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The management of renewable energy resources for the energy security of Ukraine and Europe

ABSTRACT: This article discusses the advantages of using renewable energy resources (RES), analyzes the resource potential of Ukraine in terms of energy production and substantiates the benefits of using RES for energy security. It explores the potential of the existing technological infrastructure for the sustainable development of the energy industry in Ukraine. It also identifies the structure of energy capacities and the technically achievable potential of energy production from RES and alternative fuels as a basis for different scenarios for the prospective development of alternative energy in Ukraine.

The development of solar, wind and bioenergy is analyzed in line with policy recommendation traced with the dynamics of the final volume of energy consumption in Ukraine.

This enables improvements to the methodology for determining the target parameters of energy security with the available resource potential, which forms the basis for the dynamics models of integral indices of components of energy security. These models demonstrate the current state of energy security of Ukraine in terms of resource potential, economic sufficiency, and institutional and organizational support for the use of energy resources.

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The article suggests the key management directions of energy policy in Ukraine and the mechanism of emergency response to the shortage of energy supply. The development of alternative energy is considered as a path to the energy independence of the national economy of Ukraine and Europe.

KEYWORDS: national economy, renewable energy resources, alternative energy, models of energy security components, management

Introduction

The leading direction of development in the modern world is an increased focus on the problems of using energy resources, the search for renewable energy sources (RES), and the implementation of innovative technologies to ensure the energy security of countries. Under present-day economic conditions, solutions to the task of increasing the level of energy security in Ukraine are considered in the context of the possibility of using the potential of alternative types of fuel. The studies of the Ukrainian potential of RES (Porwal and Kreuzer 2010; Dergachova et al. 2020) indicate significant opportunities for power generation and supply both the national economy and the economies of European countries. The availability of RES contributes to energy independence and security and also determines the economic benefit and environmental advantage in the country. Energy supply, based on RES, is becoming one of the optimal solutions to modern challenges. It is based on the priority view of the RES on the agenda of numerous states. The development of mechanisms for emergency response to energy supply shortages in Ukraine would enable the formation of a security system and aspects of internal economic management.

Research methodology. To achieve the goal set in the research, general scientific and special research methods were used, namely structural, system analysis, synthesis, statistical analysis and generalization.

The goal of the article is to reveal the key problems related to the functioning of a unified energy system (hereinafter UES) and to determine the target parameters of energy security with the available resource potential.

1. The potential for the development of the energy industry in Ukraine

Under the conditions of military aggression, the role and importance of the further development of the united energy system of Ukraine is increasing. According to the data provided by NEC “Ukrenergo”, as of the end of 2021, the total installed energy capacity of Ukraine

was estimated as 56.169 GW, 49.7% of which is accounted for thermal power plants (thermal power plants, combined heat and power production plants, block plants), 24.6% for nuclear power plants (NPP), 11.2% for hydroelectric power plants and hydro-accumulating power plants, 14.3% for the power plants, operating on RES – WPP, SES, BioPP (see Table 1).

TABLE 1. Installed capacity of power plants of UES, Ukraine, 2014–2021

TABELA 1. Moce zainstalowane elektrowni UES, Ukraina, 2014–2021

Year	Total installed capacity [kW]	Nuclear power stations		Thermal power stations, GK		Combined heat and power production plants and thermal power stations		Hydro-electric power stations; pumped-storage hydro stations		Wind-power stations, solar power plants, BioPP	
		GW	%	GW	%	GW	%	GW	%	GW	%
2014	55.1	13.8	25.1	27.7	50.3	6.6	12.0	2.9	10.6	1.1	2.0
2015	54.8	13.8	25.2	27.8	50.7	6.5	11.8	5.9	10.7	0.8	1.5
2016	55.3	13.8	25.0	27.8	50.3	6.5	11.8	6.2	11.2	1.0	1.7
2017*	51.8	13.8	26.7	24.6	47.5	6.0	11.5	6.2	11.2	1.2	2.3
2017**	55.7	13.8	24.8	27.9	50.0	6.5	11.6	6.2	11.2	1.3	2.4
2018*	49.7	13.8	27.8	21.8	43.9	6.1	12.3	6.2	12.6	1.7	3.4
2019*	54.4	13.8	25.4	21.8	40.0	6.1	11.2	6.3	11.6	6.4	11.8
2020*	54.7	13.8	25.2	21.8	39.8	6.1	11.1	6.3	11.5	6.6	12.1
2021*	56.11***	13.8	24.6	21.8	38.8	6.1	10.8	6.3	11.2	8.1	14.3

* The data are given without taking into account the territory of Donetsk and Luhansk regions not controlled by Ukraine.

** The data are given taking into account the territory of Donetsk and Luhansk regions not controlled by Ukraine.

*** Without taking into account 394.8 MW of industrial RES facilities, which obtained a “green” tariff, but currently they do not generate “green” electricity and 1,205 MW of domestic power plants (according to the data of NCRECP) (Wind energy of Ukraine 2014–2021).

We conducted an analysis of electricity production from alternative sources (wind turbines, solar power stations, biomass) for twelve months of the year of 2017, which amounted to 2,086 300,000 kW · h, which is 14.9% more than in the corresponding period of 2016. Generation of electricity by types of generating capacities from the general UES is presented in Figure 1.

In 2021, the overall capacity of the RES increased by 1,169.15 MW, which is almost 1.4 times less than the amount of capacity introduced in 2020 (1,660.9 MW) and almost four times less than the peak figures of 4,600.0 MW in 2019. As of December 31, 2021, the installed capacity of the RES of Ukraine reached 9,655.95 MW. As in previous years, a significant increase in the rate of capacity development in 2021 was observed only in one segment – domestic solar power plants (dSES) – the capacity of which increased by 426.15 MW in 2021, which is 36.4% of the capacities of new RES put into operation last year.

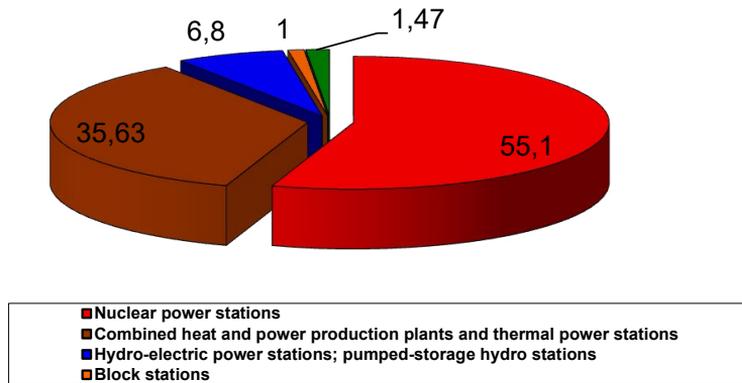


Fig. 1. The share of generating capacities in the total amount of electricity generated in 2017
(Wind energy of Ukraine 2017)

Rys. 1. Udział mocy wytwórczych w całkowitej ilości energii elektrycznej wytworzonej w 2017 roku

The total installed capacity of all household solar systems at the end of the year reached 1,205.15 MW. In contrast to the dSES sector, industrial solar energy did not show the best development indicators, with a significant reduction in growth rates. In 2021, the capacity of industrial solar generation increased only by 305.5 MW (26.1% of the capacity of new RES introduced in 2021), which is 818.1 MW or 3.6 times less than the rates of 2020, i.e. 1,123.6 MW. At

TABLE 2. Technically achievable potential of energy production from renewable energy sources and alternative fuels

TABELA 2. Technicznie osiągalny potencjał produkcji energii z odnawialnych źródeł energii i paliw alternatywnych

No	Areas of RES development	Annual technically achievable energy potential [million tons of conventional fuel]
1.	Wind energy	28.0
2.	Solar energy, including	6.0
2.1.	◆ electric	2.0
2.2.	◆ thermal	4.0
3.	Small-scale hydropower industry	3.0
4.	Bioenergy, including:	31.0
4.1.	◆ electric	10.3
4.2.	◆ thermal	20.7
5.	Geothermal heat energy	12.0
6.	Environmental energy (heat pumps)	18.0
Total volume of replacement for traditional fuel and energy resources		98.0

Designed on the basis of the data from (SAEE 2022).

the end of 2021, the total installed capacity of the solar energy sector in the country amounted to 7,586.35 MW.

We have estimated a technically achievable potential of energy production from RES and alternative fuels, which amounts to more than 98.0 million tons of conventional fuel per year (Table 2. State Energy Efficiency of Ukraine, 2021).

As for the relationship between traditional and non-traditional (alternative) energy, it will take more than a decade before these types of energy are balanced in the fuel and energy balance of the country. However, all the countries of the world have already recognized the importance of developing alternative energy. These are, first of all, territories with autonomous energy supply, and remote and hard-to-reach areas to which it is impractical to connect electric lines because of small capacities of energy-consuming enterprises. Thermal energy produced by HPPs has a wider area of economic application; it covers both decentralized and centralized heat supply areas. Secondly, these are small and medium-sized businesses with a priority on energy autonomy and independence.

2. The availability of renewable energy resources for energy security in Ukraine

Ukraine is still behind the developed countries in the use of renewable energy, although the potential of these sources in the country is extremely high.

According to experts, renewable sources in Ukraine can potentially meet 78% of electricity production needs. We carried out an estimated distribution of the potential in Ukraine for certain types of renewable energy sources (Department of Energy Efficiency of Ukraine 2021).

As seen in Table 3, the theoretical and technical potential of resources is three or six times higher than the level of energy consumption of Ukraine, and the economic potential is three times higher.

TABLE 3. Resources of renewable energy in Ukraine in 2021 and their potential

TABELA 3. Zasoby OZE Ukrainy w 2021 r. i jej potencjał

Resources	Use [MW·h/year]	Potential [MW·h/year]		
		gross	technical	economic
Solar	$81 \cdot 10^3$	$720 \cdot 10^9$	$0.13 \cdot 10^9$	$30\text{--}40 \cdot 10^6$
Wind	$0.8 \cdot 10^3$	$965 \cdot 10^9$	$0.36 \cdot 10^9$	$4.8\text{--}8.4 \cdot 10^6$
Geothermal	$0.4 \cdot 10^3$	$5.128 \cdot 10^9$	$14 \cdot 10^9$	$2,800 \cdot 10^6$
Biomass (agricultural)	$0.014 \cdot 10^3$	$12.5 \cdot 10^6$	$6.1 \cdot 10^6$	$6.1 \cdot 10^6$
Water resources	$10.2 \cdot 10^3$	$42.4 \cdot 10^6$	$21.5 \cdot 10^6$	$21.5 \cdot 10^6$

Estimations of the total actual share (i.e. the final volume of energy consumption) in each technology of renewable energy in Ukraine are carried out in thousands of tons of oil equivalent (see Table 4).

TABLE 4. Total actual share of every technology of renewable energy in Ukraine
[thousand tons of oil equivalent]

TABELA 4. Całkowity rzeczywisty udział każdej technologii OZE na Ukrainie
[tys. ton ekwiwalentu ropy naftowej]

Resources	Years				
	2014	2015	2016	2017	2018
Solar	0.1	0.1	0.5	0.5	0.6
Biomass*:	1,408.3	1,533.8	2,169.9	2,431.6	2,673.6
◆ solid	1,408.1	1,525.2	2,153.2	2,411.9	2,652.1
◆ biogas	0.2	8.6	16.3	19.7	21.5
Renewable energy from heat pumps, including:			21.4	25.4	64.7
◆ aérothermal	0.6	0.6	15.7	18.1	37.2
◆ geothermal			3.6	4.6	17.2
◆ hydrothermal			2.1	2.8	10.4
TOTAL	1,409.0	1,534.5	2,191.8	2,457.5	2,739.0
In private households**	1,069.2	1,096.1	1,505.2	1,676.9	1,812.2

* Takes into account only biomass that meets the criteria of applicable sustainability.

** In the total volume of energy consumption from renewable sources in heating and cooling systems.

Designed on the basis of the data from (SAEE 2022).

Ukraine has favorable natural conditions for the use of hydroelectric power plants. Thus, for the development of solar energy, the main indicators are the duration of sunlight and levels of cloudiness. A negative factor in the operation of SES is inconsistency of the incoming solar radiation, which results in the loss of a significant part of potential electricity. Cloudiness, as an indicator of the radiation regime, reflects the variability of physical obstacles in receiving sufficient energy on the photovoltaic plates, which causes uneven operation of the solar power plant during the day (Dziadykevich et al. 2010).

Analysis of natural and climatic conditions of Ukraine indicates favorable conditions for the development of solar energy in the central and southern administrative regions (Fig. 2).

The smallest indicator of the annual duration of sunshine is 1,827 hours in Volyn region (the city of Kovel) and the largest is 2,427 hours in the Autonomous Republic of Crimea (the city of Evpatoria). In spite of rather high indicators of the annual duration of sunshine in the western, eastern and northern regions, there is also a high average annual number of days without sunshine. This indicates definite seasonality in the operation of solar power plants.

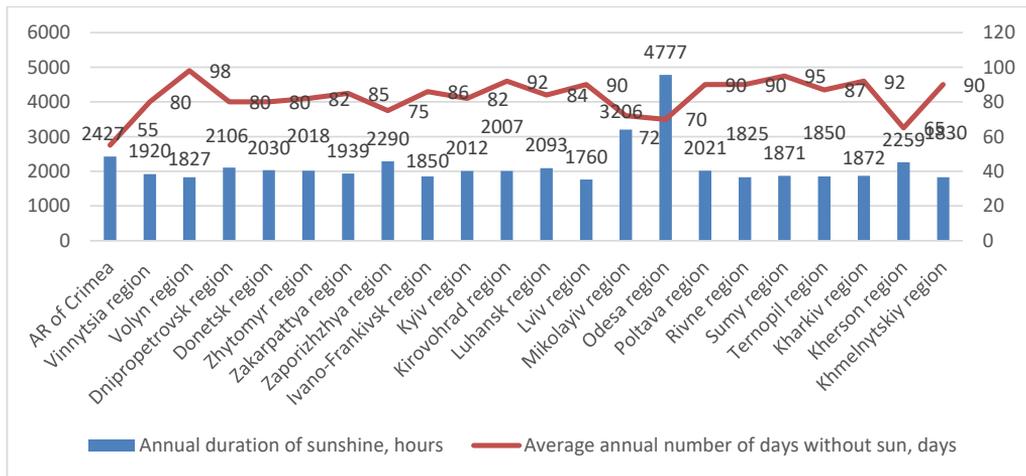


Fig. 2. Annual duration of sunshine, hours, and average annual number of days without sunshine (designed according to Climate of Ukraine 2021)

Rys. 2. Roczny czas nasłonecznienia, godziny i średnia roczna liczba dni bez nasłonecznienia

The estimated potential of solar energy in Ukraine is high enough for widespread use of both thermal and photovoltaic equipment in almost all administrative regions. The period of effective operation of a solar power plant in the southern regions is seven months – from April to October. In the northern regions, this period is two months shorter – from May to September. Thus, SPPs in Ukraine work throughout the calendar year but with variable efficiency, which indicates definite seasonality.

In general, the territory of Ukraine has an annual potential of $718.4 \cdot 10^9$ MW·h/year. The Odesa region (south of Ukraine) is an absolute leader today, because $45.4 \cdot 10^9$ MW·h/year of solar energy gets to this territory. The Kherson and Dnipropetrovsk regions follow it in ranking, with indicators that are 15% and 17% less than that of the Odesa region, respectively. An indicator of the total potential of solar energy mainly depends on the geographical location of the territory, its climatic features and the area of the region. The lowest rates are in the Volyn region – $9.6 \cdot 10^9$ MW·h/year and in the Sumy region – $15.5 \cdot 10^9$ MW·h/year. In addition to the northern location, these areas have high cloud coverage (Fig. 3).

It is known that the use of solar energy is appropriate when the total radiation per day exceeds 15 MJ/m^2 . Almost all regions of Ukraine correspond to such parameters (Fig. 4). The diagram is designed on the basis of the weather stations most typical for a specific region. In addition, a selection of regions with high rates of annual duration of sunshine and a larger average number of days without sunshine was made (see Fig. 2).

Virtually all regions of Ukraine can be used for the development of solar energy, but in the northern and western regions, the period of sunny days is reduced.

There are no established universal criteria for assessing the energy potential of wind; therefore, the rational use of wind energy in different areas depends on different decisive factors. One

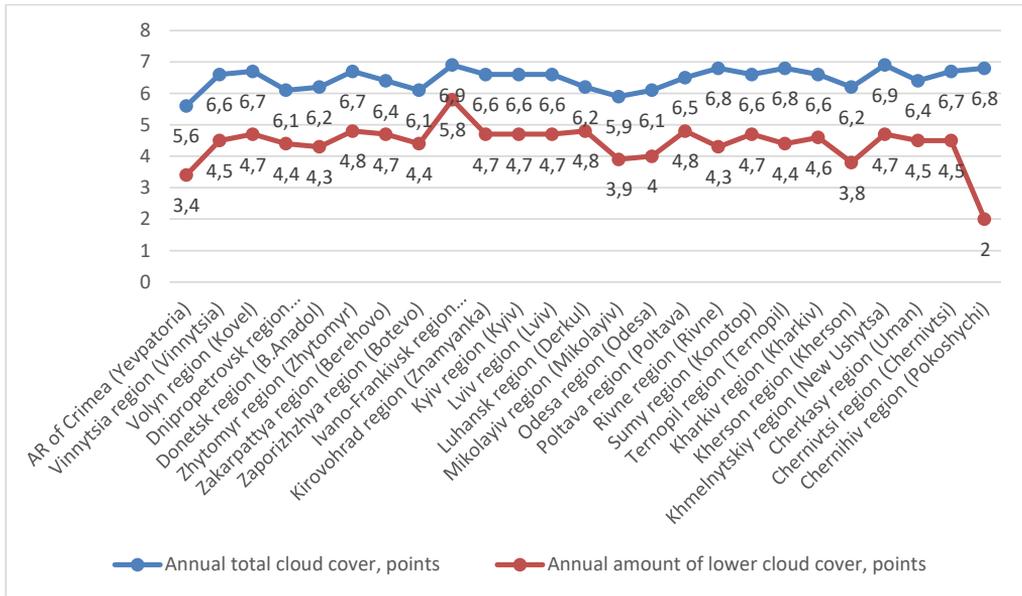


Fig. 3. Annual amount of total and lower cloud cover, score (designed according to Climate of Ukraine 2021)

Rys. 3. Roczna wielkość zachmurzenia całkowitego i z niskimi chmurami

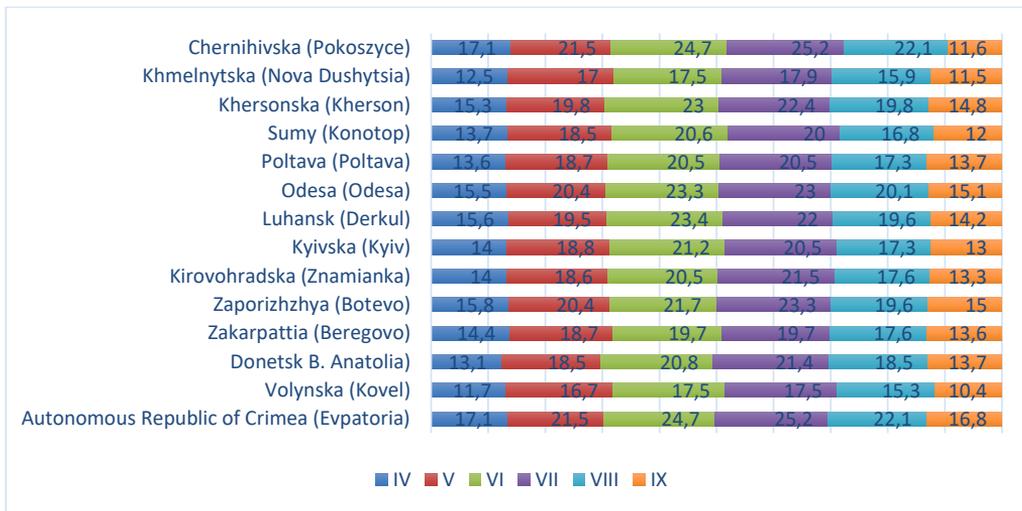


Fig. 4. Total radiation per day (April–September) [MJ/m²] (designed according to Climate of Ukraine 2021)

Rys. 4. Całkowite promieniowanie dobowe (kwiecień–wrzesień) [MJ/m²]

of the main parameters that determine the potential of wind energy is the average annual speed, which determines the power of electrical installations and their maximal speed. Weather stations with the most typical values were selected to determine the average and maximal wind speed in the administrative territorial regions (Fig. 5).

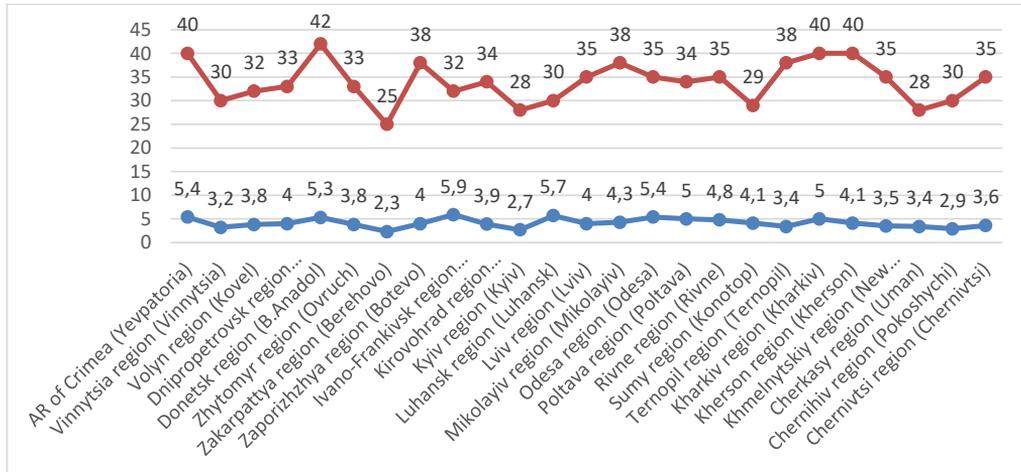


Fig. 5. Average and maximal wind speed [m/s] (designed according to Climate of Ukraine 2021)

Rys. 5. Średnia i maksymalna prędkość wiatru [m/s]

In the areas that are promising in terms of using wind turbines, the average annual wind speed reaches 5 m/s or more. An integral characteristic of wind power plant performance (WPPs) is the number of hours of using the installed capacity. A positive economic effect from the operation of wind turbines should be expected at over 2,000 hours of using the installed capacity.

The given data show that wind energy is one of the priority areas for using the hydroelectric power plants in Ukraine. This direction has already been developed and implemented significantly. Analysis of the available meteorological data shows that the best conditions in this regard can be found on the coast of the Sea of Azov, including the Sivash Bay, and the Black Sea, within the Odesa, Mykolaiv, and Kherson regions. The construction of wind power plants is advisable exactly in these areas, most of which demonstrate a significant deficit of their own generating capacities which leads to increased losses of electricity during its transmission over long distances with multiple transformations. In these areas, priority should be given to the construction of wind power plants in the adjacent water areas, in particular, in the non-freezing water area of the Sivash Bay, which is not yet used for economic activity. Owing to lower rates of inhibition of the air flow, the wind speed in water areas is 15–20% higher than in the adjacent part of the land, and the production of electricity is higher by at least 30%.

Another promising area for the construction of Ukrainian wind power plants is the Carpathians, where the average annual wind speed is the highest in Ukraine. One of the effective

options for the neutralization of wind instability and energy production by wind power plants is a combination of wind turbines and hydraulic storage power plants. In this case, the wind turbine can work specifically for the hydraulic pump that supplies water to the upper reservoir of the HPP. Whereby, the current parameters (voltage and frequency) do not require maintenance as in the case of parallel operation with the power grid. Therefore, it is possible to make wind turbine installation simpler and reduce its cost. The greatest simplification and cost-cutting of wind turbines, the reduction of operating costs and net cost of electricity in such combined wind-hydro-accumulating stations can be achieved when using wind-pumping turbines instead of wind-electric equivalents.

Biomass production in Ukraine takes place owing to the cultivation of agricultural crops. The area of agricultural land in the country is 41.4 million hectares, which makes up 19% of the territory of Europe, with 32.7 million hectares occupied by arable land; the amount of land per person is 0.90 hectares (Land Registry of Ukraine 2020). The distribution of agricultural land by regions of Ukraine is presented in Figure 6.

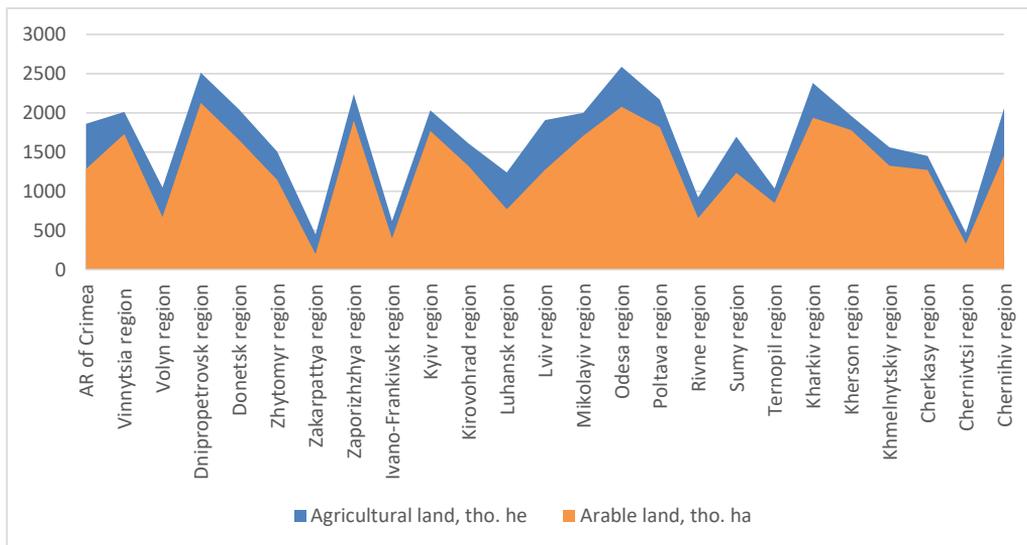


Fig. 6. Areas of agricultural land in the regions of Ukraine [thousand hectares] (designed according to the Land Registry of Ukraine 2020)

Rys. 6. Powierzchnia użytków rolnych w różnych regionach Ukrainy [tys. ha]

Analysis of the area of agricultural land in the regions of Ukraine shows high rates of both the total area and arable land. The lowest data rates are in Zakarpattia – 451 and 200 thousand ha, Chernivtsi – 470 and 331 thousand ha, and the Ivano-Frankivsk region – 621 and 401 thousand ha, respectively. High use of land for agricultural areas as well as the cultivation of agricultural crops in the arable land provides great opportunities for the development of bioenergy based on the use of biomass.

The main priorities of phytoenergy are searching for cheap bio-raw materials and founding the required infrastructure for growing and processing biomass with the use of chemical or biological processes into various types of biofuel: liquid (bioethanol, biobutanol), gaseous (methane) and solid (pellets, briquettes). The combustion heat of ethanol is: 21.1 MJ/kg, biogas (60% methane); 21.8 MJ/kg, solid biofuel; 15–18 MJ/kg depending on the type of raw material and its quality (see Table 5).

TABLE 5. Energy characteristics of agricultural crops, Ukraine

TABELA 5. Charakterystyka energetyczna upraw rolnych w Ukrainie

Agricultural crops	Biomass output [t/ha]	Type of biofuel	Biofuel heat output [MJ/kg]	Fuel equivalent	Output of biofuel		Conventional fuel yield [unit/ha]	Energy output	
					from 1 t of biomass [kg]	from 1 ha /ha [kg/ha]		GJ/ha	GWh/ha
Potato	25	Bioethanol	21.1	0.65	120.0	3,000	1,950	65	18.08
Winter wheat (grain)	4	Bioethanol	21.1	0.65	260.0	1,040	676	22	15.25
Winter wheat (straw)	4	Pellets	15.0	0.55	100.0	4,000	2,200	33	
Rapeseed (seed)	3	Biodiesel	33.1	0.91	401.5	1,204	1,096	40	19.08
Rape (straw)	3	Pellets	16.0	0.60	1,000	3,000	1,800	29	
Sugar beets (root crops)	45	Bioethanol	21.1	0.65	100.0	4,500	2,925	95	71.11
Sugar beets (hychka)	35	Biogas 60% CH ₃	21.8	0.60	200.0	7,000	4,200	161	
Corn (grain)	6	Bioethanol	21.1	0.65	240.4	1,442	938	30	72.33
Corn (biomass)	50	Biogas 60% CH ₃	21.8	0.60	200.0	10,000	6,000	230	
Sugar sorghum (biomass)	50	Bioethanol	21.1	0.65	100.0	50,000	3,250	106	92.19
	50	Biogas 60% CH ₃	21.8	0.60	200.0	10,000	6,000	230	

Designed according to the data from *Energy Plants 2017*.

The soil and climatic conditions of Ukraine are favorable for the cultivation of energy plants, which are capable of the intensive accumulation of solar energy during the growing season. These plants are characterized by a low cost of cultivation, a low level of demands on soil fertility and low requirement for the use of fertilizers and pesticides.

Areas under the main energy crops in Ukraine for 2018–2020 are presented below in Figure 7.

According to the given data, the largest areas are occupied by winter wheat, corn and potatoes. Corn biomass has the highest yield of conventional fuel, while winter wheat and potatoes have much lower rates. Along with this, the areas of sugar sorghum, which has the same high indicators of conventional fuel yield as corn, have the smallest values. However, the advantage

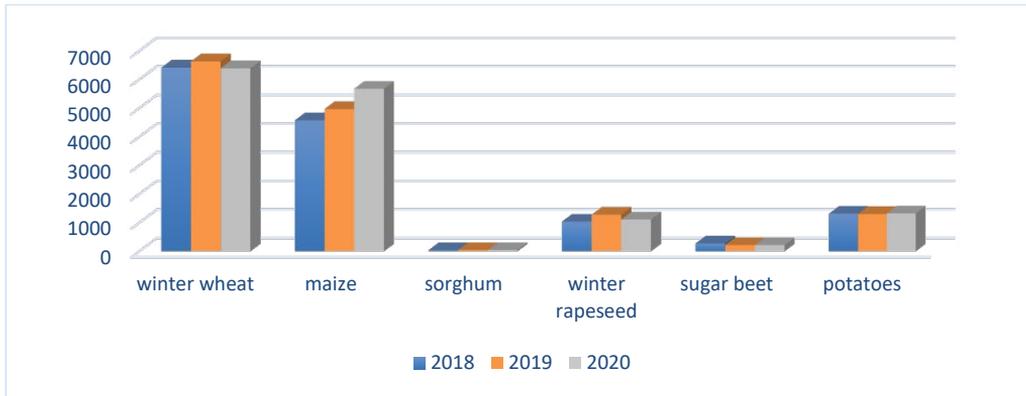


Fig. 7. Planted areas of agricultural crops by their species [thousand ha]
 (designed according to the data from the State Statistics Service of Ukraine 2021)

Rys. 7. Powierzchnie obsadzone roślinami rolnymi według ich gatunków [tys. ha]

is that Ukraine, cultivating winter wheat and other grains for the domestic and foreign grain markets, can significantly increase the level of biomass use at the expense of harvest residues.

The areas under agricultural crops in the regions of Ukraine by their types are presented below in Figure 8.

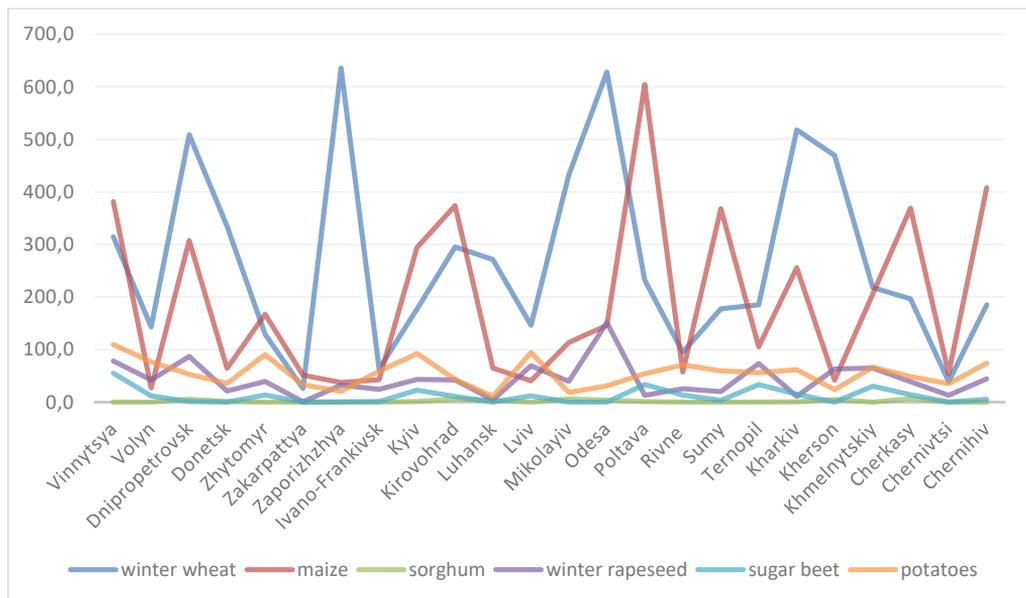


Fig. 8. The areas under agricultural crops in the regions of Ukraine by their types in 2020 [thousands of hectares]
 (designed according to the data from the State Statistics Service of Ukraine 2021)

Rys. 8. Powierzchnie obsadzone różnymi rodzajami upraw rolnych w poszczególnych regionach Ukrainy w 2020 r. [tys. ha]

The tendencies in the cultivation of the main agricultural crops presented in Figure 7 remain the same in the regions. The largest areas are occupied by winter wheat and corn.

Biomass is the oldest source of energy, but its use until recently has been limited to direct combustion with a low efficiency rate. Lately, the focus on efficient energy use of biomass has increased significantly. The amount of livestock and poultry waste by dry mass in Ukraine was about 32 million tons/year with 10.3 billion m³ of gas obtained per year. Biogas consists of methane (55–85%) and carbon dioxide (15–45%). The calorific value is 21–27.2 MJ/m³. Out of 1 ton of organic matter, 250–260 m of biogas can be obtained at a humidity of 5–10%. Processing 1 ton of fresh cow manure with a moisture content of 85% can yield from 45 to 60 m of biogas, and 1 ton of bird droppings with a moisture content of 75% can yield up to 100 m of biogas. The equivalent of 1 m³ of biogas in heat of combustion is 0.7 kg of fuel oil, 0.4 kg of gasoline, 0.6 kg of kerosene, or 3.5 kg of firewood. In addition, methane generation of organic waste produces environmentally friendly fertilizers in 5–10 days, 5 tons of which replace 80 tons of untreated manure. The combustion of 1 m³ of biogas in gas-electric generators produces 2 kW/h electricity and up to 10.5–12 MJ of thermal energy. The production of artificial liquid fuel based on rapeseed and other crops was maintained in Ukraine in the pre-war period along with the production of fuel granules (pellets) and briquettes from the remains of plant raw materials, including corn and winter wheat. Therefore, Ukraine has significant potential for the development of renewable energy sources, which can and should be used to stimulate the innovative development of the economy in the country and ensure energy security.

3. Methodology for determining the target parameters of energy security with the available resource potential

The study of expertise in resource assessment enables the identification of the advantages of efforts (Lewicka et al. 2021) from the assessment of resource potential, which is based on the analysis of economic importance, taking into account the safety of raw materials.

The identification of the target parameters was done with the help of methodology, which makes it possible to assess the state of energy security. The target parameters are grouped into the system of energy security indicators, defined by the International Energy Charter, in particular, regarding the energy investment risk assessment (EIRA). The system of indicators consists of four groups. This approach has the established limits of safe existence through determining the vectors of threshold values of energy security indicators. Each indicator undergoes the analysis of the resource percentage share in the energy balance of the country (Sukhodolya et al. 2020). The selected parameters correspond to the optimal range with the best conditions for the functioning of the energy security system.

A comparative assessment of the level of security in different periods of time is done with a scalar function I_t from individual components (indicators) – x_{it} , ($i = 1, 2, \dots, n$), which is the integral indicator (index) of the development level:

$$I_t = f(x_{1t}, x_{2t}, \dots, x_{it}) \quad (1)$$

Taking into account the non-linearity of the processes taking place in the research subject, the most adequate is the use of a multiplicative form of the integral index related to the additive form through a logarithmic function. We prefer the multiplicative (non-linear) form of the integral index since taking into account the nonlinearity of economic processes, it is more adequate to use the multiplicative form of an integral indicator of [Sukhodolis et al. \(2020\)](#).

Using correlation-regression analysis, we detect an averaged regularity that ensures an exact correspondence in a certain time period. The identification of weighting factors is more complicated because of the use of expert evaluation for their determination. The weighting factors were determined with the help of the method of principal components. It is implemented using the standard “Statistics” package. The “sliding matrix” method was used to determine dynamic weighting factors. It implies a sequential shift in the matrix of the minimum required size throughout a certain time period and the determination of the weighting coefficients for this time period ([Kharazishvili 2019](#)).

The matrix method allows the evaluation of each of the options as a function of various possible outcomes of the implementation of this alternative. The main conditions for applying the matrix method are: the availability of several alternatives for solving the problem; the availability of several situations that may occur during the implementation of each alternative; the ability to measure the consequences of the implementation of alternatives quantitatively.

Our evaluation was carried out in four stages:

- ◆ The first step is focused on the availability of the existing technological base and resource potential in Ukraine for the development of renewable energy resources (Figs. 1–8; Tables 1–3; 5).
- ◆ The second step is related to the needs of resources for the domestic market (at the level of the final volume), i.e. for the development of the national economy of Ukraine (Table 4).
- ◆ The third step implies the determination of probable risks of socio-ecological and economic orientation ([Baldzhi et al. 2019](#)).
- ◆ The fourth step is focused on the evaluation of legislative and regulatory documents referred to in reports ([EIRA 2022](#)).

We suggest introducing a new index. The main parameters of the Index of ecological and economic security include (I_{EES}) the number of electricity production facilities (CO), the state of the market (SR) and the availability of resource potential (RP). It is important to take into account the economic, environmental and social risks (R). The mutual influence of factors and risks, which are frequently in a cause-and-effect relationship, is identified. This leads to distortion of the integral result and subsequent incorrect decision-making. Therefore, it was decided to strengthen the model with a particular component which contains the elements of risk consideration:

$$I_{EES} = f(CO, SR, RP, R) \quad (2)$$

Risk (R) is defined as a set of environmental, social and economic risks, available in the region or those that may arise. The updating of the economic security management system should be continuous, taking into account the risk that ensures the accepted state of security and a specific moment in time.

Market relations significantly increase the competitive struggle between business entities and affect their economic and security status. Therefore, at the current stage of system development, the issue of organizing the management process in terms of the prevention and neutralization of all types of hazards is extremely relevant.

Methodological recommendations allow conducting analysis based on the assessment of target parameters. The latter characterize the resource potential and reveal those indicators which affect the final result most significantly. As a result, the goals and tools of the economy should be revised with a shift in emphasis in the field of resource use and an increased focus upon ensuring economic security.

4. Results of calculations

Modeling the dynamics of integral indices of the energy security components is based on the above-mentioned methodical recommendations. In comparison with the integral threshold values, modeling provides a picture of the current state of energy security of Ukraine by groups of parameters, namely: according to the resource potential, economic sufficiency, and institutional and organizational support for the use of energy resources (Figs. 9–10).

Modeling results show that in the period from 2017 to 2020, all three components (resource sufficiency, economic sufficiency, institutional and organizational support) are actually in the crisis zone. Only the development of bioenergy has a positive correspondence with regard to resource and institutional and organizational support. There is a paradox that in the presence of hydroelectric power plants in Ukraine, the model indicates the non-compliance of the components of energy security with the optimal zone. This requires significant changes in the management of foreign trade. Such shifts can become emergency response mechanisms for energy supply shortages.

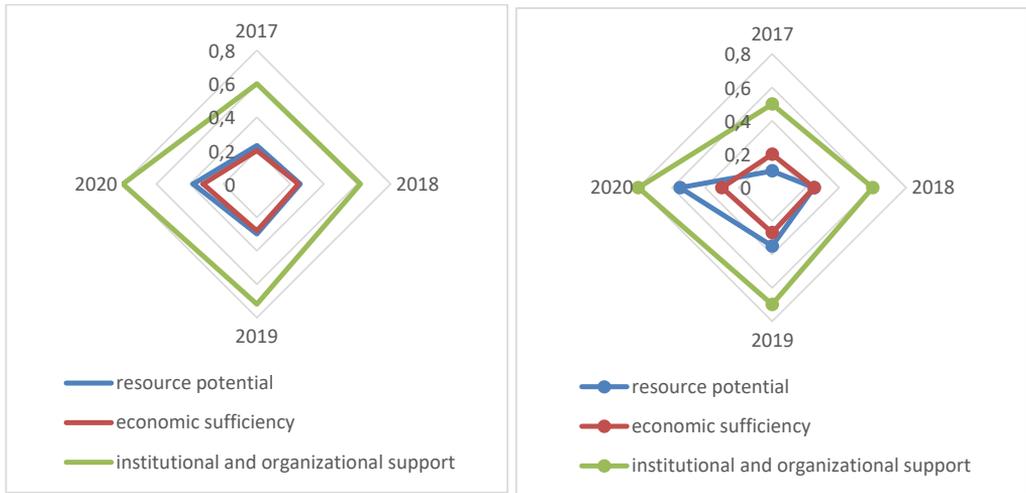


Fig. 9. Dynamics models of integral indices in energy security, according to the development of solar (a) and wind energy (b)

Rys. 9. Modele dynamiki wskaźników całkowych bezpieczeństwa energetycznego w zależności od rozwoju energetyki słonecznej (a) i wiatrowej (b)

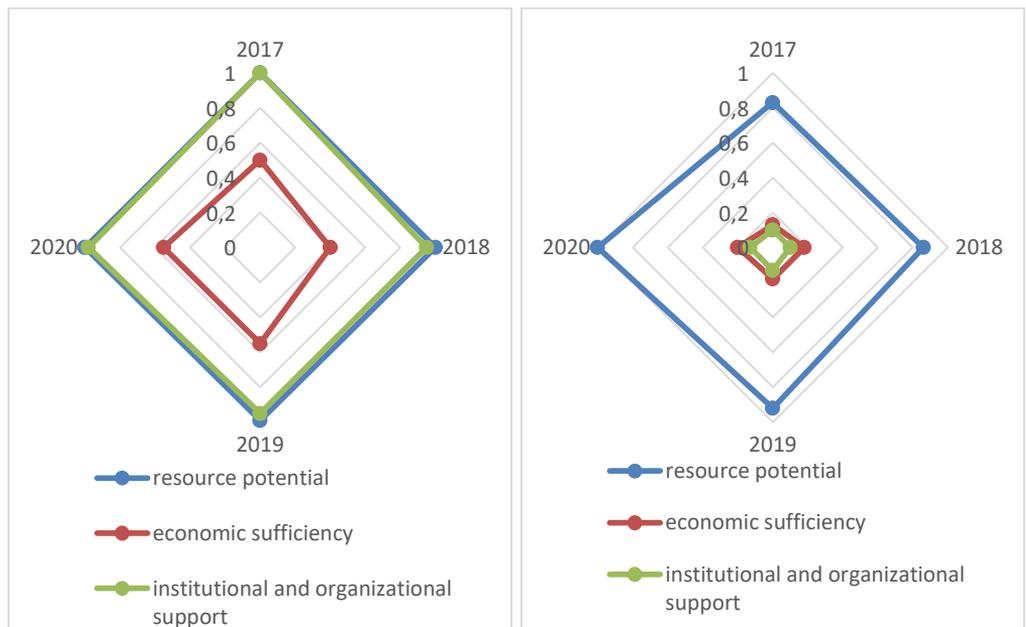


Fig. 10. Models of dynamics of energy security integral indices according to the development of bioenergy (c) and biofuels (d)

Rys. 10. Modele dynamiki wskaźników integralnych bezpieczeństwa energetycznego w zależności od rozwoju bioenergii (c) i biopaliw (d)

5. Emergency response mechanisms for energy supply shortages

In connection with aggression of Russia and its manipulation of the energy markets, both in Ukraine and in the world, there are significant changes in the approaches to the energy sector management. This leads to the development of new approaches to evaluating the state of energy security. In the system of ensuring energy security, four target areas of management are distinguished: the availability of resource potential, the availability of energy supply, the organization of functioning of energy supply and vital activities of the society, and the protection of national interests and the national economy (Azzuni et al. 2018; Sukhodolya 2019).

The main mechanism which is supposed to prevent a possible increase in the cost of own production of energy carriers should be the technological re-equipment of the industry through the introduction of innovations. We believe that Ukraine should come up with new initiatives. They should be the emergency response mechanisms for energy supply shortages that will ensure the collective energy security of Europe. The elements of these mechanisms have to fulfil the following principles:

- ◆ Every consumer should be able to use different sources of energy, including renewable ones, at different times.
- ◆ The structure of energy consumption should be determined on the basis of economic, social and environmental feasibility.
- ◆ Fuel and energy production should be decentralized, while energy flows should be fragmented, which will provide an opportunity to actively involve RES.
- ◆ The formation of strategic approaches should be directed towards the universalization of the use of fuel and energy resources.
- ◆ Reserve energy capacities must be allocated or created in order to increase the flexibility and stability of energy supply systems.
- ◆ Energy-accumulating industries require formation or restoration.
- ◆ The development of the system of minimizing electricity losses is required.

Conclusion

Energy security is one of the most important problems, the solution to which provides a guarantee of sustainable development of society both in Ukraine and in the countries of the EU. There are such main directions in looking for rational solutions to the problem as increasing energy efficiency as well as ensuring environmental protection and social stability. All this requires significant effort from society. It is required to achieve constructive and purposeful actions of all

branches of power in Ukraine, in particular, competence of management personnel, mutual trust of the government and citizens, and their readiness for business partnership.

The research results prove that we have evaluated the state of energy security of Ukraine at the end of 2021. The estimation was carried out using the matrix method and it determined a total ecological and economic risk, which affects the energy security in the UES of Ukraine. The research suggests a mechanism for preventing the increase in the cost of produced energy carriers. It analyzes the legislative framework for the establishment of the energy system and identifies the key factors which influenced the development of the industry. These factors are as follows: the formation of a price policy for the consumer and the availability of investment resources and subsidies in the framework of renewable energy. The system of ensuring energy security comprises the following targeted areas of management: availability of resource potential, accessibility of energy supply, investment component, flexibility of legislation, and protection of the national interests.

It is proven that energy supply on the basis of renewable energy is one of the optimal solutions to modern challenges. The article considers the existing background and resource potential for the development of the energy industry in Ukraine. It analyzes the availability of renewable energy resources for energy security in Ukraine and identifies its possibilities. It also substantiates favorable natural conditions for the use of hydroelectric power plants for solar, wind and bioenergy. On the basis of the method of determining the target parameters of energy security with the available resource potential, it constructs the dynamics models of integral indices of the energy security components. These proved that the constituent parts of energy security do not correspond to the optimal zone for almost all hydropower plants. It has been identified that the next task for future research is the formation of emergency response mechanisms for energy-supply shortages as elements of management at national and European levels.

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Zarządzanie odnawialnymi źródłami energii dla bezpieczeństwa energetycznego Ukrainy i Europy

Streszczenie

W artykule omówiono zalety korzystania z odnawialnych źródeł energii (OZE); poddano analizie potencjał surowcowy Ukrainy pod kątem produkcji energii; uzasadniono korzyści płynące z wykorzystania OZE dla bezpieczeństwa energetycznego. Ponadto zbadano potencjał istniejącej infrastruktury technologicznej dla zrównoważonego rozwoju energetyki na Ukrainie. Zidentyfikowano również strukturę mocy energetycznych oraz technicznie osiągalny potencjał produkcji energii z OZE i paliw alternatywnych jako

podstawę dla różnych scenariuszy perspektywicznego rozwoju energetyki alternatywnej w Ukrainie. Rozwój energetyki słonecznej, wiatrowej i bioenergii jest analizowany zgodnie z zaleceniami politycznymi dotyczącymi śledzenia dynamiki ostatecznego wolumenu zużycia energii w Ukrainie.

Może to pozwolić na doskonalenie metodyki wyznaczania docelowych parametrów bezpieczeństwa energetycznego przy dostępnym potencjale zasobowym, który stanowi podstawę modeli dynamiki integralnych wskaźników elementów bezpieczeństwa energetycznego. Modele te pokazują aktualny stan bezpieczeństwa energetycznego Ukrainy w zakresie potencjału surowcowego, wystarczalności ekonomicznej oraz wsparcia instytucjonalnego i organizacyjnego wykorzystania surowców energetycznych.

Artykuł proponuje kluczowe kierunki zarządzania polityką energetyczną w Ukrainie oraz mechanizm reagowania kryzysowego na brak dostaw energii. Rozwój energetyki alternatywnej jest uważany za drogę do niezależności energetycznej gospodarki narodowej Ukrainy i Europy.

SŁOWA KLUCZOWE: gospodarka narodowa, odnawialne źródła energii, energia alternatywna, modele elementów bezpieczeństwa energetycznego, zarządzanie