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Combined model of optimal electricity production: evidence from Ukraine

Abstract: The article proposes a methodology for the formation of a combined model of the equilibrium values of pricing and the volume of electricity production, taking into account green and traditional sources of electricity production on the example of Ukraine. In accordance with the projected price and volume of electricity production in 2021, a model for redistributing electricity sources were considered, taking into account the minimization of budgetary resources and the risk of electricity production with appropriate restrictions in the production of various types of electricity and their impact on minimizing the price for the end user.

The studies have shown that important factors in the formation of electricity prices are indicators of the cost and volume of production, distribution and transportation of electricity to consumers, which largely depends on the formation and further development of the energy market in Ukraine. Also, the redistribution of the volumes of traditional and non-traditional electricity in the common

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"pot" is of great importance while minimizing risks and budgetary constraints. Balancing the system for generating electricity from various sources will help not only optimize long-term electricity prices and minimize tariffs for the end user, but also allow planning profit in the form of long-term market return on investment.

The analysis of the results showed that the optimal distribution of energy production makes it possible to obtain energy resources in the required volume with lower purchase costs and with minimal risk.

Keywords: optimal production of electricity, electricity tariffs, combined model, traditional sources, green tariffs, resource saving

Introduction

The need to equilibrate pricing mechanisms in the energy sector, both in Ukraine and in the world, is of particular relevance, taking into account the requirements for the fundamental transformation of the electricity market, the growth in the use of non-traditional renewable energy sources and distributed generation facilities (in Ukraine, in the total structure of electricity production, traditional energy is 98, "Green" – 2%), the relevance of the implementation of measures for conservation of energy and natural resources. The existing pricing mechanism for electricity from renewable sources is imperfect, since it does not take into account the principle of a balanced electricity production system and the impact on the environment. Electricity production volumes by energy sources depend on the cost price and production capacity. At the same time, prices for "green" electricity remain extremely high and do not fully cover the cost of its production (government spending on this energy sector has reached almost nine billion Euros). Solar and wind farms are installed in the regions regardless of the need for this, but rather based on the natural and climatic possibilities, while the high concentration of tens of megawatts in a certain area leads to an imbalance in the overall energy "Pot".

In the study (Halynska and Bondar 2020), the authors improved the scientific and methodological approach for identifying, formalizing and quantifying the multiplicative effects that arise as a result of combining non-renewable and renewable energy sources. According to the combined model of tariff formation in the energy sector, electricity tariffs for the end user of the respective region must be combined both with market prices for power generation from alternative sources and prices for energy produced from traditional sources.

1. Analysis of the literature

Global forecasts show that natural gas, coal and renewable energies will remain the main sources of energy supply for the next 25 years. Natural gas consumption in 2030 will grow by about 20% and will remain at the same level until 2040, and taking into account the commitments of the countries of the world to implement the Paris Climate Agreement and the intensive development of low-carbon and renewable energy sources, natural gas consumption is projected to increase up to 45% over this period. At the same time, global trends in the development of energy are characterized by deepening integration of energy systems, an increase in the use of non-traditional renewable energy sources and distributed generation facilities (Babenko et al. 2019). It also examines the relationship between oil prices, world industrial production, central bank interest rate and monetary aggregate (Ratti and Vespignani 2016).

The analysis showed that the existing pricing mechanism for electricity from renewable sources is imperfect, since it does not take into account the principle of social justice: the anthropogenic impact and harm to public health in the regions where TPSs and CHPs are located are much greater than in regions where they are absent (Halynska and Telizhenko 2016). At the same time, the volume of electricity consumption in certain regions of Ukraine is significantly less than the volume of its "dirty" production (Ramazanov et al. 2019). Research on this topic has been the focus of many scientists over the past two decades. The amount of strategic process research has increased significantly over the past decade. Despite this upward trend, previous studies have not yet been critically assessed (Huang and Zhao 2014).

According to "The Energy Strategy of Ukraine", the requirements for the fundamental transformation of the electricity market, for the growth in the use of non-traditional renewable energy sources and distributed generation facilities are increasing (in particular from production of 2% of "green" energy projects up to 7%), there is a need to introduce energy saving measures, conservation of natural resources. It should also be borne in mind that in the face of growing consumer expectations and tightening environmental standards, environmental supply chains will now be seen as another competitive weapon (Bai and Sarkis 2018). At the same time, not only financial criteria, but also social and environmental aspects of project models using metaheuristic and heuristic approaches will be the main factors in finding solutions to mathematical models in the field of energy (Carazo 2015). The environmental, social and governance rating of companies is a useful tool for stakeholders and investment decision makers (García et al. 2020).

Among other things, COVID-19 has caused great uncertainty and has severely impacted tourism, travel, hospitality, supply chains, consumption, production, operations, valuations, safety, financial stress and prices of all products, including fossil fuels and renewables (Chang et al. 2020). Many of the consequences of environmental and energy policies can disproportionately affect people on low incomes. First, it drives up the prices of fossil fuel-intensive products that make up a significant portion of low-income budgets (eg. gasoline, heating fuel, and electricity). Second, the distribution of pollution permits to company's benefits those who own them. Third, low-income people may value food and housing more than environmental improvements, so high-income people can get the most out of pollution control (Fullerton 2017).

This means that to predict the country's economic growth, it is necessary to take into account the dynamics of GDP (Babenko 2019) due to changes in electricity prices both for the consuming sectors of production and for the population. The rise in electricity prices in Ukraine will affect the reduction in production in consumer sectors. At the same time, the share of electricity prices in the GDP indicator is constantly growing, which affects the country's macroeconomic indicators (Prokopenko and Kasyanenko 2013; Kozmenko and Oliynyk 2015).

It has been found that the rise in electricity prices has a greater impact on GDP growth than the rise in oil prices (Jimenez-Rodriguez and Sanchez 2005). Research has shown that it is very important to examine the role of target costs in managing product prices while promoting quality specifications that will meet customer requirements (Zengin and Ada 2010).

The impact of stricter environmental regulations on the dynamic structure of a deterministic competitive industry is reflected in lower own future compliance costs. The level of regulation is exogenously fixed and constant in time. A company's compliance costs at any given time depend on its current output, accumulated past investments and the level of regulation (Sengupta 2010).

Comparing European and Ukrainian tariffs for energy-intensive industry, we can say that the cost of electricity is the main negative factor in the cost of Ukrainian industry products (Getsov et al. 2017). The dynamics of electricity prices in comparison with the dynamics of other production costs indicates that electricity prices are the driver of rising expenditure for industry, which is most emphasized by industrial consumers (Pursky et al. 2019). As a result, the entire economy will suffer – inflation will remain high due to rising tariffs, and GDP growth will be extremely (Oliinyk 2018; Halynska and Bondar 2020). Analyzed and generalized types of business models in the energy sector, allowed to adjust these models to the changing market of renewable energy (Halynska and Oliinyk 2020). At the same time, it allows to propose the structure of the electricity market, which allows efficient use of available resources, effective investment in new resources, as well as take into account the characteristics of renewable energy sources at the level of public administration (Matvieieva et al. 2015; Oliinyk et al. 2018). Leveraging new advances in modeling optimization will enable managers to go beyond analyzing real-world models to find the best balance of resource price, environmental impact, and project financing with minimal risk (Better and Glover 2006).

The analysis of the formation of a reasonable price for final consumers of electricity in competitive conditions and proposed mathematical principles of modeling in the energy sector taking into account global trends in modeling energy processes (Oliinyk and Kozmenko 2019; Babenko et al. 2019) showed that the criterion base for final price formation is insufficient.

At the same time, it is necessary to reach a reasonable compromise between risk and reward when forming a combined optimization model (Liu et al. 2018). A huge role is played by the problems of trade-off between the time spent in conditions of uncertainty and the assessment of the risks of inconsistency in the formation of prices for electricity in different regions (Haghighi et al. 2019).

Adopted in 2018, the "Procedure for forming the forecast balance of electricity of the integrated energy system of Ukraine for the current year" takes into account the following indicators (Strishenets 2016):

- predicted average monthly ambient temperatures;
- growth rates/decrease of electricity consumption of UES of Ukraine and changes in the configuration of power consumption schedules;
- rates of RES commissioning and schedules of their work;
- water content of the rivers Dnieper and Dniester cascades of hydroelectric power stations;
- opportunities for export/import of electricity, based on the allowable capacity of interstate crossings;
- development plans for generation of TPPs, NPPs, HPPs, PSPs (commissioning, decommissioning, increase/decrease of installed capacity);
- socio-economic development of the country;
- volumes of own production of fuel and products of its processing, forecast prices for them;
- forecast prices for fuel and products of its processing in foreign markets;
- forecast prices for electricity in related markets to which it can be exported and from which it can be imported, for typical days.

These assumptions are determined on the basis of analysis of their actual values in previous periods, forecast information about their possible values in the next year. However, green tariffs and their role in shaping electricity pricing and traditional factors are not taken into account (Babenko 2019; Halynska 2018). Therefore, this study aims to form a combined optimization model and calculate projected electricity prices, taking into account traditional and green electricity tariffs and redistribution of power generation.

2. Research method

2.1. Prices for electricity

We propose to consider the option of finding the equilibrium price for an energy carrier using two utility functions: one function for the producer of the energy carrier, and the second for the buyers of this energy. It is clear that utility for the producer should increase with the increase in price, and the utility for the buyer should decrease with the increase in price. There are 4 different options in relation to the inclination to take risks:

- the manufacturer and the buyer are inclined to risk,
- the manufacturer is inclined, but the buyer is not inclined,
- the manufacturer is not inclined and the buyer is inclined,
- the manufacturer and the buyer are not risk averse.

In the article we consider the option of risk-averse producers and consumers of electricity.

Graphs for prone and risk-averse individuals will be concavely marked. As a result of the superposition of the two graphs, we obtain the crossing current, which satisfies both the manufacturer and the buyer of the energy carrier, while the utility function for both persons takes the same value.

Consider the case where the manufacturer is risk averse, and the buyer has a risk tendency, that is, he can take risks when concluding a deal in order to obtain greater benefit in the future.

The utility function ($0 \leq V(x) \leq 1$) has the following form:

$$V(x) = a - b \cdot \exp(-cx) \tag{1}$$

where:

a, b, c – constant.

The agreed price obtained as a result of calculations can be used in modeling the optimal production of various forms of energy.

2.2. Distribution of energy resources

2.2.1. The consumer choice problem

The formulation of the problem of rational consumer behavior in the market is to find the optimal set of the required forms of energy for a given budget constraint and at the same time the utility function is maximum. The classical formulation of the consumer choice problem is as follows:

$$\begin{cases} U(x) \rightarrow \max \\ \sum_{i=1}^{n} p_i x_i \leq K \\ x_i \geq 0 \end{cases} \tag{2}$$

where:

$U(x)$ – utility function,
x_i – the share of the i-th forms of energy,
p_i – the price of the i -th forms of energy,
$p_i x_i$ – consumption for the purchase of the i-th forms of energy,
K – cash income.

Stone's consumer choice function can be considered as a utility function, which has the form:

$$U(x) = \prod_{i=1}^{n} (x_i - a_i)^{\alpha_i} \tag{3}$$

where:

- a_i – the minimum required amount of the i-th forms of energy, which is purchased and is not a subject of choice ($x_i \geq a_i \geq 0$),
- α_i – characterize the relative "value" of the i-th forms of energy for the buyer ($\alpha_i > 0$).

Power-law utility function (Stone function) provided $\sum_{i=1}^{n} \alpha_i = 1$, coincides with the neoclassical utility function (Cobb-Douglas function).

Using the Lagrange multiplier method, one can obtain an analytical solution to problem (2)–(3) in the form:

$$x_i^* = a_i + \frac{\alpha_i (K - \sum_{j=1}^{n} p_j a_j)}{p_i \sum_{j=1}^{n} \alpha_j} \tag{4}$$

Thus, we obtain the optimal distribution of the forms of energy x_i^* for the buyer, taking into account the price of the forms of energy p_i and budget constraints K, in this case, the utility function takes the maximum value.

2.2.2. The problem of minimizing costs

By minimizing the budget constraint, we obtain the cheapest consumer package for the given forms of energy prices. The utility function takes on a fixed value u^*,specified by the customer.

This problem statement has the form:

$$\begin{cases} \sum_{i=1}^{n} p_i x_i \to \min \\ \prod_{i=1}^{n} (x_i - a_i)^{\alpha_i} = U^* \\ x_i \geq 0 \end{cases} \tag{5}$$

The solution of the system (5) allows to obtain the optimal distribution of the forms of energy x_i^* with minimal costs and a fixed utility function.

2.2.3. The consumer choice problem with additional constraints

The classical consumer choice problem (2) has an analytical solution in the form (4). With additional restrictions, the solution to this problem can be obtained using numerical methods and the corresponding software. The mathematical formulation of the problem is presented in the following form.

Target function: $\prod_{i}^{n}(x_i - a_i)^{\alpha_i} \to \max$.

Limitation: $x_i \geq a_i$; $x_i, a_i \geq 0$; $K_{\min} \leq \sum_{i=1}^{n} p_i x_i \leq K_{\max}$; $x_{i,\min} \leq x_i \leq x_{i,\max}$; $\sum_{i=1}^{n} x_i = 1$; $\sum_{i=1}^{n} \alpha_i = 1$

$$\sqrt{\sum_{i=1}^{n}\sum_{j=1}^{n} x_i x_j \operatorname{cov}(p_i, p_j)} \leq R^* \tag{6}$$

where:

$\operatorname{cov}(p_i, p_j)$ – covariance of energy prices,

R^* – the target value of the risk of the forms of energy portfolio.

As a risk, we will consider the value of the standard deviation of the investigated parameter.

The solution to problem (6) makes it possible to find the optimal distribution of the production of various types of energy resources with budget constraints and a given value of the risk of the types of energy portfolio.

Other problem statements based on system (6) can be considered, namely:

- the problem of minimizing costs. The objective function is the minimization of the budget constraint at a given value of the utility function (an extended version of system (5));
- minimizing the risk of the portfolio of energy carriers. The objective function is to minimize portfolio risk. In this case, the value of the utility function takes on a certain preset value.

Thus, it is possible to consider alternative options for the optimal distribution of energy production based on optimality criteria and various types of restrictions.

3. Results

3.1. Historical data

As a numerical experiment, let us consider the characteristics of the Ukrainian energy system by types of energy production for the period 2012–2020. We will consider the following types of energy:

x_1 – NNEGC "Energoatom" (National Nuclear Energy Generating Company of Ukraine);

x_2 – TPS (Thermal Power Station);

x_3 – CHP (Combined Heat and Power Plant);

x_4 – HPP (Hydroelectric Power Plant), HAPS (Hydro-Accumulating Power Station);

x_5 – alternative energy sources (WPP, (Wind Power Plant), SPP (Solar Power Plant) and BPS (Biomass Power Plant).

Table 1 shows the distribution of the Ukrainian energy system by types of energy production.

Table 1. The structure of electricity production in Ukraine

Tabela 1. Struktura produkcji energii elektrycznej w Ukrainie

Year	NNEGC "Energoatom"	TPS	CHP	HPP, HAPS	WPP, SPP, BPS
	TWh				
2012	90.1382	78.9084	9.6501	10.8429	0.6132
2013	83.209	78.2978	8.2818	14.216	1.2472
2014	88.3893	68.4695	6.9016	9.0926	1.7719
2015	87.6275	49.3863	6.0754	6.8085	1.5911
2016	80.950	49.9023	6.7093	9.1188	1.560
2017	85.5762	44.9602	10.8814	10.5672	1.8963
2018	84.3982	47.7915	11.0162	12.0184	2.633
2019	83.0027	44.915	10.8699	7.8686	5.5443
2020*	73.7	38.87	11.1	6.349	11.37

Source: Energo 2021.

* Forecast data.

One of the main issues in modeling is finding an indicator of the "relative importance" of the considered types of energy. It is proposed to evaluate the importance of the energy carrier taking into account the price of the energy carrier and its production volume. Table 2 shows the values of the obtained indicators of the "relative importance" of energy, based on historical data on energy production for the historical period 2012–2020.

Table 2. Values of "relative importance" of energy carriers

Tabela 2. Wartości „względnego znaczenia" nośników energii

Indicator	NNEGC "Energoatom"	TPS	CHP	HPP, HAPS	WPP, SPP, BPS
Relative importance, α_i	0.2637	0.5036	0.1190	0.0359	0.0778

The values obtained in Table 2 will be used in further calculations.

3.2. Determination of the equilibrium price for energy resources in Ukraine in 2021

3.2.1. Determination of the equilibrium price for the energy produced by NNEGC "Energoatom"

We are considering the option of risk-averse energy market participants.

Steps for constructing the utility function:

1. For each type of energy, we consider the price range that is acceptable for producers and buyers of electrical energy $[p_{min}; p_{max}]$.

2. We build the utility function by points, which are obtained as a result of the answers of the decision maker (DM). Its solution is based on the choice of two alternatives: (A) – a risk strategy and (B) – a deterministic strategy. The strategy (A) for the producer consists in the ability to sell electricity with the probability q at the price p_{min} and with the probability $(1 - q) - p_{max}$. Strategy (B) consists in the guaranteed result of selling electricity at the price p_1.

3. Considering that the utility function has the properties of monotonicity and "insensitivity" to linear transformations, it is possible to establish a unit division for the utility functions, namely: for the manufacturer $V(p_{min}) = 0$, $V(p_{max}) = 1$; for the customer $V(p_{max}) = 0$, $V(p_{min}) = 1$. Thus, we have two points for constructing the utility functions.

4. Consider the construction of a utility function for a manufacturer. The construction of subsequent points is based on the fulfillment of the equality of the utility of alternatives from the point of view of the decision maker. Find the expected utility of alternatives (A) and (B). Let's find the expected outcome of the risk strategy (A): $MA = q \cdot p_{min} + (1 - q) \cdot p_{max}$. The expected utility of the strategy (A) is: $MV(A) = q \cdot V(p_{min}) + (1 - q) \cdot V(p_{max})$.

For the proposed alternatives to be equivalent, the following condition must be met: $MV(A) = MV(B)$. If for the decision maker the named price is $p_1 < MA$, then the manufacturer is not inclined to take risks. As a result, we get one more point for plotting the utility function. Considering different intervals of prices and probabilities of a risk strategy, one can obtain a sufficient number of points necessary to construct a utility function.

5. The next step is to select the parameters a, b, c of the utility function (1), from passing through the given points using the least squares method. Table 3 shows the corresponding utility functions for producers and buyers of various types of electrical energy.

Figure 1 shows the distribution of utility functions for the producer and buyer of the energy resource NNEGC "Energoatom" depending on its price

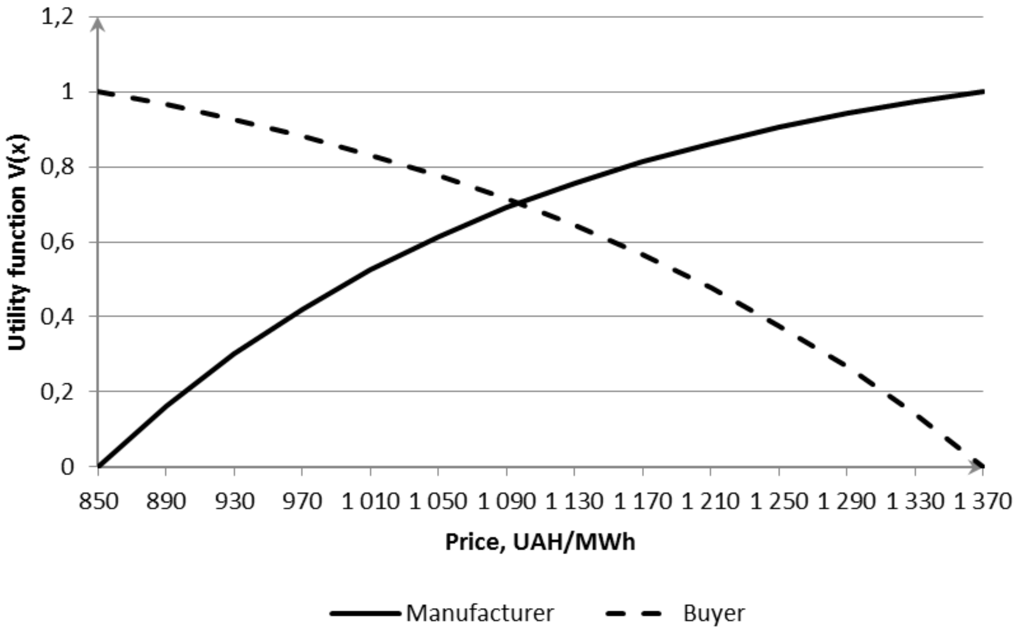

Fig. 1. Utility functions for the of the energy resource NNEGC "Energoatom"

Rys. 1. Funkcje użytkowe dla zasobu energetycznego NNEGC "Energoatom"

Table 3 presents the parameters of the utility functions (1) for the manufacturer and the buyer.

TABLE 3. Parameters of utility functions $V(x)$ for NNEGC "Energoatom"

TABELA 3. Parametry funkcji użytkowych $V(x)$ dla NNEGC "Energoatom"

Parameter	Manufacturer	Buyer
a	1.1687	1.2838
b	27.6509	0.0241
c	0.0037	–0.0029

Thus, we obtain the equilibrium price of the energy from the point of view of the manufacturer and the buyer, which is equal to 1097 UAH/MWh and it corresponds to the utility $V(x) = 0.7026$.

3.2.2. Prices for other energy sources

Table 4 presents the parameters of the distribution functions of energy resources.

The parameters that are included in these models are set based on the individual characteristics of each participant in the energy market.

Equilibrium l prices for the presented energy resources p_{opt},, UAH/MWh for producers and buyers are found from the price intervals [p_{min}; p_{max}], UAH/MWh, namely: *TPS* – p_{opt} = 4150 UAH/MWh from the interval [3500; 4800]; *CHP* – p_{opt} = 4850 UAH / MWh [4200; 5500]; *HPP, HAPS* – p_{opt} = 755UAH/MWh [690; 820]; *WPP, SPP, BPS* – p_{opt} = 6250 UAH/MWh [5600; 6900].

Table 4. Parameters of utility functions

Tabela 4. Parametry funkcji użytkowych

Parameter	TPS		CHP		HPP, HAPS		WPP, SPP, BPS	
	Manufacturer	Buyer	Manufacturer	Buyer	Manufacturer	Buyer	Manufacturer	Buyer
a	1.2194	1.2184	1.2194	1.2184	1.2204	1.2204	1.2192	0.2196
b	123.45	0.0021	310.8543	0.0008	10 747.58	0.00003	1 977.18	0.0001
c	0.0013	–0.0013	0.0013	–0.0013	0.0132	–0.0132	0.0013	–0.0013
$V(x)$	0.7024		0.7019		0.7017		0.7021	

Thus, based on the study of utility functions for producers and buyers, the equilibrium l prices for the presented energy resources prices for energy resources that satisfy all interested parties have been obtained. In the future, we will use these prices when concluding contracts and finding the optimal production volume.

3.2.3. Optimization calculations of production volumes

C1) Consider the classical consumer choice problem (2)–(3). The solution to this problem has an analytical solution in the form (4). Using the data presented in Tables 2 and 4, we obtain the following optimal distribution of energy production in Ukraine in 2021. In this problem, and in further calculations, we assume that $a_i = 0$ ($i = \overline{1.5}$) is the minimum required quantity of the *i*-th product.

Table 5. Optimal distribution of energy resources for task C1

Tabela 5. Optymalna dystrybucja zasobów energetycznych dla zadania C1

Index	NNEGC “Energoatom”	TPS	CHP	HPP, HAPS	WPP, SPP, BPS
Share, *x*	0.5384	0.2718	0.0550	0.1065	0.0279

Calculations show that the maximum utility function $U_{max}(x)$ = 0.2180. This indicator is achieved with the budget constraint K_{max} = 2240.01 UAH/MWh and the risk value R^*= 500.07 UAH/MWh.

C2) Consider the problem of minimizing risk for a given utility function. Let's write down the mathematical statement of the problem.

Target function: $\sqrt{\sum_{i=1}^{5}\sum_{j=1}^{5} x_i x_j \operatorname{cov}(p_i, p_j)} \to \min$

Limitation: $\sum_{i=1}^{5} p_i x_i \leq K_{max}; \prod_{i}^{5} (x_i - a_i)^{\alpha_i} = U^*; \sum_{i=1}^{5} \alpha_i = 1; \sum_{i=1}^{5} x_1 = 1; x_1 \geq 0; a_i = 0$ (7)

The value of the utility function is the same as in the task C1, namely:

U^* = 0.2180. To find the relative importance of energy α_i, we use the data in Table 2. In this setting, we obtain the following optimal solution:

Table 6. Distribution of energy resources for task C2

Tabela 6. Dystrybucja zasobów energetycznych do zadania C2

Index	NNEGC "Energoatom"	TPS	CHP	HPP, HAPS	WPP, SPP, BPS
Share, *x*	0.5340	0.2639	0.0568	0.1131	0.0322

The budget limitation is K_{max} = 2243.16 UAH/MWh with a minimum risk value R_{min} = = 499.58 UAH/MWh.

C3) Consider the problem of minimizing budget funds for a given value of the utility function U^* = 0.2180 and an additional restriction on the production of "green energy" in the form $x_5 \geq 8\%$. The mathematical formulation of the problem is as follows.

Target function: $\sum_{i=1}^{5} p_i x_i \to \min$

Limitation: $a_i = 0 \prod_{i}^{n} (x_i - a_i)^{\alpha_i} = U^*; \sqrt{\sum_{i=1}^{5}\sum_{j=1}^{5} x_i x_j \operatorname{cov}(p_i, p_j)} \leq R^*; \sum_{i=1}^{5} \alpha_i = 1; \sum_{i=1}^{5} x_i = 1;$

$x_i \geq 0 (i = \overline{1,4}); x_5 \geq 0.08$ (8)

The solution to this problem has the form presented in Table 7.

Table 7. Distribution of energy resources for task C3

Tabela 7. Dystrybucja zasobów energetycznych do zadania C3

Index	NNEGC "Energoatom"	TPS	CHP	HPP, HAPS	WPP, SPP, BPS
Share, *x*	0.5207	0.2417	0.0486	0.1090	0.0800

The budget constraint has the form $K_{\max}$ = 2392.18 UAH/MWh and the risk value R^*= = 524.56 UAH/MWh.

C4) Consider the problem of risk minimization based on the problem C3, with an additional restriction on the production of "green energy" in the form $x_5 \geq 8\%$. The minimum risk value is R_{min} = 524.46 UAH/MWh with a budget constraint K_{max} = 2392.56 UAH/MWh. The optimal distribution of energy resources is presented in Table 8.

Table 8. Distribution of energy resources for task C4

Tabela 8. Dystrybucja zasobów energetycznych do zadania C4

Index	NNEGC "Energoatom"	TPS	CHP	HPP, HAPS	WPP, SPP, BPS
Share, *x*	0.5192	0.2388	0.0512	0.1108	0.0800

In Table 9, we present the calculated values of the optimal distribution of energy production in Ukraine in 2021 at the projected energy prices (Table 4). In the considered options, it is assumed that the consumer utility function takes a given value U^* = 0.2180.

The projected energy production in Ukraine in 2021 according to the calculations for the types of energy carriers is 149.318 TWh. Table 10 shows the distribution of energy production based on the proposed calculation algorithm, as well as the production volumes assumed by experts (Option C5). Based on expert data on production volumes, as well as taking into account the prices for energy carriers presented in Table 4, the consumer utility function takes the value U^* = 0.2414. At the same time, the budget constraint is $K_{\max}$ = 2696.57 UAH/MWh and the risk value R^* = 591.38 UAH/MWh.

The analysis of the results presented in Table 10 shows that the optimal distribution of energy production makes it possible to obtain energy resources in the required volume at lower purchase costs and with minimal risk. Saving resources for its purchase in 2021 can reach 72 UAH/MWh, which in absolute terms corresponds to 10.7 billion UAH.

Table 9. Distribution of energy resources in Ukraine in 2021

Tabela 9. Dystrybucja zasobów energetycznych w Ukrainie w 2021 roku

Parameter	Options			
	C1	C2	C3	C4
NNEGC "Energoatom" [TWh]	80.393	79.736	77.750	77.526
	0.5384	0.5340	0.5207	0.5192
TPS [TWh]	40.585	39.405	36.090	35.657
	0.2718	0.2639	0.2417	0.2388
CHP [TWh]	8.212	8.481	7.257	7.645
	0.0550	0.0568	0.0486	0.0512
HPP, HAPS [TWh]	15.902	16.888	16.276	16.544
	0.1065	0.1131	0.1090	0.1108
WPP, SPP, BPS [TWh]	4.166	4.808	11.945	11.945
	0.0279	0.0322	0.0800	0.0800
$U(x)$	0.2180	0.2180	0.2180	0.2180
K [UAH/MWh]	2240.01	2243.16	2392.18	2392.56
R [UAH/MWh]	500.07	499.58	524.56	524.46

Table 10. Distribution of energy resources in Ukraine in 2021

Tabela 10. Dystrybucja zasobów energetycznych w Ukrainie w 2021 roku

Parameter	Options			
	C2	C3	C4	C5
NNEGC "Energoatom" [TWh]	72.285	70.986	70.822	75.233
	0.4841	0.4754	0.4743	0.5038
TPS [TWh]	47.692	44.691	44.168	41.140
	0.3194	0.2993	0.2958	0.2755
CHP [TWh]	10.363	9.153	9.616	12.79
	0.0694	0.0613	0.0644	0.0857
HPP, HAPS [TWh]	12.961	12.543	12.767	7.035
	0.0868	0.0840	0.0855	0.0471
WPP, SPP, BPS [TWh]	6.003	11.945	11.945	13.12
	0.0402	0.0800	0.0800	0.0879
$U(x)$	0.2414	0.2414	0.2414	0.2414
K [UAH/MWh]	2510.17	2624.28	2624.79	2696.57
R [UAH/MWh]	559.56	577.69	577.59	591.38

Conclusion

The studies have shown that the projected production of various types of energy in Ukraine (Table 9) in 2021 may reach 149.318 TWh. This indicates the controllability of systemic processes in the economy, which can affect the return on invested capital in the development of the electricity generation system as a whole. Also, taking into account the optimal production volumes for each type of energy, it is possible to take into account the anthropogenic load caused by the production base and infrastructure of electricity distribution and transportation in a particular region or country. The indicator of anthropogenic load includes the whole set of environmental positive and negative effects that arise as a result of electricity production, as well as in the extractive industry to provide the necessary natural resource base. The result will be an increase in the competitiveness of the producer, the region as a whole in the energy market, lower costs and increase the return on investment in the long run.

If we compare the volumes and distribution of electricity production predicted by experts (Option C5) and the volumes and distribution of electricity production obtained on the basis of the algorithm proposed by the authors (Table 10), we see that options (C3 and C4) are the most optimal. This means that the optimal distribution of energy production allows to obtain energy in the required amount with a budget constraint K_{max} = 2624.79 UAH/MWh. at lower costs for its acquisition with minimal risk R^* = 577.59 UAH/MWh. The distribution must also take into account the environmental constraint associated with the minimum amount of "green" electricity production ($x_5 \geq 8\%$). In general, the savings of financial resources for the purchase of electricity for various types of energy presented in the work in 2021 may reach 72 UAH/MWh, which in absolute terms corresponds to UAH 10.7 billion.

The expected results from the application of the combined optimization model significantly deepen the scientific principles of analysis and modeling of complex transformation processes in the energy sector of Ukraine. The creation of a scientific basis and applied methodological tools for the formation of electricity tariffs through the introduction of a differential approach to the redistribution of production of different types of electricity will help minimize the price of electricity for the final consumer.

We believe that the proposed model, which is the basis for developing a pricing map for a particular country or region and can be attributed to the so-called incentive tariff regulation in the field of electricity, which is used by many countries of the European Union. This is evidenced by one of the target functions of the economic-mathematical model of electricity pricing, which involves reducing the cost of production and distribution of electricity. Incentive tariff regulation, which is used by more and more European countries, requires a long-term planning horizon. That is, energy efficiency increases in the long run, which is associated with ensuring the efficiency of long-term investment in relevant infrastructure in the energy sector. Using this approach, it becomes possible to ensure real reliability and quality of energy supply and energy use.

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Połączony model do optymalizacji produkcji energii elektrycznej: przykład Ukrainy

W artykule proponowano metodologię tworzenia modelu łączącego równowagę ceny i wielkość produkcji energii elektrycznej, biorąc pod uwagę zielone i tradycyjne źródła produkcji energii elektrycznej na przykładzie Ukrainy.

Na podstawie przewidywanych cen i wielkości produkcji energii elektrycznej w 2021 r. rozważono model dywersyfikacji źródeł energii elektrycznej, który bierze pod uwagę minimalizację środków budżetowych i ryzyko produkcji energii elektrycznej z odpowiednimi ograniczeniami dotyczącymi różnych rodzajów energii elektrycznej i ich wpływu na minimalizację ceny dla użytkownika końcowego.

Badania wykazały, że ważnymi czynnikami tworzenia cen energii elektrycznej są wskaźniki kosztów i wielkości produkcji, dystrybucji i transportu energii elektrycznej konsumentom, co w dużej mierze zależy od sposobu tworzenia i dalszego rozwoju rynku energii w Ukrainie.

Ponadto połączenie tradycyjnej i nietradycyjnej energii elektrycznej ma ogromne znaczenie, jednocześnie minimalizując ryzyko i ograniczenia budżetowe.

Bilansowanie systemu generacji energii elektrycznej z różnych źródeł nie tylko pomoże zoptymalizować długoterminowe ceny energii elektrycznej i zminimalizować taryfy dla użytkownika końcowego, ale pozwala również na zaplanowanie zysku w formie długoterminowego zwrotu z inwestycji.

Analiza wyników wykazała, że optymalny podział produkcji energii umożliwia uzyskanie zasobów energetycznych w wymaganej wielkości przy niższych kosztach zakupu i przy minimalnym ryzyku.

Słowa kluczowe: optymalna produkcja energii elektrycznej, taryfy energii elektrycznej, model połączony, tradycyjne źródła, zielone taryfy, oszczędność zasobów