PROBLEMY EKOROZWOJU – PROBLEMS OF SUSTAINABLE DEVELOPMENT
2022, 17(2): 31-38
DOI: 10.35784/pe.2022.2.04

Post-COVID-19 Revitalisation and Prospects for Climate Neutral Energy Security Technologies

Rewitalizacja po COVID-19 i perspektywy wykorzystania neutralnych dla klimatu technologii bezpieczeństwa energetycznego

Olena Borysiak*, Vasyl Brych**

**West Ukrainian National University, Department of Marketing, Lvivska 11, 46000, Ternopil, Ukraine*
E-mail (Corresponding Author): o.borysiak@wunu.edu.ua
ORCID: 0000-0003-4818-8068, SCOPUS ID: 57219602195
***West Ukrainian National University, Department of International Tourism and Hospitality Business, Lvivska 11, 46000, Ternopil, Ukraine*
E-mail: v.brych@wunu.edu.ua
ORCID: 0000-0002-4277-5213, SCOPUS ID: 57195137291

Abstract

Dealing with the effects of COVID-19 is on the energy security agenda. Consolidation of efforts at the regional, national and international levels to exchange experience in the implementation of successful practices and the formation of institutional support of the sustainable energy development contributes to the post-COVID-19 revitalisation. With this in mind, the article is devoted to studying the peculiarities and experience of the post-COVID-19 revitalisation of the energy sector in different countries and determining the development prospects of climate-neutral technologies in the energy security sphere. A change in the behaviour of energy consumers by the secondary energy source in the context of increased quarantine restrictions has been established. In particular, a downward trend in the volume of energy consumption from traditional sources (oil, coal, etc.) has been traced. At the same time, the demand for energy consumption from renewable sources (solar energy, wind energy, etc.) has grown, which made it possible to diagnose the reduction in CO_2 emissions. Based on the analysis of measures to reduce the negative impact of the COVID-19 on energy security in different countries, the integration of the foundations of climate neutrality through the development of new critical technologies in the field of renewable energy sources has been established. As a result of a survey of green energy stakeholders using PEST analysis, it was proved that the complexity of integrating the principles of climate neutrality into the energy sector is that the result is not an economic effect but primarily an environmental effect (energy decarbonization). As a result, a methodology for determining the sustainability indicators for developing climate-neutral technologies in energy security using fuzzy set methods is proposed. The prospect of developing climate-neutral technologies in energy security lies in the transition to cross-sectoral interaction based on a closed cycle of energy consumption from renewable sources and the use of Industry 4.0 technologies. The proposed methodology will be a tool for further research on the developing organizational and innovative support and justifying the economic feasibility of introducing climate-neutral technologies based on the clustering of industries and a circular economy in the energy security sphere.

Key words: energy decarbonization, climate-neutral innovations, renewable energy, critical infrastructure, COVID-19, sustainable development, circular economy
Słowa kluczowe: dekarbonizacja energii, innowacje neutralne dla klimatu, energia odnawialna, infrastruktura krytyczna, COVID-19, zrównoważony rozwój, gospodarka o obiegu zamkniętym

Introduction

Energy resources are needed to ensure the full functioning of any socio-economic system. At the same time, a significant risk factor for the disruption of this process is the limited, inaccessible, inconsistent, non-preserved or depleted resources. Considering this, the issues of obtaining access, ensuring, and efficient use of energy resources in the conditions of COVID-19 are in the interests of both national security and global (transnational) interaction. Energy security is considered a component of national security, and the energy sector is included in the critical infrastructure of strategic importance for the sustainable energy development.

In general, "the COVID-19 pandemic has changed the electricity consumption profile by the specifics of human activity. Global household electricity consumption has risen by 40% as citizens have been forced to work from home to stop the spread of the virus. At the same time, during the aggravation of the pandemic, electricity consumption in non-residential sectors decreased" (Soava, 2021). Analytical agency Renewables Now notes "the growth dynamics of renewable energy in 2020-2021 under the influence of coronavirus by 10%" (Renewables now, 2021).

Changes in behaviour and energy consumption during the pandemic have been directly reflected in global levels of CO_2 emissions. In particular, "in 2020, an overall reduction of 2.58 Gt of energy-related CO_2 emissions was recorded in 2020 of 2.58 Gt. Overall, CO_2 emissions decreased by an average of 26% (at peaks) during the broad lockdown in selected countries" (Peng, 2021).

The energy sector is one of the industries whose activities lead to a negative impact on the climate. In this context, the results of a study by the International Energy Agency in the annual World Energy Outlook report on the world's response to COVID-19 are of interest. In particular, "demand for coal is predicted not to return to pre-COVID levels and that it will account for less than 20% of energy consumption by 2040. Oil is also experiencing fluctuations in consumption levels, and after 2030, demand for it will begin to decline. At the same time, it is predicted that renewable energy sources with zero carbon impact on climate change can meet 80% of electricity demand growth over the next ten years" (COVID-19 can change the future of energy for many years to come – IEA forecast, 2020). By 2025, renewable energy sources will replace coal as the primary means of generating electricity. Such trends in the development of the energy industry indicate the relevance of transforming the managerial, marketing and technological approaches to the formation of the energy supply chain in the post-COVID-19 period through the transition to climate-neutral energy security.

Literature review

The study results (Soava, 2021; Kuzemko, 2020; Brych, 2021; Dluhopolskyi, 2021) show that domestic or imported electricity consumption affects economic growth, while economic growth affects the level of electricity consumption in individual households. Within COVID-19, proportions observance between the types of primary energy carriers and avoiding the dominance of one or another non-renewable energy resource is among the ways to maintain the energy balance (Pysmenna, 2020). In (Peng, 2021) structural changes in energy demand and consumption are considered in a comprehensive manner, which covers the following aspects: changing patterns of energy consumption in time, space, sector and size of use; additional energy needs; energy development stabilization; restoration of the energy consumption level.

Within post- COVID-19 strengthening of energy security, the development of renewable energy is seen to ensure economic growth, improve social standards and well-being, and an environment for the implementation of climate-neutral innovations. As a result, the focus on innovative post- COVID-19 solutions in the energy sector as part of critical infrastructure is particularly significant. Along with this, scholars confirm "the vulnerability of the renewable energy sector by a bidirectional causal relationship between the energy consumption volume from renewable energy sources and economic growth in the long term" (Marinas, 2018). Among the factors of disproportion in the energy balance in renewable energy, there is "a decrease in business activity (a decrease in average daily energy consumption, which led to changes in the proportions of the electricity balance between types of energy generation); an increase in the volume and number of restrictions on generation from renewable energy sources due to a general drop in energy consumption; a decrease in the solvency of consumers and an increase in debt in the energy market; reconfiguration of the daily load schedule of the interconnected energy systems" (Pysmenna, 2020). Because of this, the search for new approaches to effective pandemic management to ensure sustainable development is particularly essential (Elavarasan, 2021; Halysh, 2021; Brych 2022).

The complexity of climate policy development in the energy market in the coronavirus context lies in need to make quick management decisions that will make it possible to prevent stagnation in the economy as soon as possible. Because of this, environmental issues (including the development of measures to adapt to climate change) are measures that "determine the unproductive costs of the economy and diversification of supplies and development of its resource base cause an increase in risks in the economy. In contrast, measures on energy efficiency, increasing the share of renewable energy sources are referred to as the measures aimed at ensuring economic growth decoupling. They have a positive impact on productivity and economic growth" (Pysmenna, 2020). In this context, it is advisable to note that energy is a critical infrastructure component that ensures the country's life. As a result, such a dualistic approach to adaptation to climate change in the energy sector necessitates deepening research on

adopting innovative solutions to ensure energy security within post-COVID-19 revitalisation in the context of the development of climate-neutral technologies.
The purpose of the article is to study the peculiarities and experience of post-COVID revitalisation of the energy sector in different countries, assess the conditions for integrating climate-neutral innovations in the energy sector and develop a methodology for determining sustainability indicators for the development of climate-neutral technologies in the energy security sphere.

Research methodology
In the context of the COVID-19, the preference of energy consumers to ensure uninterrupted energy supply to diversified channels for obtaining secondary energy (in particular, from renewable energy sources) led to the expansion of the green energy segment in the energy market and, as a result, an increase in the need for energy services. Previous studies (Brych, 2021) propose determining the positioning of *green* energy services in terms of the energy consumption level by applying difference equations. At the same time, when determining the methodology of this study, we took into account the fact that measures to decarbonize the energy sector in order to prevent climate change are considered as unproductive expenses of the economy, which indicates the need to justify the need to change such a vision. This justification was our study of evaluating the effectiveness of promoting *green* energy services (Borysiak, 2021), in which we used optimization methods.
As a result, this allowed us "to identify the indicator of maximizing the ecological (green) effect (decarbonizing the environment) and the indicator of minimizing energy consumption costs:

$$f(G) = \sum_{i=1}^{n} g_i s_i \rightarrow max \qquad (1)$$

$$f(C) = \sum_{j=1}^{m} c_j e_j \rightarrow min \qquad (2)$$

f(G) i f(C) – the functions maximizing the ecological (green) impact of the green energy services provision s_i and minimizing energy costs e_j; g_i – indicator of the level of decarbonization from the use of green energy services s_i; c_j – the cost of consuming the relevant type of energy e_j; n – number of types of green energy services (i=1…n); m – number of types of energy (j=1…m)" (Borysiak, 2021).
Because of this, the methodological basis of our current study, in particular the study of post-COVID-19 revitalization aspects and the prospects for the development of climate-neutral technologies in the energy security sphere, is based on the use of fuzzy set methods, which will determine the sustainability indicators for the development of climate-neutral technologies in the energy security sector in the absence of clear parameters of the objects under study (influence factors). A PEST analysis of the factors influencing the integration of climate neutrality into green energy was carried out by polling green energy stakeholders. The equation for calculating the elements of the combined decision matrix Xij is taken as a basis to determine the stability indicators (Elavarasan, 2021):

$$x_{ij} = (A_{ij}, B_{ij}, C_{ij}) \qquad (3)$$

$$A_{ij} = mink[ak_{ij}], B_{ij} = 1K\sum k_n, C_{ij} = maxk[ck_{ij}]$$

where a,b,c are the fuzzy numbers components associated with the decision matrix of each stakeholder, A,B,C are the fuzzy number components corresponding to the combined decision matrix, i represent the prospects (recoverability and sustainability) of the ratings, j represents the PEST coefficients and k is the number of decision makers or decision matrix.
In turn, we believe that the sustainability of the energy system functioning depends on technological modernization and the adoption of energy-efficient solutions. First of all, this concerns the creation of favourable conditions for the uninterrupted supply of secondary energy (*green* energy) to consumers and the specifics of the interaction of primary energy suppliers from renewable energy sources with producers of *green* energy. Therefore, in order to form a list of factor signs of obtaining an environmental, economic and social effect, the PEST analysis takes into account the key factors influencing the prospects for the development of climate-neutral technologies in the energy security sphere, such as the innovative potential of green energy enterprises, the diversification level of secondary energy supply sources, the digitalization level of energy supply management systems, the well-being level of the population, the environmental education level of population.

Research results
Like other business entities, the energy sector, regardless of the primary energy source (traditional and renewable energy sources), has been affected by COVID-19. "In the first quarter of 2020, global energy demand decreased by 3.8%, with most of the impact occurring in March when Europe, North America and other countries applied containment measures due to the spread of COVID-19" (Global Energy Review, 2020).
"The global demand for coal suffered the most, falling by almost 8% compared to the first quarter of 2019. Oil demand decreased by almost 5%, demand for gas decreased by about 2%. At the same time, there was a drop in demand for electricity by 20%, primarily for electricity produced from traditional energy sources (oil, gas, coal, nuclear energy). On the other hand, there is a positive trend in the growth of demand for electricity from renewable sources and directly for renewable energy sources (solar energy, wind energy, hydropower, geothermal energy), and bioenergy (biofuel) and energy production from waste. A decline in economic activity starting in the first

quarter of 2020 and continuing into the second quarter of 2020 was identified in most European countries. Activity in industry and services declined mainly in the second quarter of 2020 in Germany, Spain, France, Italy. As a consequence, a reduction in energy consumption was found. In particular, electricity consumption in Europe decreased by 11% in the second quarter of 2020 compared to the same period in 2019" (Marinas, 2018; Soava, 2021). At the same time, economic activity in European countries did not decrease evenly on the entire continent, and different isolation measures taken by countries had different effects on energy consumption. The most significant decline in energy consumption was observed in member countries with the most substantial decline in gross domestic product. "Initially, Germany saw a smaller decline in consumption due to less restrictive conditions than its neighbours and a stable industrial sector with a relatively high share of GDP. Instead, in the countries of Southern Europe (Italy, Spain and France), there was a significant reduction in energy consumption due to measures that seriously affected the tourism sector. Thus, in Italy, energy consumption decreased by almost a third compared to the same period in 2019. Energy consumption during the lockdown fell by at least 15% in France, Spain, while in Italy, at the height of the outbreak, electricity demand sometimes dropped, falling by up to 75%" (Marinas, 2018; Soava, 2021).

As a member state of the EU, Romania also experienced a drop in energy consumption. However, "in 2020, a recovery was being monitored due to implementing the terms of the EU End-Use Energy Reduction Strategy to reduce energy consumption and increase energy efficiency and resumption of economic activity" (Soava, 2021). "If in January 2020 the cost of consumption was the same as in 2019, starting from February 2020, there was a significant increase in household electricity consumption compared to the same period of the previous year, reaching the highest increase in 2020, 8.33% compared with the same month of 2019" (Soava, 2021).

In Ukraine, as in other countries, starting from 2020, a trend has been observed to revive economic activity and increase energy consumption. In particular, according to the Ministry of Energy of Ukraine, "in August 2020, the share of renewable energy reached 16.6%" (Record of Ukrainian energy, 2021). The renewable energy sector of Ukraine, as in other countries of the world during the corona-virus crisis, did not suffer a fall compared to the traditional energy sector.

The use of timely preventive measures to reduce the risks (Table 1) from the impact of COVID-19 in different countries made it possible to stabilize the situation in terms of energy security.

Table 1. Measures to prevent the negative impact of COVID-19 on energy security in different countries (Quarterly report 1, DiXi Group, 2021)

No	Country	Characteristics of anti-COVID activities
1		*Traditional energy (coal-fired power)*
	European Union	Launch of the Platform *Coal Regions Transformation* and the *Environmental Reconstruction and Repurposing Toolkit*: *EU Guidance for Managing Environmental Restoration and Asset Repurposing in Coal Regions in the Transformation Process.*
	Germany	Siemens project *Introduction of ETES Thermal Battery in Coal-fired Power Plants* in Hamburg Harbor 2019 (Electrical Thermal Storage/ETES technology uses fans from surplus electricity generation at wind farms to heat 1,000 tons of the power plant's volcanic stone to temperatures of 750-800 degrees Celsius, the resulting heat can be used for the reverse production of electricity using steam or by distributing thermal energy to end consumers).
	Hungary	Project to grow energy plants and install solar panels on the territory of a closed lignite mine owned by the Marta Power Plant coal-fired power plant (replacement of coal consumption with electricity from renewable energy sources and the creation of an industrial park based on the mine; excess heat and electricity from the power plant in the cluster industrial park, and the by-products of these enterprises (biomass) are supplied to the power plant for electricity generation).
	Great Britain	Developed by the International Council on Mining & Metals Best Practice Guide for Comprehensive Mine Closure.
	Ukraine	Development of Ukraine of the concept of reforming the coal industry *On the development of a national program for the transformation of the coal regions of Ukraine until 2027* (October 2020). Decree of the Cabinet of Ministers of Ukraine dated September 22, 2021 No. 1024 *On approval of the Concept of the State Target Program for the Fair Transformation of the Coal Regions of Ukraine for the period up to 2030*.
	China	Project for the introduction of high-efficiency natural gas generation at coal-fired power plants (transformation of a coal-burning power plant into a natural gas combined cycle power plant producing electricity and heat and reducing the negative impact on the environment).
2		*Renewable energy and green energy services*
	the EU	The European Commission has developed a comprehensive action plan to implement the principles of the European Green Deal, the main element of which is the Sustainable Europe Investment Plan, which covers investments in various sectors for their decarbonization. A Just Transition Mechanism has been created, financed from the EU budget.
	Germany	The Green Stimulus Package (June 2020) includes at least €50 billion in climate change, solar and wind energy spending.

2	*Renewable energy and green energy services – continuation*	
	Ukraine	Establishment of a *green* tariff for electricity from renewable energy sources (in accordance with the Law of Ukraine *On the electricity market*) and an incentive tariff for thermal energy from renewable energy sources (the Law of Ukraine *On Amendments to the Law of Ukraine 'On Heat Supply' to stimulate the production of heat energy from alternative energy sources*).
	Canada	A C$ 1.7 billion investment program has been initiated to clean up old and abandoned oil and gas wells to reduce pollution levels. A C$750 million Emission Reduction Fund has been created to help oil and gas companies operating onshore and offshore receive funding for environmental initiatives to reduce pollution and save jobs. A program for the availability of loans has been developed, in particular for entities of the energy sector.
	South Korea	On July 14, 2020, the country's government announced the Green New Deal initiative. The action plan is focused on stimulating the development of the renewable energy sector, gradual withdrawal of financing from the coal industry. In December 2020, the *2050 Carbon Neutral Strategy of the Republic of Korea: Towards a Sustainable and Green Society* was published, which set clear targets for reducing the carbon footprint of industries.
3	*Tariff policy*	
	the EU	The updated Electricity Market Directive, adopted in 2019 as part of the Clean Energy for All Europeans package, seeks to reduce supplier switching procedures to 24 hours, ensure the right of consumers to demand the installation of smart meters that can measure consumption in real time and remotely, as well as provide the ability to create reliable tools (sites) for comparing commercial offers from suppliers. The European Commission has published guidance on energy poverty and provides support through the European Energy Poverty Observatory. In October 2020, the European Commission provided guidance on energy poverty due to the effects of the COVID-19 pandemic.
	Great Britain	There is an independent energy market regulator, a dedicated agency called Ofgem, which is implementing a dedicated strategy focusing on supporting vulnerable customers, and working with governments, industry, and consumer groups to ensure a clean economy and the lowest cost for consumers, especially vulnerable ones. In March 2020, the country also launched a *Supervisory Service Package* along with energy suppliants to suppress the camp of companions during the COVID-19 pandemic. Guidelines have been developed for energy suppliers and other market participants that draw attention to certain risks and provide examples of best practices to support consumers affected by the effects of the COVID-19 pandemic.
	Ukraine	In February 2021, a Memorandum was signed between local authorities, the Ministry of Energy, the Ministry of Regional Development, National Commission for State Regulation in the Sphere of Energy and Utilities, and Naftogaz on the unchanged tariffs for heating and hot water until May 2021. The Anti-Crisis Energy Headquarters, chaired by the Prime Minister, approved the action plan for the implementation of this Memorandum.

In turn, effective post-COVID-19 measures in the energy sector include (Peng, 2021; Kuzemko, 2020) the following measures: digitalization of the energy sector (increased digitalization and the Internet of Things, IoT); taking into account the new way of life in cities with less energy consumption; building resilience through the circular economy; opportunities for renewable sources, energy storage and energy savings. In addition (Jiang, 2021), proposed a new concept of the relationship between health, energy and the environment under the constraints associated with climate change.

Given the fact that energy security is an integral part of national security, and energy is included in critical infrastructure facilities, an important decision to ensure energy security in the post-COVID-19 period is to create conditions for the development and implementation of critical technologies. The digitalization of energy networks is essential for the transition to Industry 4.0 technologies. After all, understanding the role of technology in supporting humanity opens up new perspectives for effective pandemic management. This role of technology is expressed in terms of uninterrupted connectivity, fast communication, mobility, technological impact in healthcare, the impact of digitalization, surveillance and security, artificial intelligence (AI) and the Internet of Things (IoT) (Elavarasan, 2021; Liakhovych, 2021).

"National Report – 2017 *Sustainable Development Goals: Ukraine* to achieve the goal *Affordable and clean energy*, four tasks are defined (Expanding and modernizing the energy infrastructure for sustainable energy supply based on innovative technologies; Diversifying the supply of primary energy resources; increasing the share of renewable energy sources) and seven indicators of sustainable development in the energy sector (electricity generation; technological costs of electricity in distribution networks; heat losses in heating networks, the maximum share of imports of primary energy resources (except nuclear fuel) from one source in the total supply; the share of one supplier in the nuclear fuel market, the share of energy from RES in total final consumption; primary energy intensity of GDP), as well as the target values of these indicators by 2030" (Pysmenna, 2020).

At the same time, the increased awareness of the climate change consequences in the last decade leads to considering the issues of assessing the level and factors of negative impact on the climate of various industries (including energy), as well as determining the level of their vulnerability to climate change and introducing climate-neutral innovations. In particular, in the context of the information analysis in Table 1, it should be noted that in preventing stagnation in the economy within the coronavirus, the issue of developing measures to adapt to climate change was also on the agenda. In particular, on February 24, 2021, the European Commission adopted the EU Strategy for Adaptation to EU Climate Change. On October 20, 2021, Ukraine adopted the Strategy for Environmental Security and Adaptation to Climate Change until 2030. In November 2021, participants in the COP26 Conference in Glasgow also focused on climate change.

It should be noted that the diagnosis of the prospects for the development of renewable energy to growth as a result of the transition to energy consumption from renewable sources in the context of the coronavirus, which led to a decrease in CO_2 emissions (by reducing the use of energy from traditional sources), indicates the importance of expanding climate-neutral activities to strengthen energy security in the post-COVID-19 period. In this context, it is of strategic importance for the industry to obtain the effect of energy security decarbonization and a positive economic effect (value-added) due to the development and implementation of critical climate-neutral innovations at all stages of the energy supply chain.

We agree with the statement that in order to establish a bidirectional relationship between the volume of energy consumption from renewable energy sources and economic growth in the long term, it is advisable in (Marinas, 2018; Brych, 2021; Pysmenna, 2020) to adjust their energy, industrial and innovation policies in order to use their own technological base, their own financial and human capital, own material resources, as well as public-private partnership mechanisms and innovative programs at the state level for the development of energy technologies from renewable energy sources to maximize the impact on the sustainability of economic growth.

The prospect of developing climate-neutral technologies for energy security lies in the transition to cross-sectoral interaction based on a closed cycle of energy consumption from renewable sources and the transition to Industry 4.0 technologies. On this path, it is vital to develop the interaction of agricultural enterprises (biomass producers) and enterprises producing *green* energy as a result of factorial modeling of biomass supply chain optimization (Brych, 2021). The next step should be the organizational and economic support for developing and implementing critical technologies in the energy security sphere based on climate-neutral clustering and optimization of the environmental and energy management of the national economy.

PEST analysis was carried out to determine the factors influencing the integration of the climate neutrality foundations in the energy efficiency sphere (Table 2). For this aim, six stakeholders were interviewed (online survey), namely, one representative from such stakeholder groups: non-governmental organizations, the media, local governments, scientific institutions, educational centres, innovation hubs). The content of the survey was the assessment of indicators for obtaining environmental, social and economic effects from the development of *green* energy (from 1 to 5 points, where 1 – the minimum level of effect, 5 – the maximum level of effect). The results of the assessments are averaged and multiplied with a significant factor.

Table 2. PEST-analysis of factors influencing the integration of the climate neutrality foundations in the energy efficiency sphere (formed on the basis of the results of the questionnaire survey)

Indicator	Expert assessment						Average rating	Factor significance	Impact assessment
	1	2	3	4	5	6			
Ecological effect									
Biodiversity conservation	3	3	2	3	2	3	2,7	0,5	1,6
Rational nature management	3	2	2	2	4	2	2,5	0,5	1,3
Decarbonization of settlements	3	3	3	4	3	3	3,1	0,6	1,9
Group average :							2,8	0,5	1,6
Economic effect									
Entrepreneurship development	5	4	4	4	5	4	4,3	0,9	3,9
Implementation of energy efficient technologies in production processes	4	4	4	5	5	4	4,3	0,9	3,9
Flexibility of energy tariff policy	3	3	3	3	3	3	3,0	0,6	1,8
Group average :							3,9	0,8	3,2
Social effect									
Building a culture of energy management	3	4	3	3	3	4	3,3	0,7	2,3
Improving the welfare of the population	5	4	4	4	4	5	4,3	0,9	3,9
Public health promotion	3	3	3	4	3	3	3,1	0,6	1,9
Group average :							3,6	0,7	2,7

Since the introduction of climate-neutral technologies is aimed primarily at achieving the effect of decarbonization in *green* energy and the units of measurement are not economic, but of an environmental one, but fuzzy set methods

were used to develop a methodology for determining the sustainability of climate-neutral technologies including methods of fuzzy cluster analysis. Appropriate characteristics are set to build a fuzzy clustering model.
The criteria according to which the PEST analysis factors are evaluated, we propose to interpret as sustainability indicators (maximum score 5) and vulnerability indicators (minimum score 1) can be characterized as sustainability criteria and vulnerability criteria.
Let a set of objects be given:

$$X = \{X_i = (x_{i1}, x_{i2}, \dots, x_{iM}), i = \overline{1, N}\} \quad (3)$$

characterized by many features:

$$K = \{K_1, K_2, \dots, K_M\},$$

i.e., x_ij is the value of the j-th feature (influence factor) for the i-th object (stakeholder). It is necessary to divide this set into G fuzzy clusters according to a given criterion, i.e. to construct an algorithm Θ, the execution of which would allow determining the degree of belonging of an object to each of the clusters, i.e.
$X_i \rightarrow (\mu_1(X_i), \mu_2(X_i), \dots \mu_G(X_i))$ where ??$_g$ (X_i) is the belonging degree of the object *Xi* of the cluster numbered g, $g = \overline{1, G}$, and X_i $\sum_{g=1}^{G} \mu_g$ (X_i)=1 (Mulesa, 2015).
The rationale for using fuzzy cluster analysis of factors influencing the resilience of critical climate-neutral technologies is that there is no clear description of the criteria list for determining the economic, social and environmental effects into which PEST analysis is broken down. "The method of fuzzy c-means (FCM method: fuzzy c-means) is used to solve the formulated problem, which, for solving the problem of fuzzy clustering, has an iterative character of sequential improvement of a certain initial fuzzy partition *R(A)={A$_v$|A$_v$ÍA}*, which is set by the user or generated automatically according to a certain heuristic rule. At each of the iterations, the values of the belonging functions of fuzzy clusters and typical representatives are recursively enumerated. The FCM method will terminate when a certain finite number of iterations specified a priori is executed or when the absolute minimum difference between the values of the belonging functions at two successive iterations does not become less than some a priori specified value" (Fuzzy logic information site, 2021).
The main difficulty in applying this method, in this case, is that, as a rule, "a significant part of the coordinates of the *Xi* vectors takes non-numeric values, which leads to the need to introduce special functions of the distance between objects. Also, when dividing objects into clusters, it is necessary to consider the clusters' features" (Mulesa, 2015).
In order to determine the number of clusters (we have three of them: environmental, economic and social effects), the factors influencing the development sustainability of critical climate-neutral technologies for energy security are divided into compact and separate (different in quality) groups (clusters) from one another. In this situation, it is recommended to use the Xie-Beni index for the FCM method (Fuzzy logic information site, 2021).
According to the results of the PEST analysis, it was found that the factors of influence (sustainability indicators) in the cluster of economic effect (3,9 points) have priority in determining the sustainability of critical climate-neutral technologies. The introduction of energy-efficient technologies in production processes is an opportunity to obtain added value. The next most crucial factor is influence factors in the social effect cluster (3,6 points). The least significant in determining the development sustainability of critical climate-neutral technologies are the impact factors (indicators of vulnerability) in the cluster of environmental effects (2,8 points). This trend is due to the opinion formed among the public that *green* energy technologies are, first of all, energy efficient technologies aimed at obtaining such an innovative effect as the rational use of energy resources.

Conclusions

The challenge of the post-COVID-19 revitalization for the energy industry is to ensure rapid economic growth, energy security and the transition to climate-neutral development. In this context, there is a shift in priorities regarding primary energy sources towards the transition to energy from renewable sources, contributing to low-carbon development. Given this, among the post- COVID-19 measures to restore the energy sector is the development of climate-neutral technologies in the energy security sphere. At the same time, the prospects for developing such technologies depend on the possibility of obtaining both environmental and economic benefits.
It requires organizational and innovative support for developing critical technologies in the national security sphere within the energy sector transition to climate-neutral development. Calculating the multiplier effect of the climate-neutral technologies' impact on the economy and climate change in energy efficiency is essential. The prospect of developing climate-neutral technologies in energy security lies in the transition to cross-sectoral interaction based on a closed cycle of energy consumption from renewable sources and the use of Industry 4.0 technologies. The suggested methodology for determining sustainability indicators for the development of climate-neutral technologies for energy security through the use of fuzzy set methods will be a tool for further research on the development of organizational and innovative support and substantiation of the economic feasibility of introducing climate-neutral technologies based on clustering of industries and a circular economy.

References

1. BORYSIAK O., BRYCH V., 2021, Methodological Approach to Assessing the Management Model of Promoting Green Energy Services in the Context of Development Smart Energy Grids, *Financial and credit activity: problems of theory and practice*, 4(39): 302-309, DOI: 10.18371/.v4i39.241319.
2. BRYCH V., MANZHULA V., BORYSIAK O., BONDARCHUK M., ALIEKSIEIEV I., HALYSH N., 2021, *Factor Analysis of Financial and Economic Activities of Energy Enterprises of Ukraine,* Proceedings of the XI-th International Conference on Advanced Computer Information Technologies (ACIT'2021), Deggendorf, Germany: 415-419, DOI: 10.1109/ACIT52158.2021.9548358.
3. BRYCH V., BORYSIAK O., HALYSH N., LIAKHOVYCH G., KUPCHAK V., VAKUN O., 2022, *Impact of International Climate Policy on the Supply Management of Enterprises Producing Green Energy,* Lecture Notes in Networks and Systems, 383.
4. BRYCH V., BORYSIAK O., YUSHCHENKO N., BONDARCHUK M., ALIEKSIEIEV I., HALYSH N., 2021, *Factor Modeling of the Interaction of Agricultural Enterprises and Enterprises Producing Green Energy to Optimize the Biomass Supply Chain,* Proceedings of the XI-th International Conference on Advanced Computer Information Technologies (ACIT'2021), Deggendorf, Germany: 425-427, DOI: 10.1109/ACIT52158.2021.9548463.
5. BRYCH V., MYKYTYUK P., HALYSH N., BORYSIAK O., ZHEKALO G., SOKOL M., 2021, Management Model of Energy Enterprises Innovative Development Within Physiological Working Conditions, *Propósitos Y Representaciones*, 9, SPE(3): e1173, DOI: 10.20511/pyr2021.v9nSPE3.1173.
6. BRYCH V., ZATONATSKA T., DLUHOPOLSKYI O., BORYSIAK O., VAKUN O., 2021, Estimating the Efficiency of the Green Energy Services' Marketing Management Based on Segmentation, *Marketing and Management of Innovations*, 3: 188-198, DOI: 10.21272/mmi.2021.3-16.
7. *COVID-19 can change the future of energy for many years to come – IEA forecast*, 2020, https://mind.ua/news/20217013-covid-19-mozhe-zminiti-majbutne-energetiki-na-dovgi-roki-prognoz-mea (25.01.2022).
8. DiXi Group , 2021, *Quarterly report 1, World best practices of green recovery during the COVID-19 pandemic: opportunities for Ukrain*e, 2021, https://dixigroup.org/wp-content/uploads/2021/04/dixi_greenrecovery_qr1-1.pdf (25.01.2022).
9. DLUHOPOLSKYI O., BRYCH V., BORYSIAK O., FEDIRKO M., DZIUBANOVSKA N., HALYSH N., 2021, Modeling the Environmental and Economic Effect of Value Added Created in the Energy Service Market, *Polityka Energetyczna*, 24(4): 153-164, DOI: 10.33223/epj/144935.
10. Fuzzy logic information site, *Methods of fuzzy cluster analysis, FCM method,* 2021, https://sites.google.com/site/ne4itkalogika/necitka-klasterizacia/metod-fcm (13.02.2022)
11. JIANG P., KLEMEŠ J. J., FAN Y. V., FU X., BEE Y. M., 2021, More Is Not Enough: A Deeper Understanding of the COVID-19 Impacts on Healthcare, Energy and Environment Is Crucial, *International Journal of Environmental Research and Public Health*, 18(2): 684. DOI: 10.3390/ijerph18020684.
12. ELAVARASAN R. M, PUGAZHENDHI R., SHAFIULLAH G. M., IRFAN M., ANVARI-MOGHADDAM A., 2021, A hover view over effectual approaches on pandemic management for sustainable cities – The endowment of prospective technologies with revitalization strategies, *Sustainable Cities and Society*, 68: 102789, DOI: 10.1016/j.scs.2021.102789.
13. Global Energy Review, 2020, *The impacts of the Covid-19 crisis on global energy demand and CO_2emissions,* International Energy Agency, https://www.iea.org/reports/global-energy-review-2020 (13.06.2021).
14. HALYSH N., BORYSIAK O., BRYCH V., KOROL V., VAKUN O., ZABURANNA L., 2021, Technical and Economic Analysis of Implementation of Standards for Solid Fuels, *Lecture Notes in Networks and Systems*, 194: 931-942, DOI: 10.1007/978-3-030-69221-6_72.
15. KUZEMKO C., BRADSHAW M., BRIDGE G., GOLDTHAU A., JEWELL J., OVERLAND I., SCHOLTEN D., VAN DE GRAAF T., WESTPHAL K., 2020, Covid-19 and the politics of sustainable energy transitions, *Energy Research and Social Science*, 68: 101685, DOI: 10.1016/j.erss.2020.101685.
16. LIAKHOVYCH G., KUPCHAK V., BORYSIAK O., HUHUL O., HALYSH N., BRYCH V., SOKOL M., 2021, Innovative human capital management of energy enterprises and the role of shaping the environmental behavior of consumers of green energy based on the work of smart grids, *Propósitos y Representaciones,* 9, SPE(3): e1293, DOI: 10.20511/pyr2021.v9nSPE3.1293.
17. MARINAS M., 2018, Renewable energy consumption and economic growth. Causality relationship in Central and Eastern European countries, *PLoS One*, 13(10): e0202951, DOI: 10.1371/journal.pone.0202951.
18. MULESA O. YU., 2015, Adaptation of the fuzzy c-means method to the problem of determining the structure of social groups, *Tekhnolohichnoy audit i reservy proizvodstva,* 2/2 (22): 73-76, https://www.uzhnu.edu.ua/uk/infocentre/get/5703 (13.02.2022).
19. PENG J., YEE V. F., JIŘÍ J. K., 2021, Impacts of COVID-19 on energy demand and consumption: Challenges, lessons and emerging opportunities, *Applied Energy*, 285: 116441, DOI: /10.1016/j.apenergy.2021.116441.
20. PYSMENNA U., TRYPOLSKA H., SOTNYK I., 2020, Vulnerability of the renewable energy sector to energy security threats exacerbated by the COVID-19 pandemic, *Pidpryiemnytsvo ta innivatsii*, (14): 79-85, DOI: 10.37320/2415-3583/14.16.
21. *Record of Ukrainian energy. In August, the share of renewable energy reached 16.6%*, 2021, https://glavcom.ua/economics/finances/rekord-ukrajinskoji-energetiki-u-serpni-chastka-vidnovlyuvanoji-energiji-dosyagla-166-707678.html (25.01.2022).
22. Renewables now, 2021, https://renewablesnow.com/ (25.01.2022).
23. SOAVA G., MEHEDINTU A., STERPU M., GRECU E., 2021, The Impact of the COVID-19 Pandemic on Electricity Consumption and Economic Growth in Romania, *Energies,* 14, 2394, DOI: 10.3390/en14092394.