ISSN 2071-1859 (Print), ISSN 2521-6635 (Online)
УДК 621.311 https://doi.org/10.33271/crpnmu/82.207

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КОНЦЕПТУАЛЬНІ ПРИНЦИПИ ВІДНОВЛЕННЯ ЕНЕРГЕТИКИ УКРАЇНИ

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CONCEPTUAL BASIS FOR POWER INDUSTRY RECOVERY IN UKRAINE

Purpose. The purpose of the article is to substantiate the conceptual principles of the three-stage post-war restoration of the energy sector of Ukraine in the context of global trends and energy transition.

The methods. Authors propose the three-phased methodology for the restoration of Ukraine's energy sector based on experience of power engineering industry experts.

Findings. The analytical description of the study is sufficiently well presented on the basis of specific examples of the principles of energy development in leading EU countries and adapted to the specific priority needs of Ukraine. The main emphasis is placed on the basic principles of the implementation of renewable energy sources, taking into account the trends of their current and prospective development. A critical analysis of the structure of the electricity generation system in Germany is performed as an example for adopting similar experience in order to effectively transform the energy sector of Ukraine.

Originality. The analytical study, which is based on the expertise of the authors, has a fundamental scientific novelty related to the definition of technical and economic prerequisites and stages of effective post-war recovery of the economy and energy of Ukraine in the context of the green transition and energy security. Key principles of the strategy for the post-war restoration of the energy sector and the economy of Ukraine are proposed, taking into account the necessary legislative and regulatory changes.

Practical implementation. The authors propose specific actions, time frames and markers for achieving results with the necessary financial investments. The most important factor can be considered the detailed description of the authors' proposed phased methodology for the restoration of Ukraine's energy sector from the standpoint of industry experts. The main tasks of each participant in the process (the state, system operators, high-tech business, investors) are detailed in terms of a comprehensive solution to the problem of sustainable energy supply to consumers in the context of effective restoration and development of energy infrastructure.

Keywords*: energy security, renewable energy sources, basic electrical equipment, generating capacities, post-war restoration.*

Introduction. The problems of energy security and energy independence are among the most urgent in relation to the sustainable development of the national economy of any country in the world. The situation is complicated due to the unstable

geopolitical situation caused by Russian aggression against Ukraine and abuses in the energy resource markets. For developing countries, this requires an in-depth analysis and use of the latest technologies, the experience of leading countries in solving the problems of energy resource diversification, considering obligations regarding low-carbon development and energy transition. The European Green Deal program promotes the widespread development of renewable energy sources (RES) systems in EU countries [1, 2].

The development of the electric power industry for a long time provided for the creation of powerful generating systems (their parts), the expansion of electric networks, ensuring their reliability and safety, and the improvement of monitoring tools. This principle of building generating capacities remains for the future. But due to the insufficient level of diagnostic and management tools, the number of accidents increased, and the efficiency of the system decreased.

The main strategically important principles of the recovery of the sector of power engineering in Ukraine, which combine national interests and create the prerequisites for the investment attractiveness of the sector:

– creation of the ecosystem with transparent market regulatory mechanisms that stimulate the flexible development of the industry by attracting powerful private capital;

– liberalization, demonopolization of the electricity and gas markets;

– scientific and technical substantiation of the internal needs of the industry in equipment and energy complexes with a study of the ability of their implementation by enterprises of domestic high-tech business;

– research and long-term (10–20 years) strategy of the interaction in foreign markets.

The global trend of decarbonization of the economy (orientation towards low-carbon energy) involves the transition to the global use of electrical energy as a basic source. The key role in the successful solution of urgent energy problems will be determined by innovative technologies of the new generation aimed at the development of "intelligent" energy systems [3–6]. Renunciation of the dominance of electricity sources based on hydrocarbon fuels and orientation towards the ever-increasing introduction of renewable energy sources is underway. Corresponding changes are also taking place in Ukraine, which is actively moving in the direction of the general global trends in energy development. This problem becomes especially important during the transition of the Integrated Power System (IPS) of Ukraine to the synchronous mode with European continental energy system – the European Network of Transmission System Operators for Electricity (ENTSO-E).

Results and Discussion. *Prospects for the development of renewable energy sources (RES).* RES stations have several important advantages over traditional sources: practically free use and availability of resources with uneven distribution, a short investment cycle (except for "large" hydropower), renewable sources, acceptable ecological impact on the environment. The absence of water in production processes is typical for wind and solar energy. The disadvantages of RES include dependence on weather conditions, existing uneven territorial distribution of resources, relatively low efficiency of solar stations (5–15 % – for panels made of amorphous silicon, 22–25 % – for panels made of monocrystalline silicon) [2]. Energy accumulators based on lithi-

um-ion batteries reduce the impact of the stochasticity of RES generation on the reliability of the electric network [7].

Figures 1 and 2 show the potential of the rationally predicted real structure of the renewable energy in Ukraine, as well as the dynamics of the development of the relevant power engineering sector before a full-scale terrorist Russian invasion and the destruction of the infrastructure facilities of the production, transmission and distribution system.

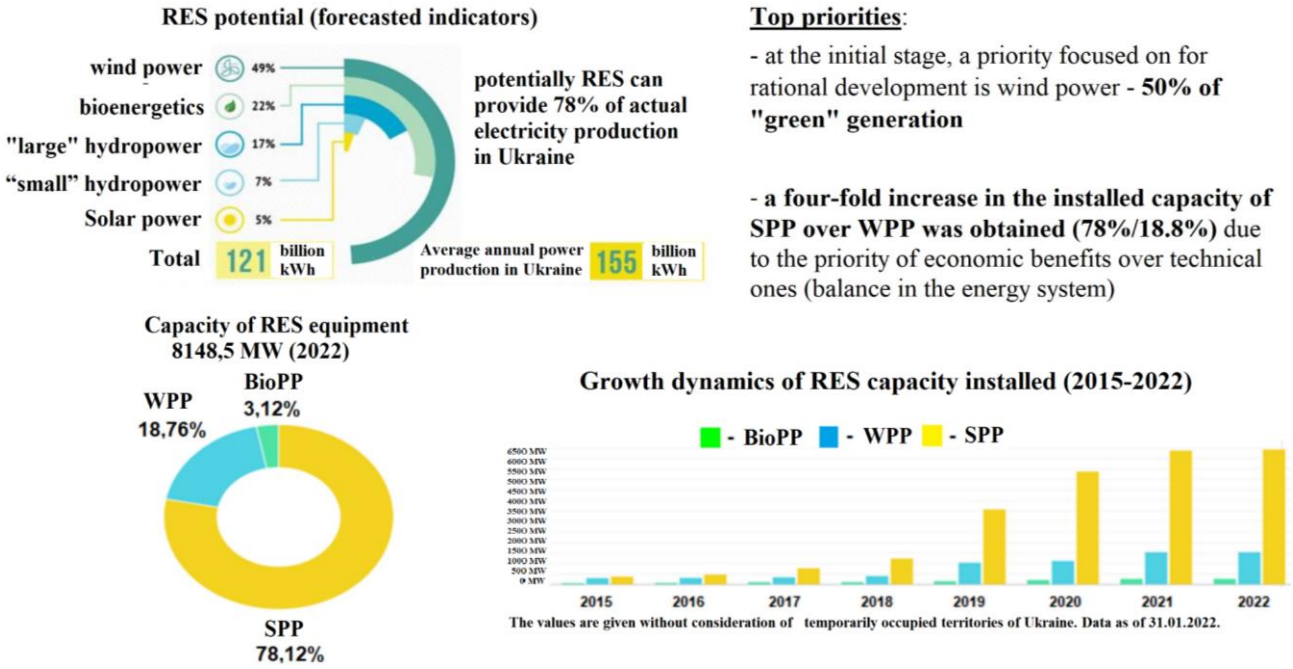

Fig. 1. Potential and existing structure of RES in Ukraine [6]

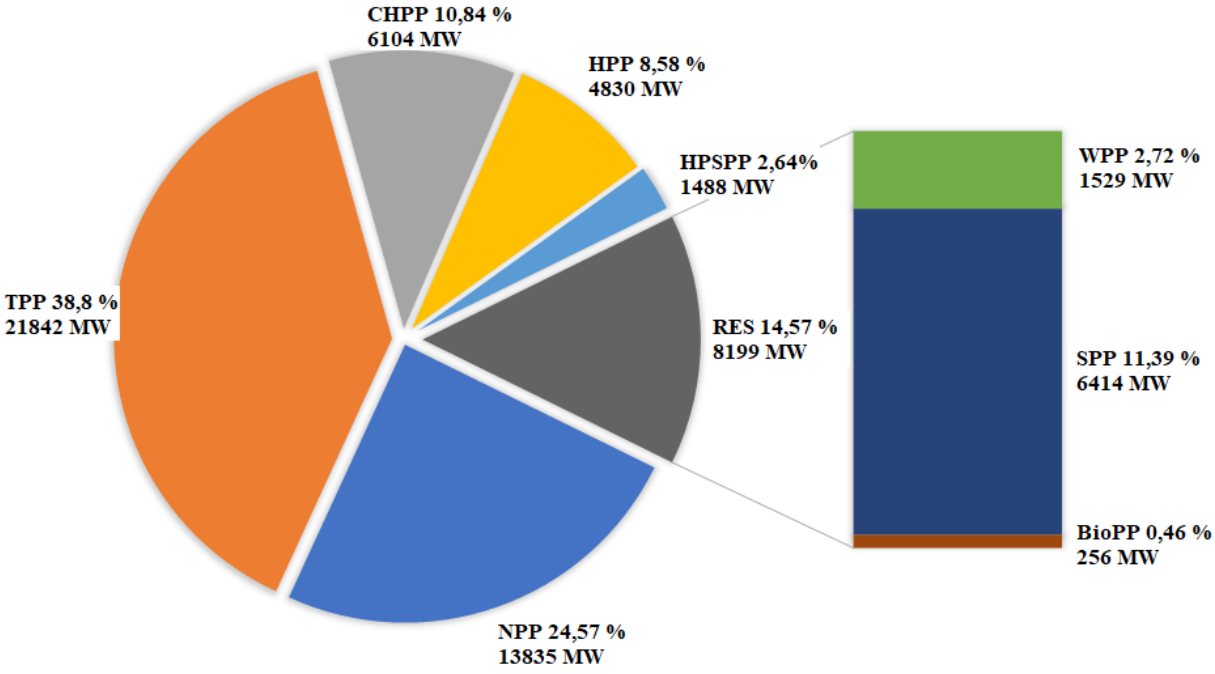

Fig. 2. Structure and installed capacity of IPS of Ukraine (56297.9 MW) by types of generation till 2022 [6]

In 2022, there were more than 6 GW of photovoltaic plants (PV) and about 1.7 GW of wind power plants (WPP) operating in the Ukrainian power grid [3]. In 2022–2023 (before the start of Russian aggression), it was expected to complete the construction of about 2–3 GW of WPP in southern Ukraine and continue to increase the capacity of PV plants. However, due to the destruction of the energy infrastructure, during 2022–2024, negative changes occurred in the structure of generating capacities (Fig. 3), a significant part of which was destroyed (TPP, HPP) or occupied (NPP, TPP, WPP). The loss to the sector of power engineering is estimated at more than 10 billion USD.

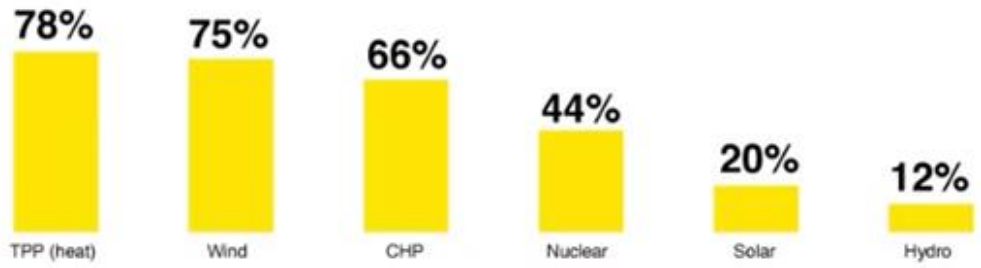

Fig. 3. Share of capacities occupied or damaged due to the war till 2024 [6]

Taking into account the forced transformation of the power engineering sector, Ukraine should make use of the experience of, for example, Germany in the fields of energy efficiency, transformation of coal regions, development of renewable energy, taking into account the conceptual principles of the scientific and technical problems which have already been solved. In particular, it is true for the problem of balancing the proportional capacities of traditional and renewable generation sources. Over the past 20 years, the structure of Germany's energy supply (Fig. 4) has changed significantly through a sharp increase in the share of renewable energy sources. In terms of installed capacity, solar and wind power plants are practically equivalent [1]. This increases the stability of the energy system compared to the structure of renewable energy sources in Ukraine, where the installed capacity of solar plants is 4 times higher than that of wind plants. In Germany, battery systems for storing electricity are being actively implemented, the capacity of which is 11.3 GW and the capacity is 16.4 GWh [8].

Approaching problem solving in the sphere of power industry recovery. The issue of decarbonization is controversial and complex. Low-carbon energy has certain features that can create a negative reverse effect, which will consist in reducing the stability of the energy system and the need for additional implementation of fast-acting systems of maneuverable generation. In market conditions, different types of generation can be combined with each other only with the provision of intelligent monitoring and control systems. It is important to assess the introduction of RES into the Integrated Power System of Ukraine, which is not fully ready for the transition to low-carbon energy. The pace of such a transition is restrained on account of insufficient balancing capacities; low flexibility of the energy system; lack of resources for effective regulation of the main mode parameters (power, voltage, frequency) [9].

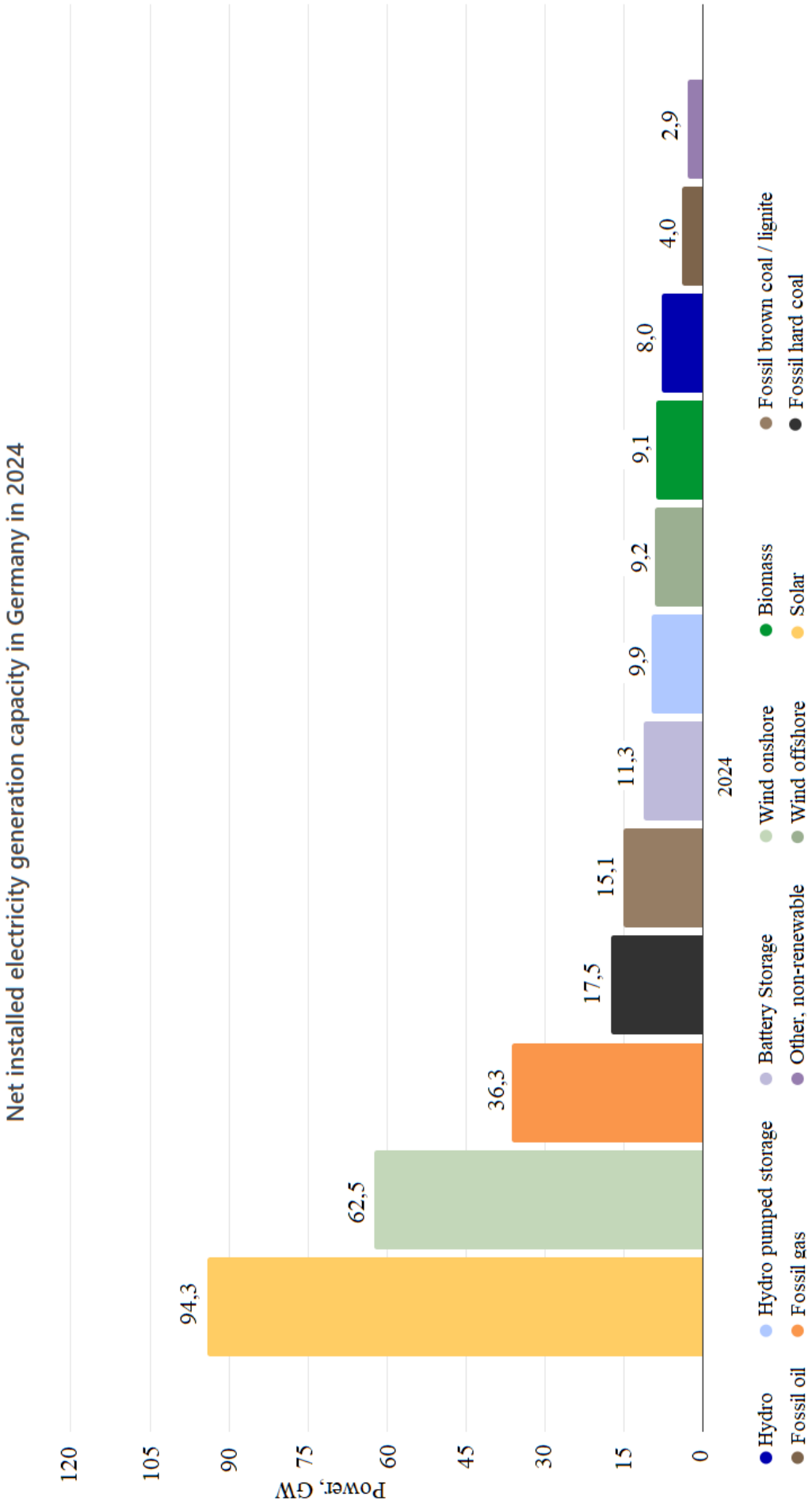

Fig. 4. Net installed electricity generation capacity in Germany in 2024 [8]

The constant building up the capacities of renewable energy sources necessitates the transformation of the existing generation structure, the introduction of new balancing capacities, and the bringing of changes in all components of the energy system into compliance with the requirements that are determined by renewable energy sources. The transformation of Ukraine's energy sector (energy transition) is taking place according to the well-known "3D" concept: decarbonization, decentralization, digitalization.

The country is undergoing a transition from the dominance of energy sources based on hydrocarbon fuels and vertically integrated powerful energy companies to a flexible structure of energy systems due to the increase in the share of renewable and distributed generation. Distributed generation is the most important sector of global energy in the future. This is a system of energy production and transmission (a great number of consumers is expected), which at the same time are producers of energy and heat for their own needs, and capable of transferring the excess energy to the general network. The widespread introduction of distributed generation into the electrical networks of developed countries relates to the need to satisfy the ever-growing demand for electricity, to solve the urgent problems of environmental protection, and to obtain a significant economic effect when using innovative solutions and new energy sources based on scientific achievements. Improvement of technologies and increased attention to environmental problems, exhaustion of energy resources (coal and oil) will change the structure of demand for primary energy resources and will require revision of traditional principles and mechanisms of power system operation, development and implementation of new modern technologies based on RES, capable of ensuring sustainable development, improvement of consumer properties and energy efficiency. At the same time, there is a transition to a decentralized energy market, the development of smart electrical networks and systems (Smart Grid concept) in connection with the creation of high technologies and the electricity storage market, the emergence of active energy consumers.

The Smart Grid concept envisages the progressive development of the energy sector due to the systematic transformation of the country's energy sector at the stages of the electric power process: generation, transmission, transformation, distribution, and consumption of energy. The energy system is considered as an extensive network infrastructure designed to support and ensure energy, information, economic and financial relationships between energy market entities. This system becomes the main object of forming a new technological business. As part of such a transition, there is a change in the structure of the system from centralized electrical networks with unidirectional flows of electricity (from the generator to the consumer) to a new package of technologies – distributed electricity generation based on RES, the use of power electronics, monitoring and control systems, energy storage, hydrogen energy. Such an updated structure of the energy system provides a significant increase in the efficiency of energy consumption, high reliability, and stability of the system, which is extremely important during the state of war in the country and in case of possible acts of terrorism. Of particular importance is the transformation of the factors regulating the electricity market – the transition from the support of RES and competition in the energy market to the priority of consumer support.

The implementation of such components of modern technologies allows us to assert the creation of smart power systems. Such systems are aimed at solving the problems of optimizing the overall efficiency and balance of interconnected energy technologies and processes implemented within the framework of the system. This is achieved by dynamic power supply and demand management; enhanced monitoring of electrical, thermal and fuel components; control and optimization of equipment, devices, and services; ensuring integration of distributed energy into the system, as well as minimizing costs for suppliers and consumers.

A smart energy system based on the Smart Grid concept is a system that integrates the actions of all users connected to it, namely generators, consumers, and other objects to effectively ensure a stable, economical, and safe supply of electricity.

This is realized by performing a whole range of tasks. It is a matter of facilitating the connection and operation of generators of all capacities and technologies; allowing consumers to take an active part in optimizing the system operation and providing consumers with the necessary information and the opportunity to select solution options.

The proposed concept provides full interaction between all producers and suppliers of electricity, trade in electricity and services. At the same time, mode control of the power system is carried out at the expense of direct transactions between users. The system provides for the implementation of «peer-to-peer» architecture and equal rights of all participants, when its elements can interact with each other directly.

Smart networks implement such functions as self-diagnosis and self-regeneration after an accident, advanced maintenance, availability of highly efficient and high-quality transmission networks, flexible controllability, improvement of transmission reliability.

A transition to a new level of information provision was made, which was implemented through the introduction of innovative specialized devices of the system level. The devices were designed and developed by scientists of the Institute of Electrodynamics of the National Academy of Sciences of Ukraine based on a unified approach that meets the requirements of European power systems, within the framework of a single information base with a unified graphical and tabular multi-window interface.

By decision of the ENTSO-E Energy Council (February 28, 2022), considering the importance of ensuring emergency synchronization of the Ukrainian energy system with the European energy system in the conditions of the country's martial law, permission was obtained for the integration of energy systems in a test mode with zero crossflow. The integration of Ukraine's IPS with Europe's energy system allowed Ukrainian consumers and the Armed Forces of Ukraine to be guaranteed to be guaranteed supplied with electricity during hostilities caused by Russian aggression. The integration of the Ukrainian Unified Power System into the European system and the synchronization of the operating mode with ENTSO-E with complete separation from the power grid of Russia and Belarus open up promising EU markets for our country.

Impact achieved. On a provisional basis, the post-war recovery of Ukraine's sector of power engineering, according to the authors, can be divided into 3 stages, each of which should have a clearly defined planning horizon and be implemented in parallel with the others:

1. Recovery and balancing of generating capacities in networks (by 2030), estimated volume of investment attraction – 30–50 billion US dollars;

2. Achieving balance and energy independence in the production-consumption model (2030-2040), estimated volume of investment attraction – 70–120 billion US dollars;

3. Increasing carbon-neutral capacities to 70–80% (2030–2050) with entry into the European market as a competitive supplier of electricity and energy carriers, estimated investment volume – 50–100 billion US dollars

The main tasks of stage 1 are to overcome certain existing regulatory contradictions and to provide scientific, technical and economic substantiation for transparent business models for the creation of specific generation facilities at specific points of the electricity networks, rationally distributed in the power grid of Ukraine from the standpoint of ensuring its stability and energy balance. Currently, taking into account the need to ensure rapid rates of restoration and construction of energy facilities, the main tasks are as follows:

• simplification of the rules for connecting to networks, allowing the client (investor) to connect the linear component;

• possibility of creating new distribution system operators (DSOs) and the unhindered emergence of new small distribution systems (SDSs);

• centralized creation of the register of all existing projects and sites for energy facilities with the simultaneous development of technically and scientifically sound mechanisms for managing the creation of new generation facilities depending on the dynamics of demand growth;

• development of scientifically and technically sound models for determining the basic cost per generation facility (CAPEX) and the optimal cost of electricity for projects in relation to the type of generation and region;

• maximum liberalization of rules for the growth of small distributed generation;

• development of the plan for restoring the transmission system operator (TSO) networks, including measures to protect against attacks;

• development of a mechanism for creating regional network development plans synchronized with urban planning and regional development plans

• determining the state's need for its own production capacities for the production of basic electrical equipment (transformers, switchgear equipment of various voltage classes, complete transformer substations (CTS), photovoltaic modules, turbines, storage batteries, etc.) with the development of the plan for the creation of new enterprises, reorganization and modernization of existing ones, and further focus on export;

• engaging power engineering industry in markets, developing individual economically feasible models for the development of these markets in accordance with the general strategy of the state until 2050;

• developing an urgent investment-attractive plan for balancing the power grid (2–3 GW) with manoeuvrable capacities;

• creating a completely transparent market mechanism for the purchase and sale of electricity and other services on the market.

The main objectives of stages 2 and 3 are to achieve the balance in the production-consumption model (2030–2040), to ensure energy independence, and to approach maximum carbon neutrality of 70–80% (2030–2050).

It requires taking the following measures:

– creation of a global national information and analytical data centre, which promptly collects, processes, analyses and accumulates information on all traditional and renewable generation facilities and main consumption sectors;

– demonopolization of markets and creation of 3–5-year plans for market players in order to enable strategic planning of the activities of enterprises (producers, TSOs, DSOs);

– creation of transparent mechanisms for flexible involvement of investors in energy projects;

– formation of the basis for obtaining the minimum market price of electricity, creation of strong prerequisites for the export of energy carriers to the European markets with a projected cost of 5–6 eurocents per 1 kWh;

– development of generating capacities in accordance with the export potential (forecasted demand for energy carriers in Europe);

– creation of powerful grid interconnectors for the transmission of electricity and hydrogen to Eurozone countries;

– maximum replacement of "carbon-polluting industries and technologies" with "green technologies" in the energy, industry and consumer sectors.

After the war, our country will be able to participate in trade operations with Europe. This will contribute to significant profits for European energy traders and access to cheaper energy for Ukrainian consumers. Stability of operation of the IPS of Ukraine during the relevant period convincingly proved its ability to function in an isolated mode and in difficult conditions, which were accompanied by active hostilities and destruction of the energy infrastructure. This state of the country's power system attests to the advantages of the decentralized small/regional generation model, which is more resistant to damage and more efficient.

Thus, the platform on which the energy system of Ukraine used to work is fundamentally changing. It is about reaching a new level of information support when solving tasks of operational management, implementing new approaches to the reliability and stability of the operation of the IPS of Ukraine, as well as transition to the use of international standards for the management of energy systems. This will speed up harmonization with European electricity supply standards. The synchronization of the IPS of Ukraine with ENTSO-E has set new goals for the further development of the Ukrainian electricity industry, in the direction of the integration of the Ukrainian segments of the electric energy market into the ENTSO-E interstate energy exchanges, the creation of scientific and technical foundations for the intellectualization of the energy industry of Ukraine.

In the post-war period, the characteristics of the IPS of Ukraine will differ from the pre-war period due to structural changes and certain emphases in priorities regarding the priority investment of projects using high technologies for individual objects and areas of development of the energy system. Structural changes will take place in

the IPS of Ukraine, it will work synchronously with the European energy system ENTSO-E [1, 10]. Along with the post-war changes in the relevant infrastructure, the restoration and further development of the country's energy system should take place considering global trends and application of modern electric power technologies.

Conclusions. The problems of energy security and energy independence are among the most urgent in relation to the sustainable development of the national economy of any country in the world. The development of the electric power industry for a long time provided for the creation of powerful generating systems (their parts), the expansion of electric networks, ensuring their reliability and safety, and the improvement of monitoring tools. This principle of building generating capacities remains for the future. But due to the insufficient level of diagnostic and management tools, the number of accidents increased, and the efficiency of the system decreased.

The global trend of decarbonization of the economy (orientation towards low-carbon energy) involves the transition to the global use of electrical energy as a basic source. The key role in the successful solution of urgent energy problems will be determined by innovative technologies of the new generation aimed at the development of "intelligent" energy systems.

The country is undergoing a transition from the dominance of energy sources based on hydrocarbon fuels and vertically integrated powerful energy companies to a flexible structure of energy systems due to the increase in the share of renewable and distributed generation. As part of such a transition, there is a change in the structure of the system from centralized electrical networks with unidirectional flows of electricity (from the generator to the consumer) to a new package of technologies. The implementation of such components of modern technologies allows us to assert the creation of "smart" energy systems. This is achieved thanks to: dynamic supply and demand management; enhanced monitoring of electrical, thermal and fuel components; control and optimization of equipment, devices and services.

Successful post-war restoration of Ukraine's sector of power engineering with a total investment of 150–270 billion USD can be implemented in 3 main stages. These stages will simultaneously ensure coordinated restoration and balancing of generating capacities in networks (by 2030), achieving balance and energy independence in the "production-consumption" model (2030–2040) by increasing carbon-neutral capacities to 70–80% (2030–2050) and the prospect of entering the European market as a competitive supplier of electricity, energy carriers, and electrical equipment.

Accelerated coping with the tasks of restoring Ukraine's sector of power engineering can be ensured by studying positive practices and experience of countries with developed low-carbon energy and economies, which will avoid technical errors in the implementation of technologies and ensure the stability and efficiency of the energy system.

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АНОТАЦІЯ

Мета. Метою статті є обґрунтування концептуальних засад 3-етапного післявоєнного відновлення енергетичного сектору України в контексті світових тенденцій та енергетичного переходу.

Методика. Авторами запропоновано 3-етапну методологію відновлення енергетичного сектору України, що базується на досвіді та експертизі фахівців енергетичної галузі.

Результати. Аналітичний виклад дослідження достатньо повно представлений на основі конкретних прикладів принципів розвитку енергетики провідних країн ЄС та адаптований до специфічних пріоритетних потреб України. Основна увага приділена базовим принципам впровадження відновлюваних джерел енергії з урахуванням тенденцій їх сучасного та перспективного розвитку. Виконано критичний аналіз структури системи електрогенерації Німеччини як прикладу для адаптації аналогічного досвіду з метою ефективної трансформації енергетичного сектору України.

Наукова новизна. Аналітичне дослідження, що базується на експертних оцінках авторів, має фундаментальну наукову новизну, пов'язану з визначенням техніко-економічних передумов та етапів ефективного післявоєнного відновлення економіки та енергетики України в умовах «зеленого» переходу та забезпечення енергетичної безпеки. Запропоновано ключові принципи стратегії післявоєнного відновлення енергетичного сектору та економіки України з урахуванням необхідних законодавчих і нормативних змін.

Практичне значення. Авторами запропоновано конкретні заходи, часові рамки та індикатори досягнення результатів із залученням необхідних фінансових інвестицій. Найважливішим чинником можна вважати детальний опис запропонованої авторами поетапної методології відновлення енергетичного сектору України з позицій експертів галузі. Деталізовано основні завдання кожного учасника процесу (держави, системних операторів, високотехнологічного бізнесу, інвесторів) у контексті комплексного вирішення проблеми сталого енергозабезпечення споживачів в умовах ефективного відновлення та розвитку енергетичної інфраструктури.

Ключові слова: *енергетична безпека, відновлювані джерела енергії, основне електротехнічне обладнання, генеруючі потужності, післявоєнне відновлення.*

дата першого надходження статті до видання	03.07.2025
дата прийняття до друку статті після рецензування	05.08.2025
дата публікації (оприлюднення)	08.09.2025