ISSN 2786-7102 (Online), ISSN 2786-7633 (Print)
https://doi.org/10.15407/srenergy2023.02.038

UDC 620.621.31:339.944

Tatiana Eutukhova[1], PhD (Engin.), Associate Professor, https://orcid.org/0000-0003-4778-2479
Iliya Iliev[2], Dr. Sci. (Engin.), Professor, https://orcid.org/0000-0002-0947-4865
Oleksandr Novoseltsev[3]*, Dr. Sci. (Engin.), Senior Research Scientist, https://orcid.org/0000-0001-9272-6789
Yevhen Nikitin[3,4], Dr. Sci. (Engin.), Senior Research Scientist, https://orcid.org/0000-0002-0173-6461
Yevhen Shcherbyna[3], PhD (Engin.), https://orcid.org/0000-0002-1565-4547
[1]Interregional Academy of Personnel Management, 2, Frometivska St., Kyiv, 03039, Ukraine;
[2]University of Ruse Angel Kanchev, 8 Studentska St., POB 7017, Ruse, Bulgaria;
[3]General Energy Institute of NAS of Ukraine, 172, Antonovycha St., Kyiv, 03150, Ukraine;
[4]The Gas Institute of the NAS of Ukraine, 39, Degtyarivska St., Kyiv, 03113, Ukraine
*Corresponding author: anovos@nas.gov.ua

METHODOLOGICAL PLATFORM FOR DETERMINING ENERGY EFFICIENCY INDICATORS OF A COMPLEX SYSTEM

Abstract. *The correct determination of the energy efficiency (EE) of a complex system is a problematic task that requires the use of specialized methods and approaches. Most often, EE is considered as an indicator of the quality-of-service provision, which most fully corresponds to the technical and economic essence of this indicator. The structural and functional organization of the system of such indicators is carried out either on a bottom-up approach or a top-down approach, gradually deploying macroeconomic indicators defined at the system levels. This paper considers the tensor form of organization of the system of such indicators, which allows combining within a single model not only their organizational levels (economy as a whole, economic sectors, enterprises, technologies and equipment), but also the types of activities that reflect these indicators (energy, financial, economic, institutional, environmental, social, etc.), and the factors of changes in energy use (structural, technological, resource, managerial, regulatory, etc.). The paper presents the mapping of this model on the plane of structural and functional factors in the form of classification tables (matrices) of these factors (system elements). The paper describes the procedure for optimizing indicators, which can be carried out for each of these factors separately, their aggregate at each level and for the system as a whole, taking into account the need to implement iterative procedures for coordinating the global (system-wide) goal and local objective functions. Given the use of optimization variables measured in energy and monetary units, this problem is formalized within the framework of the set-theoretic approach. For the purpose of comparing the results, the paper examines the relevant provisions of the International Energy Agency methodology, which uses the direct method of three-factor Laspeyres decomposition analysis, and the Sectoral Methodology for Calculating Harmful Emissions of the Ministry for Communities and Territories Development of Ukraine.*
Keywords: Energy efficiency, energy efficiency indicators, system analysis, tensor approach.

1. Introduction

Energy efficiency (EE) is recognized worldwide as a strategic priority for providing consumers with reliable, sustainable, competitive and affordable energy. According to the EU directives [1]–[2], energy efficiency is defined as the ratio of the output of products, services, goods or energy to the input energy, and by its market nature is currently considered by the scientific and business community as an indicator of the quality of services that are improved when a certain level of service is provided using less energy or services are improved with a certain amount of energy [3]–[5].

Despite the simplicity and transparency of the definition, the results of implementing EE measures are ambiguous both conceptually and practically due to the over-simplification of efficiency calculation procedures based on the principle of one input energy parameter – one output energy parameter. This is especially problematic at the macroeconomic scale, where a significant amount of essential information is lost due to data aggregation. At the same time, EE indicators should also cover such areas as reducing pollutant emissions, energy security, prices and tariffs of fuel-and-energy resources (FER), labor productivity, job creation, ensuring equal access to energy resources, public health and welfare, etc.

The need and expediency of applying a system approach to identify the essence of EE was proven by the scientific community several decades ago [3]–[5]. According to this approach, the structural and functional organization of the system of EE indicators, covering both local (subordinate) and system-wide indicators, is carried out either on a bottom-up approach, gradually aggregating the efficiency indicators of technologies and equipment, located at the lower level of the hierarchy (at the level of final energy use), or by the top-down approach, gradually deploying macroeconomic indicators defined at the level of the system under consideration (the country as a whole, sectors of the economy, enterprises, complex technologies and equipment, etc. But direct aggregation, which is carried out by summing up, grouping, or in other ways reducing local (partial) indicators into one generalized indicator, leads, as a rule, to the loss of a significant part of the essential information embedded in partial indicators. The deployment procedure leads to practically the same result.

In order to overcome this problem and highlight the contribution of EE to the reduction (increase) in energy consumption, methods of decomposition (factor, etc.) analysis of indicators are most often used to identify the cause-and-effect relationships leading to changes in energy consumption [3], [6]–[9]. The magnitude of these changes, the so-called 'efficiency effect', is used to quantify EE improvements, which can also be categorized into activity, structure, and efficiency categories of indicators [10]. Activity indicators are classified by sectors (subsectors) and types of end-users of energy and are reflected in the corresponding impact indicators, primarily such as value added, population, passenger and ton-kilometers in transport. The structure indicators are determined by the factors of influence for each sector (subsector) of activity, primarily such as the share of production in each subsector of the economy, the area and number of residential premises, the distribution of ownership in the residential sector, the share of passenger and freight vehicles by their types, etc. EE is measured by the amount of energy used per unit of activity in each sector (subsector). Among other fruitful approaches of decomposition analysis to determining the performance indicators of complex systems, we note the possibility of using multi-stage and balance-product models [11]–[12].

The results of a deep comparative analysis of the disadvantages of the simplified and advantages of the structural and functional approaches to determining the system of EE indicators are presented in the paper [13], where, based on the concept of the metabolic model of socio-ecological systems, an alternative method in the form of an end-use matrix is proposed. This method makes it possible to study the EE of complex systems, largely avoiding the practical and conceptual problems of simplification associated with the calculation of input/output coefficients.

The purpose of this work is to improve the efficiency of complex systems by building a methodological platform for determining energy efficiency indicators, which makes it possible to improve the methods for their calculation and practical use in complex systems.

Achieving this purpose required the development of a new, generalized approach for determining energy efficiency indicators in complex systems, which differs from the known ones by new possibilities for taking into account input/output indicators at each stage of their aggregation due to theoretical set methods of their structural and functional organization, presented in tensor form, which makes it possible to preserve the essential properties of these indicators.

2. Methods and materials

The application of the tensor form of the structural and functional organization of the system of indicators presented in paper [5], made it possible to combine within a single model not only organizational levels of performance indicators (economy as a whole, economic sectors, enterprises, technologies and equipment), but also the types of activities that reflect these indicators (energy, financial, economic, institutional, environmental, social, etc.), and the factors of changes in energy use (structural, technological, resource, managerial, regulatory, etc.).

The mapping of this model to the plane of the j-th level of structural and functional factors in the form of a classification table (matrix) of these factors (system elements) is presented in Table 1.

Table 1. Components of mapping the tensor form of the system of indicators on the plane of structural and functional factors

Structural factors / *Functional factors*	Conditionally permanent funds	Conditionally variable resources	Labor resources and management	Efficiency and quality	Measurement costs	Natural & social needs	Competition losses
Administrative & organizational	F_1^{j1}	F_1^{j2}	F_1^{j3}	F_1^{j4}	F_1^{j5}	F_1^{j6}	F_1^{j7}
Production & technological	F_2^{j1}	F_2^{j2}	F_2^{j3}	F_2^{j4}	F_2^{j5}	F_2^{j6}	F_2^{j7}
Financial & economic	F_3^{j1}	F_3^{j2}	F_3^{j3}	F_3^{j4}	F_3^{j5}	F_3^{j6}	F_3^{j7}
Normative & legal	F_4^{j1}	F_4^{j2}	F_4^{j3}	F_4^{j4}	F_4^{j5}	F_4^{j6}	F_4^{j7}
Strategic & innovative	F_5^{j1}	F_5^{j2}	F_5^{j3}	F_5^{j4}	F_5^{j5}	F_5^{j6}	F_5^{j7}
Ecological	F_6^{j1}	F_6^{j2}	F_6^{j3}	F_6^{j4}	F_6^{j5}	F_6^{j6}	F_6^{j7}
Information & marketing	F_7^{j1}	F_7^{j2}	F_7^{j3}	F_7^{j4}	F_7^{j5}	F_7^{j6}	F_7^{j7}

The elements of this table are two-element tuples of the Cartesian product of sets $F_h^j i = S_h^j i \times G_h^j i, i = (1, n), h = (1, m),$ where S_h^{ji} represents structural and G_h^{ji} represents functional factors of influence, n × m is the number of elements of the classification table. Note that the limitation of the field of factors in Table 1 to 7×7 is not accidental. It reflects the categories of these factors determined by the results of a systemic analysis of the Ishikawa, Gantt, Pareto, Lorenz, etc. models developed in the theory of product quality management [14]–[17] and supplemented by factors that reflect natural and socio-political conditions, consumer needs, and the specifics of competitive interaction and struggle [5].

The list of defined structural factors includes: S_h^{j1} – conditionally permanent resource funds (building structures, equipment and technologies, structural elements of any nature, etc.); S_h^{j2} – conditionally variable resources (materials, fuel and energy and other natural resources); S_h^{j3} – labor resources (management and staff); S_h^{j4} – methods and mechanisms for improving the efficiency and quality of the system, profitability, etc.; S_h^{j5} – measurement and verification costs; S_h^{j6} – natural and socio-political conditions, priorities and needs of consumers; S_h^{j7} – resources and costs of competitive interaction and struggle. The corresponding list of functional factors includes: G_1^{ji} – administrative and organizational; G_2^{ji} – production (technical and technological); G_3^{ji} – financial and economic; G_4^{ji} – regulatory; G_5^{ji} – strategic and innovative development; G_6^{ji} – environmental; G_7^{ji} – information and marketing.

For example, in the process of further decomposition, it is proposed to distinguish between [5], [18]–[19]:

– The S_h^{j4} category of factors includes methods and mechanisms for integrated resource planning, energy management, regulatory and tariff regulation, and economic incentives for energy efficiency and energy saving;

– Among the category of factors S_h^{j6} are those that take into account the specific characteristics of different consumer groups (population, households, industrial enterprises and budgetary institutions, etc.): per capita income, average monthly wages by consumer category, their availability of FER, natural conditions (temperature, wind speed, number of sunny days, etc.);

– S_h^{j7} factors include rivalry between competitors within the industry, the threat of new competitors and entry barriers, threats from competitors trying to flood the market with substitute goods, the ability of suppliers of materials, fuel and energy resources, equipment, etc. to dictate their terms.

3. Results and discussion

It is clear that, according to the tensor model, the reflection of the factors of influence of the j-th level can be generalized at the (j+1)th level or detailed at the (j-1)th level of the hierarchy of performance indicators of the complex system under consideration. At the same time, optimization of these indicators can be carried out for each of these factors separately, their aggregate at each level and for the system as a whole, which, in turn, will require the implementation of iterative procedures for coordinating the global (system-wide) goal and local objective functions. The described optimization procedure is a multi-criteria optimization problem, which is complicated by the need to implement a systematically coordinated change in the parameters of the objective functions. There is no general solution to the formulated problem, but if the optimization variables are measured in energy and monetary units, its formalization becomes possible within the framework of the set-theoretic approach [5]. Thus, applying in our case the mathematical signs of intersection of sets, at the level of functional factors of influence, we obtain the system of the following equations:

$$\begin{cases} \theta_s^j = (\theta_1^j \cap \theta_2^j \cap \theta_3^j \cap \theta_4^j \cap \theta_5^j \cap \theta_6^j \cap \theta_7^j) \to opt; \\ \theta_1^j = (L_1^{j1} \cap L_1^{j2} \cap L_1^{j3} \cap L_1^{j4} \cap L_1^{j5} \cap L_1^{j6} \cap L_1^{j7}) \to opt; \\ \theta_2^j = (L_2^{j1} \cap L_2^{j2} \cap L_2^{j3} \cap L_2^{j4} \cap L_2^{j5} \cap L_2^{j6} \cap L_2^{j7}) \to opt; \\ \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \\ \theta_1^j = (L_7^{j1} \cap L_7^{j2} \cap L_7^{j3} \cap L_7^{j4} \cap L_7^{j5} \cap L_7^{j6} \cap L_7^{j7}) \to opt; \end{cases} \qquad \begin{cases} \theta_s^j - \theta_1^j \to min; \\ \theta_s^j - \theta_1^j \to min; \\ \theta_s^j - \theta_2^j \to min; \\ \dots\dots\dots\dots; \\ \theta_s^j - \theta_7^j \to min, \end{cases} \quad (1)$$

where: θ_s^j – system-wide objective function; θ_h^j – local objective functions of functional factors, $h = \overline{1,7}$; L_h^{ji} – objective functions of the constituent functional factors detailed at the level of structural factors.

It should be noted that among the local optimization objective functions, the most commonly used in business activities are the following: revenue growth, increase in volume and expansion of the range of products (services), reduction of their cost and improvement of quality, focus of products (services) on meeting consumer needs, improvement of employee welfare, etc. It is important that the objective functions formalized on their basis have a strict correlation with efficiency (energy, technological, economic, environmental, social, etc.). At the same time, we note that the organizational structure of the factors of influence of energy services has its own specific features that require separate consideration and justification, and where the matrix form of displaying the structure of these services is among the problematic issues [3], [20]. Among other influential factors of energy efficiency, we note the feasibility of technical implementation, viability of energy efficiency measures, the degree of use of materials and equipment of domestic production, which contribute to strengthening the national economy and affect the employment and income of the population, transparent procedures for access to the market of energy services. At the same time, in any circumstances, the time factor should be decisive, which integrally covers the resources required to implement energy efficiency measures, from the development of design and construction documentation to obtaining an energy-saving effect, and where short-term measures will have a higher priority over medium- or long-term ones [21].

Further detailing of the variables in equations (1) to the level of parameters of functioning of energy-intensive equipment is no less difficult task, which will require taking into account the impact of a comprehensively integrated set of performance indicators for the provision of energy services of the production system as a whole, which in turn cover such subsystems as [5], [21]–[22]:

– energy management, based on the Schuchart-Deming PDSA model of continuous quality improvement (W. Shewhart and W. Deming), which consists of a logical sequence of four stages: planning, execution, inspection and action;

– demand-side management, which is based on incentivizing consumers to use less energy instead of increasing investment in generation systems. For example, the U.S. Energy Policy Act of 2005 uses time-based pricing or incentive payments to encourage lower electricity consumption during times of high market prices or when grid reliability is at risk;

– integrated resource planning, which covers the entire range of alternatives for the use of FER, including the construction of new generating capacities, energy saving and energy efficiency, cogeneration, district heating and cooling, use of renewable energy sources (RES), etc. to provide energy to consumers at the lowest system costs;

– comprehensive implementation of a package of services (measures) to improve energy efficiency and use of renewable energy sources in energy-intensive technological processes, such as heating, cooling, lighting, ventilation, etc.;

– taking into account the influence of central and local (municipal) authorities, regulators, commercial banks, investors, manufacturers of EE and RES equipment, primary energy suppliers, consumers of products and services, etc.;

– organizing the process of managing the risks of implementing energy-saving measures, including using financial support mechanisms.

The most complete detailing of the performance indicators of energy-intensive technologies and equipment is presented in [3], [23] and their specification for heat and power systems is presented in [24]. These papers consider natural gas, coal, renewable sources, etc. as primary energy sources, and electricity and heat as secondary energy sources. The decomposition at the level of economic sectors distinguishes between such sectors and subsectors of total final energy consumption as housing and communal (domestic), industrial (by type of energy-intensive technology), trade (commercial) and public services, transport, and others, while the disaggregation of performance indicators at the level of the housing and communal and service sectors includes such indicators as heating and cooling of premises, supply of cold and hot water, lighting, cooking, household appliances, etc.

The scheme of detailing EE indicators at the level of economic sectors or subsystems under consideration can be summarized as determined by the following hierarchically organized structure of indicators: total energy consumption by the sector, calculated separately or as a share of total final consumption in the country (system) as a whole; share of each type of energy source in the total energy balance of the sector (system); specific energy consumption in the sector (system) per capita (per employee); distribution of total energy consumption in the sector (system) by types of economic activity and/or by individual types of energy-intensive technologies (technological equipment, etc.). A similar hierarchical structure is used to decompose the indicators at lower levels of the hierarchy by taking into account the specifics of the influencing factors.

The final stage in the formation of a system of EE indicators is to determine methods and algorithms for calculating and further optimizing their numerical values in order to improve the structure and modes of operation of the system they characterize. Among such methods and algorithms, we would like to mention, first of all, benchmarking, which includes: studying and adapting the methods and tools of other enterprises (organizations, etc.) in order to identify best practices; comparing indicators, functions and processes of their activities with similar functions and processes of their own enterprise (organizations); estimating the costs of improving their own results; creating benchmarks for assessing internal EE indicators in comparison with best practices; developing methods for making operational decisions; and developing methods for improving the efficiency of the system. In other words, the scope of benchmarking should cover not only the technological, but also the economic and financial aspects of the activities of enterprises and organizations, allowing them to save time and money on inventing and testing various practices, products and processes by implementing the best of them and avoiding competitors' mistakes [25].

It is clear that the implementation of these tasks should be carried out on the principles of continuous improvement of planning, design, implementation, measurement and correction of the results achieved, which becomes possible on the basis of intelligent (smart) information management systems aimed at motivating management actions to achieve strategic, tactical and operational goals of the enterprise (organization), and the creation of benchmarks for assessing internal EE indicators in comparison with best practices should be carried out on the basis of market-based normalizing tools.

The concepts of norm and standardization are widely used in the world practice, where they serve for comparison with normalized or benchmark performance indicators of the same category of facilities and are responsible for implementation and/or monitoring of energy or carbon taxation, financial schemes and economic incentives, sanctions, standards and agreements, energy labeling schemes etc., resulting in reduction of final energy consumption and CO_2 emissions [1]–[2], [25]. In this context, the term rate of consumption of material resources is usually understood as the maximum allowable planned amount of raw materials, materials, fuel, energy for the production of a unit of output. According to the Law of Ukraine [26], the norms of specific fuel and energy consumption define the regulated value of specific FER consumption for a given production, process, product, work, service. Consumption rates should take into account specific conditions, technology and organization of production, advances in science and technology, be focused on the best practices of FER use and be systematically reviewed taking into account the achieved EE indicators and objective changes in production conditions. It should be added that regulation becomes an effective tool for eliminating the irrational use of FER when implemented on the principles of economic incentives for FER saving and financial responsibility for their irrational use.

The final step in the analysis of EE indicators is to identify sources and quantify the contribution of the most important factors to changes in energy consumption that occur due to improved technologies, structural changes in the economy as a whole and in individual industries, for example, due to an increase in the share of less energy-intensive activities, changes in the utilization of production equipment, prices for energy, equipment, materials and services, in weather conditions, the level of housing improvement, etc. To highlight the impact on the dynamics of energy consumption of technical and technological factors that most fully reflect changes in EE, different countries use different forms and methods of decomposing the contribution of individual factors to energy consumption.

The theoretical foundations of such a decomposition analysis are discussed in many scientific works, for example, in [3], [9], [27]–[29], where, first of all, the methods of Simple and Refined Laspeyres Indices, methods of Log Mean Divisia Index (LMDI I and LMDI II), Fischer Ideal method, Tornqvist Simple Average/Arithmetic Mean, Parametric and Adjusted Divisia Methods (PMD I and PMD II), Paasche method, etc.

For example, one of the most widely used methodologies of the International Energy Agency (IEA) uses the direct method of three-factor Laspeyres decomposition analysis, presented in additive and/or multiplicative forms. According to this method, the decomposition in the additive form of changes in the final energy consumption of a complex system (object of research) formalizes as follows. Among the list of main factors, the IEA methodology defines activity ("A"), structure ("S", types of activities, etc.) and energy intensity ("I"). Then the total energy consumption (E) of the system is represented by the sum of the energy consumption of its individual subsystems in the form [30]:

$$E = \sum_i E_i = A \cdot \sum_i \left(S_i \cdot I_i \right) , \quad (2)$$

where: A is the system performance indicator; S_i is the share of the i-th subsystem in the total system performance, if all shares are measured in the same units, or the ratio of the performance indices of the i-th subsystem to the system as a whole; I_i is the energy intensity of the i-th subsystem.

Then, the partial time derivative of E as a function of the three variables (A, S, I) in equation (2) will be as follows:

$$\frac{\partial E}{\partial t} = \sum_i (S_i \cdot I_i) \cdot \frac{\partial A}{\partial t} + A \cdot \sum_i I_i \cdot \frac{\partial S_i}{\partial t} + A \cdot \sum_i S_i \cdot \frac{\partial I_i}{\partial t}.$$

Hence, through finite increments on the time interval [0, T], we obtain:

$$\Delta E_{0,T} = \Delta E_{0,T}^{A} + \Delta E_{0,T}^{S} + \Delta E_{0,T}^{I} + \Delta R_{0,T} = \left(E_T^A - E_0^A\right) + \left(E_T^S - E_0^S\right) + \left(E_T^I - E_0^I\right) + \Delta R_{0,T},$$

where:

$$\begin{aligned} \Delta E_{0,T}^{A} &= \left(E_T^A - E_0^A\right) = A_T \cdot \sum_i (S_0^i \cdot I_0^i) - A_0 \cdot \sum_i (S_0^i \cdot I_0^i), \\ \Delta E_{0,T}^{S} &= \left(E_T^S - E_0^S\right) = A_0 \cdot \sum_i (S_T^i \cdot I_0^i) - A_0 \cdot \sum_i (S_0^i \cdot I_0^i), \\ \Delta E_{0,T}^{I} &= \left(E_T^I - E_0^I\right) = A_0 \cdot \sum_i (S_0^i \cdot I_T^i) - A_0 \cdot \sum_i (S_0^i \cdot I_0^i), \end{aligned} \qquad (3)$$

$\Delta E_{0,T}^{A}, \Delta E_{0,T}^{S}, \Delta E_{0,T}^{I}$ – distinguish changes (growth) in the components of the system's energy consumption at the beginning and end of the time interval [0, T] due to the influence of each of the factors (*A*, *S*, *I*), respectively; $\Delta R_{0,T}$ is the residual part of the analysis; *i* is the number of the subsystem or type of final energy consumption.

Let's consider the possibility of further specifying the contribution to the total energy consumption of individual factors of influence reflected in (2)–(3).

Thus, if it is necessary to separately take into account the level of production capacity utilization, which significantly affect the dynamics of energy consumption, the components in formula (2) take on the following meaning: the actual output of marketable products in the time interval [0, T] is used as the activity factor (A) of the system; the structure factor is $S_i = G_i \cdot k_{Gi}$, where: G_i is the share of products produced by the i-th technology in the time interval [0, T], and k_{Gi} is the coefficient determined by the ratio of the actual weighted average capacity of the equipment used by the i-th technology to the nominal (nameplate) capacity of this equipment in the time interval [0, T] or the ratio of the actual output of marketable products by the i-th technology in the time interval [0, T] to the planned (design) output; the energy intensity factor I_i is defined as the specific energy consumption in the time interval [0, T] for the production of a unit of marketable product by the i-th technology under the conditions of the nominal load of the equipment. At the same time, the technological structure of production and the level of production capacity utilization fall within the scope of decomposition analysis.

Accordingly, at the level of subsystems analysis, for example, for the residential and public buildings heating subsystem, the components of formula (2) take on the following meaning: the total floor area of residential and public buildings at the time interval [0, T] is used as the activity factor (*A*) of the system; the structure factor is $S_i = F_i \cdot k_{Fi}$, where: F_i is the share of i-th building type (multi-storey, single-storey private houses, etc.), and k_{Fi} is the share of heated living space in i-th building type at the time interval [0, T]; the energy use intensity factor is defined as $I_i = \left(I_{Fi} \cdot HDD_i\right)$, where: I_{Fi} is the specific energy consumption for heating 1 m^2 of floor area per 1 degree day of the heating period for buildings of the i-th type under normal weather conditions or base year conditions; HDD_i is the number of degree days of the heating period in the time interval [0, T] depending on the geographical location of the building.

If there is a need to analyze gross emissions of pollutants and greenhouse gases, primarily CO_2 emissions from fuel combustion at power plants, the content of the components in formula (2) is proposed to be determined as follows: use the consumption B_i of the i-th type of fuel at the time interval [0, T] as a factor of system activity *A*; the structure factor S_i is determined by the emission rate k_{iCO_2} for the i-th type of fuel burned at the time interval [0, T]; and the energy use intensity factor I_{iCO_2} is the lower heating (calorific) value of the i-th fuel Q_i^r.

To perform numerical calculations of gross CO_2 emissions entering the atmosphere with flue gases from a power plant over a time interval [0, T], the dimensionality of the presented above components is as follows (see, for example, [31]–[32]):

$$W_i\left(m\right)=10^{-6}\cdot B_i\left(m\right)\cdot k_{iCO_2}\left(\frac{g}{GJ}\right)\cdot Q_i^r\left(\frac{MJ}{kg}\right),$$

where W_i is the gross CO_2 emissions from the combustion of the i-th fuel for the reporting period.

For example, when burning natural gas, $B_i = V\cdot h$, where *V* is the volume of gas consumed (m^3), *h* is its density under normal conditions, kg/m^3.

An environmental tax is established at the national level for the emission of pollutants and greenhouse gases into the environment, the rates of which in Ukraine in 2023 were equal to: for carbon dioxide (CO_2) – UAH 30.00 per ton; for carbon monoxide (CO) – UAH 96.99 per ton; for nitrogen oxides (NO_X) – UAH 2574.43 per ton, etc. [33].

4. Conclusions

Simplifications associated with the use of the concepts of composition/decomposition of energy efficiency indicators of the input/output type, for example, the energy intensity of GDP determined on this basis, do not allow objectively solving the problems of improving the energy efficiency of complex socio-economic systems, where it is necessary to take into account the structural and functional processes of changing energy flows at different levels of system organization.

This requires the development of other concept and methods that make it possible to form energy efficiency indicators for the functioning of socio-economic systems, distinguishing between different types of energy resources, the processes of their production, distribution and final consumption, and ultimately achieving their more justified reflection in the system of energy efficiency indicators. This is especially important when introducing new technologies that change the profile of the use of fuel and energy resources and lead to their redistribution among different sectors of the economy.

Finally, the approach proposed in the paper for the structural and functional organization of energy efficiency indicators for the functioning of complex systems by representing them in a tensor form is an open tool that allows to formalize the process of determining these indicators to a large extent, while covering various organizational levels of the economy and its sectors, their technical and technological content, types of economic activity and factors of change in energy consumption, which is essential for the sustainable, low-carbon development of the country's fuel and energy complex as an integral part of its economy.

Prospects for further development of research in this direction lie in the development of software for the formalized calculation of energy efficiency indicators for complex systems.

References

1. Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, OJ L 315, 14.11.2012, 1–56. URL: https://eur-lex.europa.eu/legal-content/en/ALL/?uri=celex%3A32012L0027 (Last accessed: 14.03.2023).
2. Directive (EU) 2018/2002 of the European Parliament and of the Council of 11 December 2018 amending Directive 2012/27/EU on energy efficiency, OJ L 328, 21.12.2018, 210–230. URL: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2018.328.01.0210.01.ENG
3. Garnier, J.Y., Quadrelli, R., Zyzniewski, A., Park, T. et al. (2014). Energy Efficiency Indicators: Fundamentals on Statistics, Paris: IEA Publications, 387 p.
4. Belzer, D.B. (2014). A Comprehensive System of Energy Intensity Indicators for the U.S.: Methods, Data and Key Trends. Washington: Pacific Northwest National Laboratory, 215 p.
5. Kovalko, O.M. (2014). Vstup do teoriyi energoefektyvnosti bagatorivnevykh system: metody ta modeli energetychnogo menedgmentu v systemi gytlovo-komunalnogo hospodarstva. Kovalko, O.M., Novoseltsev, O.V., Yevtuhova, T.O. Кyiv: Instytut tekhnichnoyi teplofizyki NAN Ukrayiny. 252 p. [in Ukrainian].
6. Danny Harvey, L.D. (2010). Energy Efficiency and the Demand for Energy Services. London: Cromwell Press Group, 614 p.
7. Brown, T.A. (2006). Confirmatory factor analysis for applied research, New York: Guilford Press, 474 p.
8. Comparison tool: Benchmarking with indicators "ODYSSEE-MURE". (2017). Paris: Enerdata, 11 p.
9. Choi, Ki-H., & Ang, B.W. (2012). Attribution of changes in Divisia real energy intensity index – An extension of index decomposition analysis. *Energy Economics*, 34, 171–176.
10. Energy Efficiency Indicators Highlights. (2017). Paris: IEA, 150 p.
11. Bilan, T., Kaplin, M., Makarov, V., Perov, M., Novitskii, I., Zaporozhets, A., Havrysh, V., & Nitsenko, V. (2022). The Balance and Optimization Model of Coal Supply in the Flow Representation of Domestic Production and Imports: The Ukrainian Case Study. *Energies*, 15: 8103. https://doi.org/10.3390/en15218103
12. Horskyi, V.V., Maliarenko, O.Y., Maistrenko, N.Y., Teslenko, O.I., & Kuts, H.O. (2022). Modified three-stage model for forecasting the demand for energy resources at various hierarchy levels of the economy. *IOP Conference Series: Earth and Environmental Science*, 1049: 012054. https://doi.org/10.1088/1755-1315/1049/1/012054
13. Velasco-Fernandez, R., Dunlop, T., & Giampietro, M. (2020). Fallacies of energy efficiency indicators: Recognizing the complexity of the metabolic pattern of the economy. *Energy Policy*, 137: 111089. https://doi.org/10.1016/j.enpol.2019.111089
14. Bruhn, M., & Grund M.A. (2000). Theory, Development, and Implementation of National Customer Satisfaction Indices: The Swiss Index of Customer Satisfaction (SWICS). *Total Quality Management,* 11(7), 1017–1028. https://doi.org/10.1080/09544120050135542
15. Gastwirth, J., Modarres, R., & Bura E. (2005). The use of the Lorenz curve, Gini index and related measures of relative inequality and uniformity in securities law. *International Journal of Statistics,* LXIII(3), 451–469.
16. Lockamy, A., & Khurana, A. (1995). Quality function deployment: total quality management for new product design. *International Journal of Quality & Reliability Management*, 12(6), 73–84. https://doi.org/10.1108/02656719510089939
17. Huff, L., Fornell, C., & Anderson, E.W. (1996). Quality and Productivity: Contradictory and Complementary. *Quality Management Journal*, 4(1), 22–39. https://doi.org/10.1080/10686967.1996.11918772
18. Porter, M.E. (1979). How Competitive Forces Shape Strategy. *Harvard Business Review*, 57(2), 137–145.
19. Porter, M.E. (1998). On competition. Boston: Harvard Business School Publishing, 485 p.
20. Eutukhova, T., Kovalko, O., Novoseltsev, O., & Woodroof, E. (2020). Energy Services: A Proposed Framework to Improve Results. *Energy Engineering*, 117(3), 99–110. https://doi.org/10.32604/EE.2020.010864
21. Kholod, N., Evans, M., & Roshchanka, V. (2016). Energy Efficiency as a Resource: Energy Efficiency's Role in Meeting Ukraine's Energy Needs. Washington: Pacific Northwest National Laboratory, 58 p.
22. Deshko, V.I., Kovalko, O.M., Novoseltsev, O.V., & Yevtukhova, M.Y. (2020). Energy Services Market: Conceptual Framework and Mechanism of Forming. *International Journal of Civil, Mechanical and Energy Science*, 6(6), 48–55. https://doi.org/10.22161/ijcmes.66.4
23. IEA. (2019). Energy Efficiency Indicators: Database Documentation. Paris: IEA Publications, 50 p.
24. Kovalko, O.M., Novoseltsev, O.V., & Yevtuhova, T.O. (2017). Vertykalno-integrovani stuktury upravlinnya efektyvnistyu funktsionuvannya system komunalnoyi teploenergetyky. Kyiv: Instytut tekhnichnoyi teplofizyki NAN Ukrayiny. 258 p. [in Ukrainian].
25. Atkinson, A.A., Kaplan, R., Banker, R., & Young, S.M. (1997). Management Accounting 2nd Edition, New York: Prentice Hall, 741 p.
26. Zakon Ukrayiny pro energosberezhennya vid 01.07.1994 № 75/94-BP iz zminami vid 20.09.2019. URL: https://zakon.rada.gov.ua/laws/show/74/94-%D0%B2%D1%80#Text (Last accessed: 18.01.2023) [in Ukrainian].
27. Boer, P., & Rodrigues, J. (2020). Decomposition analysis: when to use which method? *Economic Systems Research*, 32(1), 1–28. https://doi.org/10.1080/09535314.2019.1652571

28. Reuter, M., Patel, M.K., Eichhammer, W., Lapillonne, B., & Pollier, K. (2020). A comprehensive indicator set for measuring multiple benefits of energy efficiency. *Energy Policy*, 139, 1–20. https://doi.org/10.1016/j.enpol.2020.111284
29. Ang, B.W., Mu, A.R., & Zhou, P. (2010). Accounting framework for tracking energy efficiency trends. *Energy Economics*, 32(5), 1209–1219. https://doi.org/10.1016/j.eneco.2010.03.011
30. Hoeven, M. (2014). Energy Efficiency Indicators: Essentials for Policy Making. Paris: IEA Publications, 162 p.
31. GKD 34.02.305–2002. (2002). Vykydy zabrudnyuvaknyh rechovyn u atmosferu vid energetychnyh ustanovok. Metodyka vyznachennya. Kyiv: OEP "GRIFRE", 43 p. [in Ukrainian].
32. Haluzeva metodyka rozrahunku shkidlyvyh vykydiv, yaki nadhodyat vid teplogeneruyuchyh ustanovok komunalnoyi teploenergetyky Ukrayiny: Nakaz Minbudu Ukrayiny vid 16.03.2006 № 67. URL: https://zakon.rada.gov.ua/rada/show/v0067667-06#Text (Last accessed: 1.02.2023) [in Ukrainian].
33. Podatkovy kodeks Ukrayiny vid 02.12.2010 № 2755-VI. Redaktsiya vid 20.03.2023. URL: https://zakon.rada.gov.ua/laws/show/2755-17#Text (Last accessed: 24.03.2023) [in Ukrainian].

МЕТОДОЛОГІЧНА ПЛАТФОРМА ВИЗНАЧЕННЯ ПОКАЗНИКІВ ЕНЕРГОЕФЕКТИВНОСТІ СКЛАДНОЇ СИСТЕМИ

Тетяна Євтухова[1], к.т.н., доцент, https://orcid.org/0000-0003-4778-2479
Ілія Ілієв[2], д.т.н., професор, https://orcid.org/0000-0002-0947-4865
Олександр Новосельцев[3]*, д.т.н., ст. наук. співр., https://orcid.org/0000-0001-9272-6789
Євген Нікітін[3,4], д.т.н., ст. наук. співр., https://orcid.org/0000-0002-0173-6461
Євген Щербина[3], к.т.н., https://orcid.org/0000-0002-1565-4547
[1]Міжрегіональна академія управління персоналом, вул. Фрометівська, 2, м. Київ, 03039, Україна;
[2]Університет Русе Ангел Канчев, вул. Студентська, 8, м. Русе, п.п. 7017, Болгарія;
[3]Інститут загальної енергетики НАН України, вул. Антоновича, 172, м. Київ, 03150, Україна;
[4]Інститут газу НАН України, вул. Дегтярівська, 39, м. Київ, 03123, Україна
*Автор-кореспондент: anovos@nas.gov.ua

Анотація. *Коректне визначення енергетичної ефективності (ЕЕ) складної системи є проблемним завданням, яке для свого вирішення потребує залучення спеціалізованих методів і підходів. Найчастіше ЕЕ розглядається як показник якості надання послуг, що найбільш повно відповідає техніко-економічної сутності цього показника. Структурно-функціональна організація системи таких показників здійснюється або за принципом знизу-вгору (bottom-up approach), або зверху-вниз (top-down approach), поступово згортаючи або розгортаючи показники. У роботі розглядається тензорна форма організації системи таких показників, що дозволяє об'єднати в межах єдиної моделі не тільки їх організаційні рівні (економіка у цілому, галузі економіки, підприємства, технології і обладнання), а й види діяльності, які відображають ці показники (енергетична, фінансово-економічна, інституційна, екологічна, соціальна тощо), та фактори виникнення змін у використанні енергії (структурні, технологічні, ресурсні, управлінські, регуляторні тощо). Представлено відображення цієї моделі на площину структурно-функціональних факторів у вигляді класифікаційних таблиць (матриць) цих факторів (елементів системи). Описана процедура оптимізації показників, яка може здійснюватися для кожного з зазначених факторів окремо, їх сукупності на кожному рівні та по системі у цілому з урахуванням необхідності реалізації ітераційних процедур узгодженого координування глобальної (загальносистемної) мети та локальних цільових функцій. За умов використання змінних оптимізації, що вимірюються в енергетичних та грошових одиницях, цю задачу формалізовано в межах теоретико-множинного підходу. З метою порівняння результатів у роботі розглядаються відповідні положення методики Міжнародного енергетичного агентства, що використовує прямий метод трифакторного декомпозиційного аналізу Ласпейреса, та Галузевої методики розрахунку шкідливих викидів Мінбуду України.*

Ключові слова: енергетична ефективність, індикатори ефективності, системний аналіз, тензорний підхід.

Надійшла до редколегії: 06.04.2023