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Assessment of the Energy System of Ukraine: Ways of Recovery, Cases of Development

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Abstract
The economy of Ukraine is partially destroyed and poses an energy threat to European countries. The article analyzes trends in the development of consumption in Ukraine, and assesses the prospects for development. Energy Ukraine's system depends on fossil fuels. The government sought to diversify risks and ensure sustainable development. The energy consumption market is characterized by a decline and an increase in the use of gas.
The article develops cases for making decisions on the necessary investments in the energy system of Ukraine after the war. We analyze energy consumption trends and justify the need for investment in the nuclear industry, which occupies a large part of the country's energy consumption. A model for assessing and forecasting the energy consumption market has been developed. The model shows an upward trend in oil and gas consumption. Our approach allows us to quantify the net increase in energy consumption in the future.

Keywords: energy, energy supply, renewable energy, energy strategy, energy resources.

1. Introduction

The development of modern energy has paved the way for the economic growth and evolution of the world. At the moment, the attractiveness of technological progress and economics is growing, and the future faces serious challenges, namely the growth of the share of renewable energy sources.
The normal state of the economy and energy, as its component, is institutionalized on equilibrium, when none of the players considers it profitable for themselves to spend resources on restructuring relations. Even inefficient "rules of the game" and stagnant economic forms can exist long enough ago, if there is a hidden interest of the state or powerful groups in it (North, 1997with. 111-112).
But for the global energy industry, the time of abnormality has come, the time of institutional imbalance.
The processes taking place received from the World Energy Council (WEC) the name Grand Transit, which means the Great Transition to the energy trilemma (World Energy Trilemma) with the following components: energy security (Energy security), equality of energy access (Energy equity) and environmental status (Environmental sustainability).

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It should be noted that the Grand Transit caused inconsistency in the state of major players in the world energy industry. In the case of intensive greening of the energy industry, fuel corporations risk losing the lion's share of revenues.
According to experts in the russian oil industry, despite all the hype around renewable energy, 75% of the world's energy balance will continue to be fueled by oil, gas, and coal consumption. The rapid increase in gas and electricity prices even before the beginning of the winter of 2021-2022 is the result of the "advanced society" underestimating the duration of the transition period, a kind of Interregnum (Inter-Tsars), as they said in ancient times.
The IAEA also lobbies for its policy. In 2016, this organization presented the "Harmony" scenario, which emphasizes the need to introduce 100 GW of new nuclear power by 2050 and increase the supply of electricity from nuclear power plants to 25%.
The seriousness of the world community's attitude to environmental problems and combating climate change is confirmed by the Rome G204 summit and the COP265 conference Glasgow, which took place in October-November 2021. The statement of a member of the World Energy Council H. Davis "... Today we are on the threshold of a new era, when concerns are caused not only by assets reduced in price, but also by the impact of devalued resources on the economy of individual countries" (Statistical Review of world Energy 2021).
The Government of Ukraine supports these tendencies. Ukraine has taken up the reduction of global greenhouse gas emissions to combat global warming. Fulfilling this obligation, as European experience shows, requires the transformation of the entire structure of the country's economy in the direction of low-carbon development.
One of the most important aspects of this approach is the need to fulfill Ukraine's environmental obligations to the EU regarding the reduction of local harmful emissions, according to which the situation in Ukraine today is the worst in Europe. Thus, during 2019-2021, Ukraine successfully completed the separation of gas transmission network operators and the gas transmission system. This is confirmed by their certification. Key structural changes took place in the gas and electricity markets. Corporate governance in state-owned companies in the energy sector of Ukraine is being reformed (Statistical Review of world Energy 2021).
Reforming the Ukrainian energy industry is and will remain a key factor in the development of the country's economy. After all, the development of energy in Ukraine corresponds to the current long-term strategy for the development (until 2035) of the energy sector of the state (Decision of the Cabinet of Ministers of Ukraine, 2017, this is referred to in the long-term term energy). Before the war, the energy system of Ukraine was in the stage of modernization. However, a real model of energy consumption market assessment has not been developed.
An important aspect of Ukraine's energy policy should be reforming the energy sector using world (especially European) experience by adapting it to domestic conditions. However, it is obvious that after February 24, 2022, the situation in the country's energy sector has changed significantly, completely different problems and needs have come to the fore.

In 2021, the energy industry found itself at a crossroads, waiting to see what vector of energy development the state would choose. A single approach to energy consumption and the development of renewable energy has not been developed.

2. Previous research

With regard to methodological approaches to assessing the energy market, we can highlight the works Axon, Darton, Abdullah, Iqbal, Hyder, Jawaid, Azzuni, Breyer, Brown, Wang, Sovacool, D'Agostino, Lyulyov, Pimonenko, Kwilinski, Dzwigol, Dzwigol-Barosz, Pavlyk, Barosz, Mazurkiewicz, Lis, Miskiewicz, Pająk, Kvilinskyi, Fasiecka, Iyke, Tran, Narayan, Huang, Zhang, Ma, Bai, Ren, Shpak, Dvulit, Maznyk, Sroka, Zaverbnyj, Levchenko (Axon, etc. 2021, Darton, etc. 2021, Abdullah,etc. 2020, Azzuni,etc. 2017), Brown etc. 2014, Lyulyov, etc. 2021, Mazurkiewicz, etc. 2018, Miskiewicz, etc. 2018,Pająk, etc. 2017,Iyke, etc. 2021,Huang, etc. 2018,Shpak, etc. 2023). The study (Axon, etc. 2021) evaluates Pakistan's energy. Security performance is based on the study of its energy security index in the period 1991-2018, which focuses on the concepts of "Accessibility", "Accessibility", "Technology", "Governance" and "Environmental Wednesday". The study (Axon, etc.2021) aims to evaluate the energy market state using sets of indicators, indices, and structures, taking into account their dependence on various fuels, their general economic position, energy pricing policies, access to renewable energy sources, and international relations.

Peter Donk, Sebastian Streal made a simulation of energy balance optimization for adequate planning of the energy system, the study was carried out in Suriname, taking into account climate change scenarios for the period 2030-2040 (Donk, etc. 2023).

James MacGregar identified an optimal strategy for investing in the economy of Kazakhstan, developed an approach to making a decision to invest in energy in the amount of $67 million, which will ensure sustainable development, applied a structural approach to costs and profits. This approach provided an alternative way to invest. This approach is interesting for the energy system of Ukraine. In the article, we will use the main idea of the alternative approach, but due to the difference in economic development, and the destruction of the energy sector, we will determine our own path (MacGregor, etc. 2017).

Ukraine is not an energy country like Kazakhstan. The country also uses fossil fuels. The country imports 30% of energy resources, but the state is trying to reduce this part. Nuclear power plants are subject to modernization. The consumer market in Ukraine is constantly changing due to economic changes in the structure of the economy.

The difference in Ukraine is that the existing experience and traditional modes of operation of the energy system of Ukraine do not correspond to the sustainable energy systems of European countries. Most publications on this issue do not meet modern requirements. To a greater extent, they relate to the tasks of analyzing the expected balance of generation and consumption. Economic models for forecasting the energy consumption market have not been developed. To ensure the current energy balance, mainly short-term and medium-term forecasting is needed.

The problems of ensuring the energy balance when introducing renewable energy sources impose even more complex requirements on forecasting methods, since renewable energy sources introduce a large share of uncertainty (Wooldridge, etc. 2013). In energy markets

with a significant (up to several percent) level of penetration of renewable energy sources, a predominantly deterministic approach is practiced (Sukhodolia, etc. 2019).
A significant number of scientific works of foreign and domestic scientists are devoted to the issues of assessing the energy market and the development of renewable energy. The main energy issue is the need to adapt the experience of leading European countries to the energy problems of Ukraine.
Insufficient attention is paid to the assessment of both Ukraine's energy consumption and the development of renewable sources. Ukraine has not developed a unified model for a comprehensive assessment of energy consumption. The end result of this study should be conclusions and recommendations for assessing the energy consumption market. The purpose of the article is to identify long-term factors and trends in the development of Ukraine's energy sector and the possibility of adapting to international requirements, and to model the energy consumption market in the context of declining gas imports and depreciation of power plants.

3. Materials and methods

The energy market is a complex and dynamic economic system, the study of which requires the use of adequate methods in order to identify a set of influencing factors (internal, external) on the functioning of the market, as well as establishing the main trend of its development in order to ensure the energy security of the country.
Researching the energy market of Ukraine. In the process of researching the energy market of Ukraine and its needs, expert (qualitative), formalized (quantitative) and combined methods (formed by combining the procedures of qualitative analysis and formalized algorithms of logical transformations and numerical calculations) are applied.
The models described in the course of the study were used in the following publications(Statistical Analysis and Modeling… 2022, Kotu, etc. 2019, Economic forecasting … 2020).
Expert methods are research methods that allow you to reveal the behavior of the energy market as an economic system based on the use of professional knowledge and competencies of researchers, and their ability to generalize their own and adapt borrowed experience.
Formalized methods are usually divided into two groups:
- methods of extrapolation of patterns of development;
- methods of modeling causal relationships.

The main tasks that arise in the process of building such a model include: establishing the presence of a relationship between dependent and independents features; detection of the form of dependence between features; estimation of model parameters; testing the model for adequacy. (model identification); assessment of the practical suitability of the model (model verification).
The methods of extrapolation of patterns of development services to reflect the main tendency of the studied indicator by smoothing (equalizing) the dynamic series - replacing the actual levels with rough calculations. Estimated values are less prone to fluctuations, which helps to more clearly identify the main trend.
Smoothing methods are divided into the following:

- algorithmic - based on the averaging of several levels of the series;
- analytical - are based on the presentation of the trend in the form of some function known with precision to the parameters.

4. Mathematical model of the country's energy market

The mathematical model of analytical smoothing of the development of the country's energy market has the following form (Statistical Analysis and Modeling… 2022, Kotu, etc. 2019, Economic forecasting … 2020).:

$$y_t = f(t) + \varepsilon_t, \tag{1}$$

where y_t - level of the dynamic series for the period (at the moment) of time t; $f(t)$ - deterministic component describing the main trend (trend) of change in the economic indicator y_t over time; ε_t - random component

At the same time, the level of the time series - t accumulates (takes into account) the influence of such factors as the price of energy resources and the volume of GDP.
Given the complexity of the energy market as an object of research, the functioning of which is represented by a number of economic indicators (demand and supply of energy products, product price, production volumes of energy products by their types, primary energy supply, final energy consumption, energy consumption structure, etc.), it is appropriate is the application of models of causal relationships (multifactor econometric models (2):

$$y_t = f(x_{1t}, x_{2t}, \dots, x_{mt}) + \varepsilon_t,, \tag{2}$$

where x_{jt} is the level of the j-th dynamic series for the period (at the moment) t.
Energy market research methods based on the establishment of cause-and-effect relationships are considered more informative compared to methods of extrapolation of development patterns. The main problem of building multifactorial econometric models of the energy market is the formation of an information base.
The use of combined methods of researching the energy market of Ukraine consists in a combination of methods of expert assessments, extrapolation of patterns of development, and modeling of causal relationships. An illustration is the extrapolation of the dynamics of indicators that are characterized by "saturation" (using a logistic curve, a modified exponent, a Gompertz curve, etc.).

For example, if we assume that the limit value of the logistic function:.

$$y_t = \frac{k}{1+ae^{-bt}}, \tag{3}$$

is set by an expert (equal to), then other parameters can be determined using the method of least squares (LSM), having previously performed the transformation:

$$\ln\left(\frac{k^*}{y_t} - 1\right) = \ln a - bt$$

5. Results and discussion

Analyzing the development of Ukraine's energy system. The basis of the electric power industry of Ukraine is the unified energy system of Ukraine - a set of nuclear, thermal, hydroaccumulative power plants, thermal power plants, as well as power plants based on renewable energy sources (wind, solar, etc.), main electric networks of Ukrenergo and distribution electric networks, which are united by a common method of production, transmission and distribution of electric and heat energy. Centralized dispatching management of the energy system of Ukraine is carried out by Ukrenergo. Communication with power systems of other countries is carried out by interstate power transmission lines(Abdullah, etc.2020).

In Ukraine, since the 1990s, a model of the wholesale electricity market has been operating, the basis of which was the experience of Great Britain. The basis of this model is the preservation of the country's unified electric power system and its centralized management. At the end of the 90s of the last century, the liberalization of the electricity industry of Ukraine began. Producers of electric energy are business entities that legally own or use generating capacities, produce electric energy for the purpose of selling it on the electric energy market and/or provide auxiliary services. Among them: the old enterprise "Energoatom" - the operator of 4 operating nuclear power plants of Ukraine, on which 15 nuclear power units are operated. The company provides about 55% of Ukraine's electricity needs, in the autumn-winter period this indicator reaches 70%. According to the indicator of the installed capacity of nuclear power plants, Ukraine ranks seventh in the world.

At the end of the USSR (1990) consumption of fuel and energy resources by the Ukrainian economy reached 11.3 EJ (270 million tons).

During the period from 2000 to 2012, the consumption of fuel and energy resources in Ukraine was relatively stable and with a probability of 0.95 amounted to 5.7-5.8 EJ (137±2 million toe) per year. The financial and economic crisis of 2009 led to a drop in demand to 4.7 EJ (113 million tons), that is, it turned out not to be such a disaster for the national economy as in the early 1990s, but a significant test. Events caused by political and armed conflict in the east of the country caused fuel demand to drop to 4.2 EJ (Statistical Review of world Energy 2021). Each crisis was more difficult than the previous one. Under the influence of a complex of reasons, the structure of the country's resource base began to change a long time ago, but the tendency to replace natural gas with coal is most evident recently.

For a number of reasons, the structure of the resource base began to change, and the trend towards replacing natural gas with coal became permanent. Under an optimistic scenario, the situation may change to the development of renewable energy (Fig. 1). (Site of the State Statistical Service 2023). Under the existing conditions and the destruction of a share of power plants, the energy system of Ukraine may become subsidized.

In the case of transition of Ukraine according to the scenario of transition to renewable energy sources, a situation may arise where there is no possibility of transition of the majority of enterprises to renewable sources of energy. Since most enterprises use outdated technological processes.
Despite the complex economic and political phenomena, Ukraine remains a powerful energy state. In 2020, the country produced 0.54 EJ (149,021.5 million kWh) of electricity, of which 51% was provided by nuclear power plants (NPP), 26.6% by thermal power plants (TPP), 9.8% by the thermal energy of power plants (TES), 3.7% - hydroelectric power stations and hydro accumulating stations, alternative sources - 7.3%(Statistical Review of world Energy 2021).

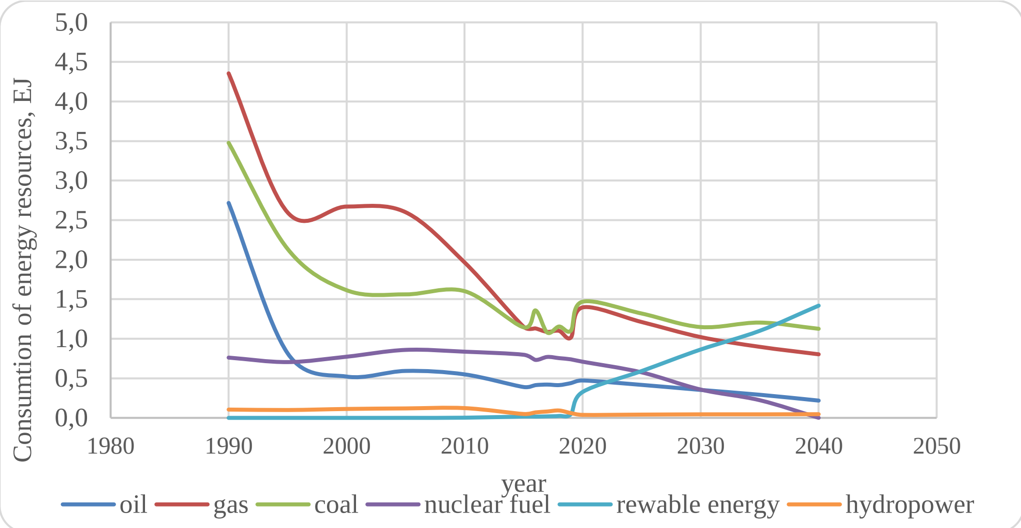

Figure 1. The dynamics of changes in the structure of the resource-based public transport system of Ukraine (Statistical Review of world Energy 2021)

Over the course of thirty years, the specific consumption of fuel energy resources per 1 person decreased non-linearly from 220 GJ in 1990 to 99 GJ in 2020, and the specific consumption over the same period per $1. The United States at purchasing power parity in 2017 prices - from 14.0 to 12.3 MJ, but the change processes were parabolic in nature.
According to the characteristic given by the decree of the Cabinet of Ministers of of Ukraine dated August 4, 2021 No. 907-r "Energy Security Strategies", the energy infrastructure of the country is worn out and characterized by high energy losses during production, transportation, and consumption, the absence of energy-efficient changes, and the structure and characteristics of the connections of generating capacities do not meet the needs of the United Energy System of Ukraine and the interests of consumers in providing affordable and high-quality electricity. As of the beginning of 2014, power units of thermal plants with a total capacity of about 12 million kW (more than 40% of the total capacity of the TPP) required replacement (Statistical Review of world Energy 2021).
The wear and tear of electrical networks is more than 50% of their total volume, and in among individual companies – more than 70%, in the utility sector – 70%; about 40% of

heating points are in an emergency state, 15.8% of the total length of heating networks are emergency, out of 309 thousand km of gas the service life of distribution networks has expired for 18,500km, at least another 15,000 km of networks are in an emergency state.
More than 44% of energy is lost during conversion and transportation to of the final consumer (while the EU average is 32%) (Statistical Review of world Energy 2021).
A high share of imported energy resources in the structure of fuel and energy complex reduces the level of energy security. A certain threat to the energy security of the country is the import of electricity from the Republic of the public of Belarus and the russian federation, which since the beginning of 2021 has periodically exceeded 1 GW of capacity (Statistical Review of world Energy 2021).
In 2020, imported gas accounted for about 30% of the total consumption of natural gas in Ukraine. Ukraine has become 85% dependent on the import of oil products. At the same time, the share of oil products produced in the russian federation or from russian raw materials (primarily in the Republic of Belarus) in the structure of imports exceeds 80% (Statistical Review of world Energy 2021). In 2020, Ukraine imported oil products from the russian federation and the Republic of Belarus in the amount of more than 2.4 billion dollars. USA. The unsatisfactory level of diversification of sources and routes of supply and the lack of an established system of reserves of oil products makes Ukraine at once left in the case of purposeful cessation of oil product supplies.
Almost all power units of thermal power plants and thermal power plants have used up their park resource, and are technologically outdated. Coal-fired power plants are among the biggest polluters of the environment, are at the limit of their finite resources and physical wear, and need to be replaced by more sustainable, environmentally friendly energy production. The current unsatisfactory technical condition of the fuel energy complex and the low level of energy efficiency create challenges for Ukraine, related to the ability to fulfill international obligations and adapt to EU initiatives, in particular, the European Commission initiative "European Green Course". The introduction of the concept of "carbon footprint" by the EU will be a requirement for the possibility of including the economy of Ukraine in the general chain of production in the EU. In the future, it is possible to introduce mechanisms to limit access to credit financing of individual commercial projects, if certain environmental requirements are not met.
In general, innovations and new technologies are not used in the fuel and energy complex, there is already a shortage of qualified personnel, and this trend is intensifying.
The level of harmful emissions exceeds not only the EU norms by 5-30 times but also the current norms of Ukraine, in particular, emissions of solid ash particles formed during coal combustion by 20-34 times. As of the beginning of 2014, TPP power units with a total capacity of about 12 million kW (more than 40% of the total TPP capacity) required replacement.
Ukraine fulfilled its obligations to comply with the limited volumes of pollutant emissions during 2018-2021 only at the expense of a significant reduction (up to 40%) of electricity production at coal-fired thermal power plants due to the drop in electricity production and consumption caused by the events in eastern Ukraine and the reduction of the raw material base of coal-fired power generation (Site of the State Statistical Service 2023). As of January 1, 2018, the construction of a single facility was not started at the TPP of Ukraine innovations in cleaning flue gases from sulfur dioxide and nitrogen oxides. First of all, this

is due to the lack of financial mechanisms for the implementation of environmental protection measures. If the existing state is maintained due to failure to complete the reconstruction of thermal power plants, all power units of the TPP should be stopped in 2026.
The existing power units of nuclear power plants must be decommissioned in connection with the end of their service life (Vecchi, etc. 2021).

6. Assessment of the import dependence of the Ukrainian energy sector

In Ukraine, there are not enough powerful energy storage systems to cover peak loads. In the structure of electricity production from renewable energy sources, the production of electricity from solar energy, which is characterized by high variability of production, developed rapidly. As of the beginning of 2021, the amount of renewable energy capacity in Ukraine was 7,737 MW (Site of the State Statistical Service 2023).
In the table 2 presents the dynamics of Ukraine's net energy import (as a percentage of energy consumption) during 2003-2020. Ukraine's net energy import is calculated by subtracting from the consumed energy the produced energy expressed for proportionality in oil equivalent (Table 1) (Site of the State Statistical Service 2023).

Table 1. Ukraine's net energy import

Year	Net import, as a percentage of energy consumption	Years	Net import, as a percentage of energy consumption
2003	45.0	2012	30.3
2004	44.2	2013	25.7
2005	43.3	2014	27.2
2006	39.6	2015	26.3
2007	39.0	2016	25.4
2008	37.3	2017	18.3
2009	30.6	2018	25.2
2010	40.4	2019	20.8
2011	32.3	2020	19.2

Source: built on (Site of the State Statistical Service 2023)

The graphs of the initial and smoothed series of Ukraine's net energy imports using a three-term simple moving average are shown in Fig.2. (Site of the State Statistical Service 2023). Visual analysis of Fig. 2 generally indicates a downward trend. In addition, the downward trend of net energy imports of Ukraine is also characterized by negative values of the average annual absolute increase ($\bar{\Delta}y = -2{,}52\%$) and growth rate ($\bar{T}_B = -4{,}89\%$).

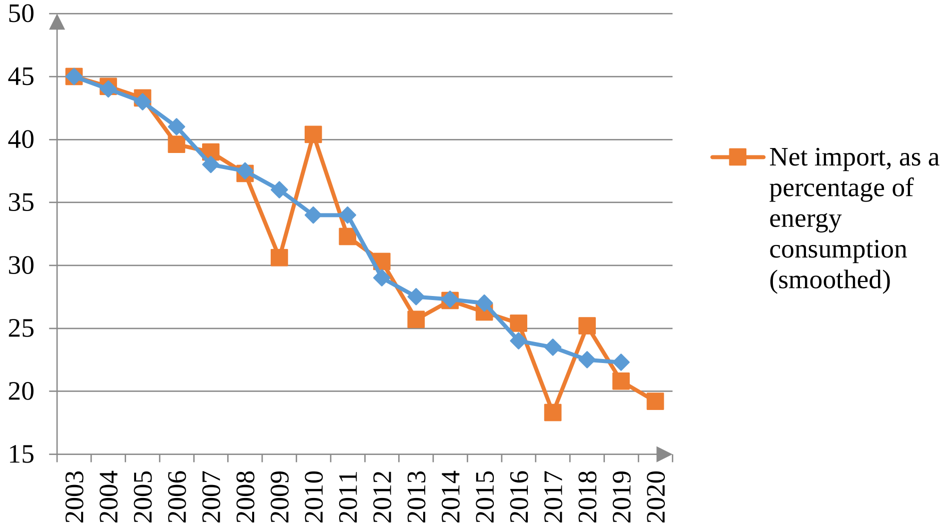

Figure2. Graphs of the dynamics of the initial and smoothed series of net energy imports of Ukraine (Statistical Review of world Energy 2021, Site of the State Statistical Service 2023)

Analyzing the graph of the initial dynamic series presented in fig. 2 and the values of average annual absolute growth and growth rates, we can come to the conclusion that for the extrapolation of patterns of changes in the net energy import of Ukraine, it is appropriate to consider the following trend functions:

$$y_t = b_0 + b_1 \cdot t\hat{y}_t = b_0 + b_1 \cdot t \text{ – linear;} \tag{3}$$

$$\hat{y}_t = b_0 + b_1 \cdot \frac{1}{t} \text{–hyperbolic;} \tag{4}$$

$$\hat{y}_t = e^{b_0 + b_1 \cdot t} \text{–exponential;} \tag{5}$$

To estimate the parameters of models (3) – (5), we use the method of least squares. Models (4) and (5) are reduced to a linear form by replacing:

$$y_t = b_0 + b_1 \cdot z, \qquad z = \frac{1}{t};$$

$$u_t = b_0 + b_1 \cdot t, \qquad u_t = \ln y_t.$$

The results obtained using the standard LINEST function of the EXCEL spreadsheet processor are presented in the table 2.

The coefficients b_0 and b_1 in models (3) and (5) are statistically significant and amenable to meaningful interpretation, and the coefficients of determination and mean squared errors of the regression equation are equal from a practical point of view. Model (3) is linear, so it should be preferred. The expected forecast value of Ukraine's net energy imports in 2023, calculated on the basis of model (3), is 13.6 %.

Table 2. Trend models of Ukraine's net energy import

Models trends	Coefficient of determination	Adequacy of the model according to the Fisher test	Mean squared error of the regression equation
$\hat{y} = 46.591 - 1{,}570 \cdot t$	R^2=0,907	The model is adequate	δ_ε=2,751
$\hat{y} = 26.496 - 26{,}658 \cdot \frac{1}{t}$	R^2=0,492	The model is adequate	δ_ε=6,460
$\hat{y} = e^{3.904-0.051 \cdot t}$	R^2=0,896	The model is adequate	δ_ε=2.773

The coefficient of the model b_1=-1,570 indicates a tendency (Table 1) to increase the level of energy independence of Ukraine.

It is logical to assume that time series levels are sensitive to factors that cannot be quantified (economic conditions, political situation, etc.). In such cases, dummy variable models are an effective tool for extrapolating development patterns. Since Ukraine has been at war since 2014, it is worth considering the following model.

$$y_t = b_0 + b_1 \cdot t + \alpha \cdot d + \varepsilon_t, \tag{6}$$

where: d is a dummy variable (d = 0 - no military actions, d = 1 - military actions take place). The regression equation built on the basis of Table 1 is as follows:

$$\hat{y} = 46{,}937 - 1{,}646 \cdot t + 0{,}947 \cdot d \tag{7}$$

Table 3. Dynamics of influencing factors on Ukraine's net energy import

Year	Gross domestic product, billion international dollars, x_1	Final energy consumption, thousand tons, $x_2 x_1$	Total supply of primary energy, thousand t.e., x_3	Energy intensity, t.e/ thousand international dollars	
				Final energy consumption, x_4	Total primary energy supply, x_5
2008	596.7	85,955	139,330	0.144	0.234
2009	610.4	83,283	134,562	0.136	0,22
2010	520.3	67,555	114,420	0.13	0.22
2011	540.3	74,004	132,308	0.137	0.245
2012	569.8	75,852	126,438	0.133	0.222
2013	571,2	73,107	122,488	0.128	0.214
2014	571.0	69,557	115,940	0.122	0.203
2015	533.6	61,460	105,683	0,115	0.198
2016	481.5	50,831	90,090	0.106	0.187
2017	492.2	51,649	94,383	0,105	0.192
2018	504.4	49,911	89,462	0,099	0.177
2019	521.5	51,408	93,526	0,099	0.179
2020	538.2	49,665	89,359	0.092	0.166
2021	518.0	47,773	86,363	0.092	0.167

Source: built on (Site of the State Statistical Service 2023)

In the regression equation, the coefficient on the dummy variable (α=0.947) is statistically insignificant, so the theoretical and applied use of model (7) is not appropriate.
In our opinion, the main factors influencing the net energy import of Ukraine are the volume of the gross domestic product (GDP), the level of energy intensity (Table 3), as well as military actions.
We will build on the basis of the data in the Table 3 (Site of the State Statistical Service 2023). models of cause-and-effect relationships from the specified factors, will describe the dynamics of Ukraine's net energy import (Table 4). Of all the models of causal relationships that describe the dynamics of Ukraine's net energy imports (Table 4), the best is model,

$$y = -25{,}020 + 264{,}974 \cdot x_5 + \varepsilon_t$$

for which the coefficient of determination is equal to R^2=0.892, and the mean square error of the regression equation isδ_ε =2.391.

Table 5 shows the dynamics of primary energy supply in Ukraine during 2007-2020 years.

Table 4. Econometric models of cause-and-effect relationships from of net energy imports of Ukraine

Factors	Trend models	Coefficient of determination	Correlation coefficient	Mean square error of the regression equation
Gross domestic product, billion international dollars, x_1	$\hat{y} = -33{,}121 + 0{,}114 \cdot x_1$	R^2=0,392	R=0,626	δ_ε=5,678
Final energy consumption, thousand tons,x_2	$\hat{y} = -0{,}758 + 0{,}001 \cdot x_2$	R^2=0,785	R=0,886	δ_ε=3,378
Total supply of primary energy, thousand t.e., x_3	$\hat{y} = -5{,}357 + 0{,}002 \cdot x_3$	R^2=0,827	R=0,909	δ_ε=3,032
Final energy consumption,x_4	$\hat{y} = -13{,}484 + 358{,}231 \cdot x_4$	R^2=0,853	R=0,924	δ_ε=2,790
Total primary energy supply,x_5	$\hat{y} = -25{,}020 + 264{,}974 \cdot x_5$	R^2=0,892	R=0,944	δ_ε=2,391

Source: built on (Site of the State Statistical Service 2023)

Tabel 5. Total supply of primary energy for 2012-2021, thousand tons of oil equivalent

Indicator	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Energy production	85,485	85,247	85,914	76,928	61,614	66,323	58,863	60,883	60,452	57,017
Import of energy	58,055	46,520	39,722	34,437	31,575	29,152	35,145	33,795	34,708	30,655
Export of energy	10,303	8,007	8,213	6,967	1,447	1,427	1,944	1,462	1,841	1,246
International maritime and aviation bunkers	246	306	126	131	124	157	251	300	121	32
Stock changes	-6,552	-966	-1,356	1,417	-1,529	492	-2,351	611	-3,840	-32
General supply of primary energy	126,438	122,488	115,94	105,683	90,090	94,383	89,462	93,526	89,359	86,363
Coal and peat	41,490	42,718	41,427	35,576	27,344	32,450	25,757	28,055	26,076	22,847
Crude oil	9,100	5,050	3,978	3,043	2,851	2,806	3,351	3,635	3,786	4,196
Oil products	3360	6559	5928	7645	7700	8387	9345	9637	9690	9947
Natural gas	46,841	43,018	39,444	33,412	26,055	25,603	24,554	25,739	23,383	23,844
Nuclear energy	23,672	23,653	21,848	23,191	22,985	21,244	22,449	22,145	21,771	19,994
Hydropower	941	901	1187	729	464	660	769	897	560	650
Wind and solar energy	10	53	104	134	134	124	149	197	426	794
Biofuel and waste	1,563	1,522	1,875	1,934	2,102	2,832	2,989	3,209	3,349	4,243
Electricity	-541	-987	-851	-725	-116	-323	-445	-522	-348	-208
Heat energy	...	...	1000	745	571	599	546	534	667	56

Source: built on the basis of (Site of the State Statistical Service 2023)

7. Modeling of primary energy supply in Ukraine.

The largest share in the total supply is occupied by the following energy products: natural gas (up to 41.7%), coal and peat (35.7%), nuclear energy (25.5%), crude oil and oil products (16.4%).

At the same time, the relative share of natural gas (Y_3) in the total supply has been steadily decreasing over the past three years, while crude oil and petroleum products (Y_2) have been increasing (Table 5 and Fig. 3).

For clarity, let's show this graphically (Fig. 3).

The best trend models that describe the patterns of change in the supply of the main types of primary energy are presented in Table 6. All models are adequate according to the Fisher criterion, and their coefficients are statistically significant.

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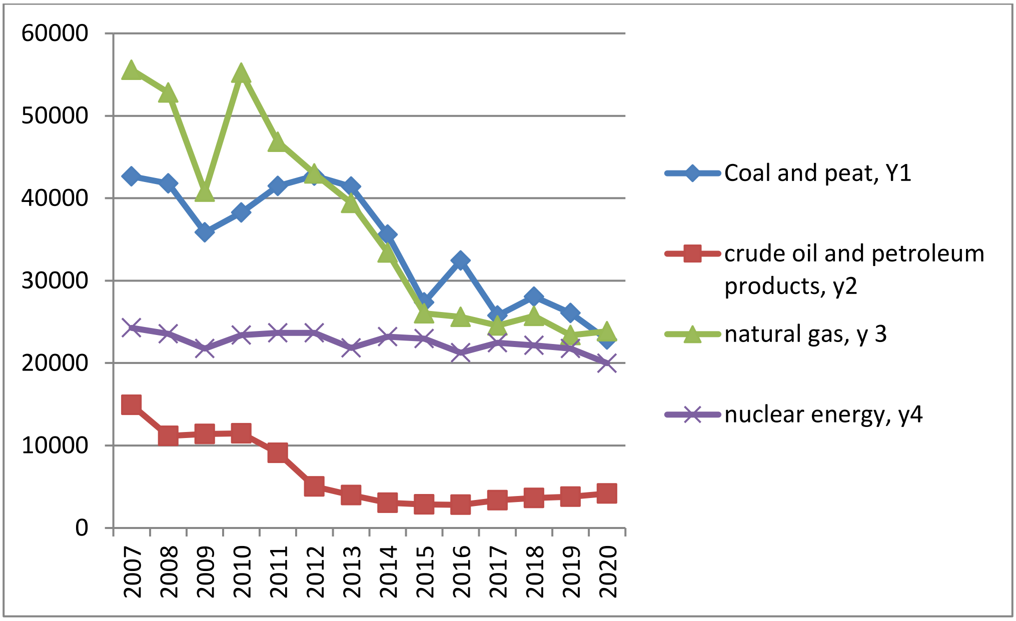

Figure 3. Dynamics of supply of the main types of primary energy in Ukraine (Y_1 - coal and peat, Y_2 - crude oil and petroleum products, Y_3 - natural gas, Y_4 - nuclear energy), thousand tons of oil equivalent (Site of the State Statistical Service 2023)

Econometric models describing the dynamics of crude oil and oil products $\widehat{Y_2}$) and nuclear energy (Y_4) supply are characterized by relatively high determination coefficients and relatively small mean square errors of the regression equation (Table 6) and therefore can be used for forecasting.

Table 6. Econometric trend models of primary energy supply in Ukraine

Types of energy products	Trend models	Coefficient of determination	Mean square error of the regression equation
1. Coal and peat	$\widehat{Y_1} = 45749{,}571 - 1506{,}457 \cdot t$	R^2=0,758	δ_ε=3709,233
2. Crude oil and oil products	$\widehat{Y_2} = 17178{,}467 - 1544{,}438 \cdot t + 96{,}874 \cdot t^2$	R^2=0,867	δ_ε=199,931
3. Natural gas	$\widehat{Y_3} = e^{11{,}031 - 0{,}076 \cdot t}$	R^2=0,886	δ_ε=4665,926
4. Nuclear energy	$\widehat{Y_4} = 24072{,}396 - 200{,}681 \cdot t$	R^2=0,512	δ_ε=853,888

Source: built on (Site of the State Statistical Service 2023)

The forecast values of these energy products for 2023 are as follows:
- crude oil and petroleum products:
* point forecast - Y_2^{dot}=18920 (thousand tons of oil equivalent.);
* interval forecast (probability P = 0.95) -

18491 $\leq y_2^{int} \leq$ 19349 (thousand tons of oil equivalent);
- natural gas:
* point forecast - Y_4^{dot}=20661 (thousand tons of oil equivalent);
* interval forecast (probability P = 0.95)
1829$\leq y_4^{int} \leq$ 22492 (thousand tons of oil equivalent).

The forecast shows a steady upward trend in the consumption of natural gas and crude oil imported from russia. It is advisable to replace these fuels with nuclear power, which is cheaper. But the reactors are old and need to be reconstructed. A big problem is the use of enriched uranium from russia. Ukraine has uranium, but after it is enriched, it cannot be used in nuclear power plants. Companies that produce uranium are unprofitable, as the cost of production is higher than the market price. A possible option is to supply uranium from other European countries.

Nuclear power is a strategic component of Ukraine's energy balance. To date, the country has 15 nuclear power units at four nuclear power plants, which provide about 50% of its electricity needs. However, most of them were built during the Soviet era and require modernization and extension of the term of operation. According to the International Atomic Energy Agency (IAEA), Ukraine has 15 reactors in four NPPs, but only 13 are operational as of 2020.

The need for investment in Ukraine's energy system. Low-cost modernization of the TPP, which includes the reconstruction of boiler units, modernization of turbine units, and replacement of electrostatic precipitators, requires investments in the amount of about 600 USD/kW of installed capacity. The implementation of such measures can extend the life of power units to 15-20 years. However, this is not enough to meet the requirements of the Energy Community and Directive 2010/75/EC. It is necessary to build a new gas cleaning system at each power unit, to completely reconstruct or replace the boiler and turbogenerator equipment(Site of the State Statistical Service, 2023).

The "Energy Security Strategy" of Ukraine states that the nuclear industrial complex of Ukraine is still critically dependent on the resources, technologies, and services of suppliers from russia. Our own uranium mining enterprises are in financial crisis and need significant investment to increase production. Nuclear power plants need continued implementation of measures to ensure the safety of their operation, and urgent modernization, in particular with the aim of improving technical characteristics and making decisions regarding the construction of new power units(Mills 2019, Phoumin, etc. 2021, Spaiser, etc. 2017).

Therefore, Ukraine develops and implements various projects for the modernization of the nuclear power industry which are aimed at the improvement of safety, efficiency, and competitiveness of nuclear power plants as well as diversification of nuclear fuel and equipment supplies. The implementation of these projects requires significant investments, which are estimated at tens of billions of dollars. Sources of financing can be both the own funds of the National Nuclear Energy Generating Company Energoatom and borrowed funds from international financial institutions, governmental agencies, and private investors.

While analyzing the existing projects of modernization of nuclear power industry of Ukraine the research has identified the most effective ones:

- to extend the service life of 12 nuclear power units till 2030, which will enable them to maintain their capacity and safety at a high level. The cost of the project amounts to about $1.7 bln.
- construction of two new nuclear power units at Khmelnytskyi NPP, which will increase the capacity up to 4 thou MW and replace the lost capacity of Chornobyl NPP. The cost of the project is about $6 bln.
- construction of a centralized storage facility for spent nuclear fuel on the territory of the Chornobyl Exclusion Zone, which will reduce the cost of storage and transportation of spent nuclear fuel to Russia. The cost of the project is about $300 million.
If all nuclear power units are replaced, the investment will amount to $80 billion (the average price of the nuclear unit is $5 billion).
To create an independent position in the nuclear industrial complex, Ukraine needs to:
Increase domestic uranium production and processing to reduce dependence on imports. Ukraine has abundant reserves of uranium, but its current production only covers about 30% of its nuclear fuel needs. The rest is imported mainly from Russia and Kazakhstan. According to the national program adopted in 2021, Ukraine plans to invest 9.1 billion hryvnias ($335 million) over the next five years to increase uranium mining and processing capacity and achieve self-sufficiency in uranium supplies by 2026.
- Diversify nuclear fuel suppliers and develop domestic fuel production capacity. Ukraine has been diversifying its nuclear fuel sources since 2014 when it signed a contract with Westinghouse Electric Company to supply fuel for some of its VVER-type reactors. However, Ukraine still relies on Russian TVEL for most of its fuel assemblies and lacks its own fuel fabrication capacity. To solve this problem, Ukraine intends to cooperate with Westinghouse to establish a nuclear fuel fabrication plant in Ukraine by 2025.
The structure of the investments for the modernization of the nuclear power industry of Ukraine can be summarized as follows:
- About 60% of the investments will come from the state budget and state-owned enterprises, such as Energoatom, which operates all NPPs in Ukraine.
- About 30% of the investments will come from international loans and grants, such as those provided by the European Bank for Reconstruction and Development (EBRD), the European Atomic Energy Community (Euratom), and the IAEA.
- About 10% of the investments will come from private sources, such as foreign companies and investors that are interested in participating in joint projects with Ukrainian partners.
Developing new nuclear capacities and technologies, such as small modular reactors (SMRs) and fast reactors. These technologies can offer more flexibility, efficiency, and sustainability for the nuclear power industry and reduce its environmental impact. Ukraine has expressed interest in cooperating with international partners to explore the potential of SMRs and fast reactors for its energy system.
The modernization of the nuclear power industry of Ukraine is expected to bring significant benefits to the country's economy, environment, and security. It will help to ensure a stable and low-carbon electricity supply, create new jobs and industries, enhance technological innovation and competitiveness, and reduce geopolitical risks and vulnerabilities.

8. Conclusions

The main characteristics of the fuel and energy complex are:
1) critical deterioration of the main generating funds and energy infrastructure;
2) low environmental suitability of enterprises of the fuel and energy complex;
3) chronic deficit, a large share of imports, and lack of diversification of fuel suppliers, economic and technological inefficiency of the domestic fuel and mining industry.
Factors that will determine the development of Ukraine's fuel and energy complex in the coming decades: shortage of maneuvering capacities and coal, as regulatory functions are mainly performed by coal-fired thermal and electric power systems; political factors to ensure environmental requirements for sustainable development and European integration.
The forecast shows a steady upward trend in the consumption of natural gas and crude oil imported from Russia. It is advisable to replace these fuels with nuclear energy, which is cheaper. However, the reactors are old and need to be reconstructed.
There are 15 power units in Ukraine that need modernization. Today, there is no official data on the modernization of the nuclear industry. While analyzing the existing projects of modernization of nuclear power industry of Ukraine the research has identified the most effective ones:
- to extend the service life of 12 nuclear power units till 2030, which will enable them to maintain their capacity and safety at a high level. The cost of the project amounts to about $1.7 bln.
- construction of two new nuclear power units at Khmelnytskyi NPP, which will increase the capacity up to 4 thou MW and replace the lost capacity of Chornobyl NPP. The cost of the project is about $6 bln.
- construction of a centralized storage facility for spent nuclear fuel on the territory of the Chornobyl Exclusion Zone, which will reduce the cost of storage and transportation of spent nuclear fuel to Russia. The cost of the project is about $300 million.
If all nuclear power units are replaced, the investment will amount to $80 billion (the average price of the nuclear unit is $5 billion).
Renewable energy accounts for only 7 percent, and its development will have to start from almost zero, which includes the purchase of wind farms, solar panels, and one option - hydrogen production through electrolysis.
ENTSO-E with the disconnection of Ukraine from the common power grid with the Russian Federation and Belarus; in terms of greening the domestic energy industry and maintaining reformed coal generating funds in operation, the creation of vertically integrated systems with the participation of nuclear power plants may be promising(wind or solar power plants), chemical enterprises for the production of hydrogen (ammonia) and reformed coal power plants, which will mainly operate on hydrogen (ammonium) fuel in shunting modes; spread of energy storage on liquid air (nitrogen); decentralization of heat energy systems based on hydrodynamic water heating, able to work according to the scheme of virtual power plants; energy diversification of mining regions based on the transformation of mines into power plants. In the future, it is expedient to consider in more detail the issue of energy and economic efficiency of hydrogen energy, prospects for photovoltaic plants and energy storage in liquid air; develop a pilot project for a vertically

integrated system involving nuclear plants, a reformed coal-fired thermal power plant, and a chemical enterprise for the production of hydrogen (ammonia); to determine the economic feasibility of creating energy hubs that use mine lifting installations, cregions of concentration of deep mines.

The potential directions of the problems outlined in the article are as follows. Increasing the level of energy security by reducing the import dependence of Ukraine's energy sector (own renewable sources, reforming nuclear energy by switching from large to smaller power plants, etc:

- Increase domestic uranium production and processing to reduce dependence on imports. Ukraine has abundant reserves of uranium, but its current production only covers about 30% of its nuclear fuel needs. The rest is imported mainly from Russia and Kazakhstan. According to the national program adopted in 2021, Ukraine plans to invest 9.1 billion hryvnias ($335 million) over the next five years to increase uranium mining and processing capacity and achieve self-sufficiency in uranium supplies by 2026.
- Diversify nuclear fuel suppliers and develop domestic fuel production capacity. Ukraine has been diversifying its nuclear fuel sources since 2014 when it signed a contract with Westinghouse Electric Company to supply fuel for some of its VVER-type reactors. However, Ukraine still relies on russian TVEL for most of its fuel assemblies and lacks its own fuel fabrication capacity. To solve this problem, Ukraine intends to cooperate with Westinghouse to establish a nuclear fuel fabrication plant in Ukraine by 2025.
- To extend the service life of 12 nuclear power units until 2030, which will allow to maintain their capacity and safety at a high level. The cost of the project is about 1.7 billion dollars.
- Construction of two new nuclear power units at Khmelnitsky NPP, which will increase capacity to 4,000 MW and replace the lost capacity of Chernobyl NPP. The cost of the project is about 6 billion dollars.
-Construction of a centralized SNF storage facility in the Chernobyl Exclusion Zone, which will reduce the cost of SNF storage and transportation to Russia. The cost of the project is about $300 million.
- Determine how much renewable energy and non-renewable energy investment is needed. Most European countries see a renewable energy-dominated Ukraine after the war.

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