	258
TPP	54	36	64	81	74	54	36	64	84	88	54	36	65	87	102
HPP	5.6	2.5	6.2	6.5	8	5.6	2.5	6.4	6.9	8	5.6	2.5	6.7	7.3	8
NPP	76	96	106	105	111	76	96	117	119	117	76	96	128	133	123
WPP	0.7	2.0	4.2	8.3	11.9	0.7	2.0	4.4	8.9	11.9	0.7	2.0	4.6	9.5	11.9
SPP	0.4	3.9	9.1	11.3	12.4	0.4	3.9	9.1	11.5	12.4	0.4	4.0	9.2	11.9	12.4
Generating capacities	**GW**														
Total	52.4	42	64.6	77.3	83.5	52.4	42.1	68.7	83.8	91.2	52.4	42.1	72.4	90.7	99.3
TPP	28.0	19.8	35.4	45	41	28	19.8	35.4	46.6	48.8	28.0	19.8	35.9	48.3	56.6
HPP	13.8	16.0	19.6	19.7	20.40	13.8	16	20.3	20.9	20.4	13.8	16.0	21.2	22.1	20.4
NPP	4.8	1.8	4	4.2	5.2	4.8	1.8	4.4	4.7	5.5	4.8	1.8	4.8	5.3	5.8
WPP	1.0	0.80	1.64	3.23	4.6	1.00	0.80	1.72	3.47	4.6	1.0	0.8	1.8	3.7	4.6
SPP	4.8	3.71	8.70	10.7	11.80	4.80	3.71	8.70	10.9	11.8	4.8	3.8	8.8	11.3	11.8

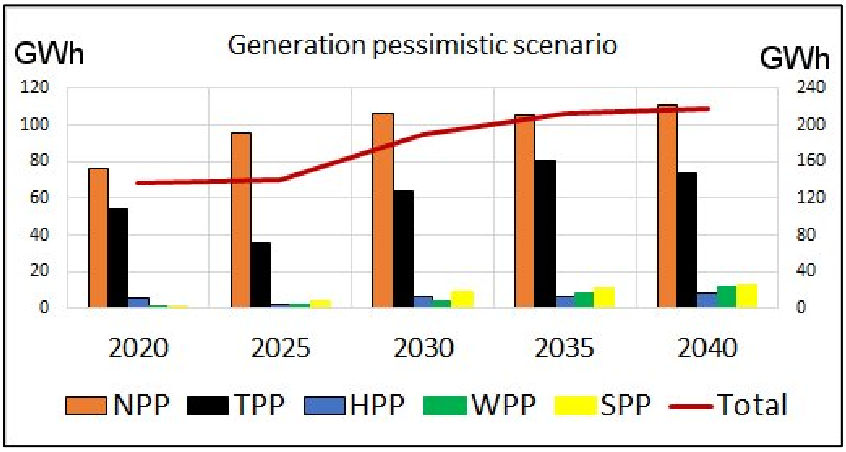

Fig. 1. Pessimistic generation scenario

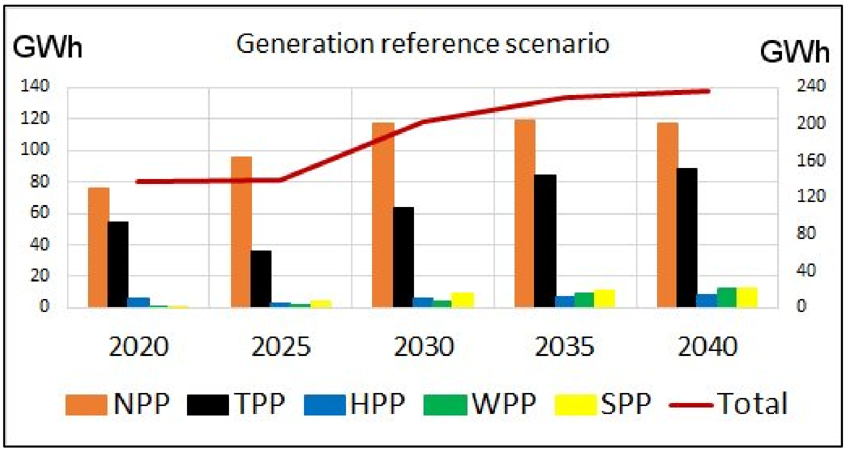

Fig. 2. Reference generation scenario

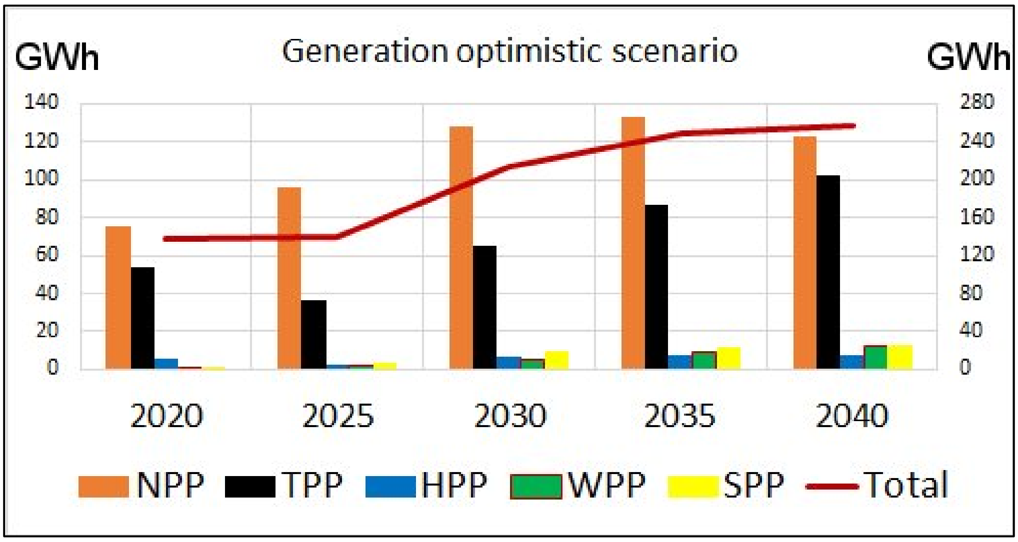

Fig. 3. Optimistic generation scenario

4. Discussion

The use of the proposed dynamic model for the development of reference scenarios of the power system in the conditions of low-carbon transition, made it possible to make forecast calculations of the development of the annual volumes of the total generation for the IPS of Ukraine until 2040. In the process of these calculations on the modeling horizon from 2020 to 2040, a forecast of the generating capacities structure was obtained. The results obtained allow us to consider the proposed approach to modeling integrated power systems promising.

5. Conclusions

The proposed model for dynamic development of the Integrated Power System (IPS) of Ukraine is built upon a set of considerations and assumptions. The model takes into account the balance between resource stocks, consumption, and production growth, incorporating constraints and inequalities to ensure a systematic and sustainable approach. The primary assumptions involve the necessity for the stock of each resource to meet the system's demands. The dynamic nature of the model is driven by the need for system reserves to generate gross output, balancing consumption and production growth. Fundamental limitations are established through inequalities, ensuring that the reserves at each step are sufficient to meet the required gross output. These constraints form the basis for the dynamic modeling, emphasizing the interconnectedness between current and future stocks, as well as the growth of reserves. The proposed model provides a comprehensive framework for understanding the dynamics of resource stocks, consumption, and production growth within the context of the IPS of Ukraine. It offers a valuable tool for decision-makers to optimize electricity generation strategies, considering a range of scenarios and constraints for a sustainable and cost-effective energy system.

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ДИНАМІЧНІ МОДЕЛІ РОЗРОБКИ ЕТАЛОННИХ СЦЕНАРІЇВ ЕНЕРГЕТИЧНОЇ СИСТЕМИ В УМОВАХ НИЗЬКОВУГЛЕЦЕВОГО ПЕРЕХОДУ

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Анотація. *Запропоноване дослідження спрямоване на розробку динамічних моделей «витрати-випуск» в системах розвитку енергетики. Основне завдання полягає в тому, щоб знайти оптимальні сценарії, що визначаються як послідовності оптимальних балансів між виробництвом і капітальними інвестиціями. Основою цих моделей є концепція Леонтьєва «вхід-випуск» з акцентуванням на умовах впровадження нових виробничих систем. У статті розглянуто економічну інтерпретацію та математичні умови міжгалузевих моделей, а також їх застосування до проблем, пов'язаних з енергетикою. У моделі використовується концепція збалансованого рівноважного зростання, при якій відношення споживання до чистого виробництва однаково для всіх ресурсів, а резерв хоча б одного ресурсу використовується повністю. Темп зростання системи є найважливішим параметром, що визначає траєкторію збалансованого зростання. Розв'язання системи нерівностей дає збалансовані траєкторії зростання, в яких ключову роль відіграє домінуючий корінь і пов'язаний з ним вектор характеристик. Збалансований рівноважний темп зростання має властивості мінімаксу з наявністю сідлоподібної точки, що вказує на його важливість у досягненні ринкової рівноваги при недопущенні скорочення запасів. Описано практичне застосування моделі. Наведено результати розрахунків песимістичного, референтного та оптимістичного сценаріїв виробництва електроенергії в ОЕС України. Використовується офіційна статистична інформація та економічні прогнози, враховуються технологічні та економічні обмеження. Модель спрямована на мінімізацію загальної вартості виробництва електроенергії з дотриманням екологічних та експлуатаційних обмежень. Запропонована модель забезпечує комплексну основу для розуміння динаміки ресурсних запасів, споживання та зростання виробництва електроенергії ОЕС України. Може бути корисною для осіб, що приймають рішення, є цінним інструментом для оптимізації стратегій виробництва електроенергії з урахуванням низки сценаріїв та обмежень для сталої та економічно ефективної роботи енергетичної системи.*
Ключові слова: динамічні моделі витрати-випуск, оптимальні сценарії, збалансоване рівноважне зростання, швидкість зростання системи.

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