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ALTERNATIVE ENERGY IN UKRAINE. SYSTEM DYNAMICS METHODOLOGY IN RES RESEARCH

The growing demand for electricity, which is expected to double by 2030 and quadruple by 2050 compared to 2000, underlines the urgent need for widespread deployment of renewable energy sources (RES) such as wind, solar, bioenergy, hydro and geothermal ones. Initiatives of many countries reflect the growing recognition of the need of transition to sustainable energy systems. According to the UN, Sustainable Development Goal 7 is "to ensure access to affordable, reliable, sustainable and modern energy for all". The paper examines the foreign experience of mixed energy development strategies and discusses the hypotheses of RES impact on key processes taking place in various spheres of life. In Ukraine, the transition to renewable energy is vital due to not only ecological or economic necessity, but also to a strategic one. According to the updated energy strategy of Ukraine until 2030, alternative energy should make up 25% of the total energy production, which corresponds to the country's obligations to the European Energy Community. But Ukraine faces a number of economic barriers that prevent deployment of renewable energy sources. These include high initial investment costs, unstable public policy frameworks and limited access to necessary financing, which together create a difficult investment climate that discourages domestic and foreign investors. By the start of the war in 2022, renewable energy sources accounted for about 13.4% of total energy production in Ukraine. However, the destruction of energy infrastructure throughout the country, including that of the renewable energy sector, led to a sharp decrease in this indicator up to 5-6%. A special attention in this study is paid to the use of the System Dynamis (SD) concept of simulation in RES research. Analysis of the latest publications and reference models testify to the effectiveness of the SD methodology and allowed to form the base model assumptions. Paper presents a structural SD model for the analysis of the implementation of renewable energy in Ukraine, taking into account the complex interaction of economic, social and environmental challenges to assess the long-term potential consequences of the transition to RES.

Keywords: **renewable energy sources, energy strategy, economic barriers, system dynamics, structural model, UN SDG7.**

JEL Classification: Q01, Q20, Q42, Q43, Q50.

Introduction. The escalating demand for electricity, anticipated to double by 2030 and quadruple by 2050 compared to 2000, underscores the pressing need for the widespread adoption of renewable energy sources (RES) such as wind, solar, bioenergy, hydro, and geothermal. The contribution of alternative energy to the total production of electricity in the world currently stands at almost 23%, with a significant portion, 16.6%, sourced from hydropower (Renewable Energy Performance Index, 2023). This substantial reliance on renewable energy highlights its vital role amid the rapid depletion of organic fuel reserves and ongoing supply challenges, compounded by severe environmental degradation from pollutants such as nitrogen, sulphur oxides, and carbon dioxide.

The response to these challenges is evident in the ambitious targets of countries like the United States and the European Union to expand offshore wind power. By 2030, the U.S. aims to achieve 30 GW of offshore wind capacity, while the EU has set a goal of at least 60 GW, and it is planning to expand this to 300 GW by 2050 (Демченков, 2022). Such initiatives reflect a growing recognition of the necessity to transition towards sustainable energy systems and serve as a beacon of hope, inspiring other nations to follow suit and contribute to the global shift towards renewable energy.

The economic viability of a rapid green energy transition is increasingly recognised. Probabilistic forecasts suggest that moving from fossil fuels to renewable energy could result in net savings of up to $12 trillion by 2050, according to an Oxford University's study (Way et al., 2022). This substantial potential saving not only highlights the economic benefits of transitioning to a net-zero energy system well before the mid-century but also underscores the significant potential for economic growth and job creation in the renewable energy sector, challenging previous assumptions of prohibitive costs and underscoring the underestimation of renewable technology cost reductions by traditional energy-economy models.

According to the UN, Sustainable Development Goal 7 (SDG7)? which is one of the goals of the 2030 Agenda) is "to ensure access to affordable, reliable, sustainable and modern energy for all". But as economies around the world face the worrisome impact of skyrocketing energy prices, it seems the UN is still a long way from achieving SDG7. Currently, the vast majority of people in developed countries cannot afford today's energy prices. And the prospect of "affordable" energy becoming available to people in developing countries seems extremely remote. It is all the more important to clearly assess the prospects for the use of renewable energy sources and their role in the overall electricity generation and supply in specific countries and regions.

In Ukraine, the push towards renewable energy is not just an environmental or economic imperative but also a strategic necessity of the highest order. The ongoing war has intensified the country's focus on achieving energy independence and enhancing security through diversified and domestically sourced renewable energy solutions.

A special focus of this study is the use of the system dynamic system dynamics (SD) methodology in RES research and SD model development for analysing the introduction of renewable energy in Ukraine, considering the complex interplay of economic, social, and ecological challenges to evaluate long-term potential benefits of this transition.

Overview of the current state of renewable energy in Ukraine. Despite significant challenges due to ongoing conflicts, the renewable energy sector in Ukraine continues to play a crucial role in the country's energy mix. As of early 2024, the capacity for renewable energy has seen substantial changes due to war-related damages. Approximately 90% of wind energy facilities and 40% of solar power plants have been damaged or are under occupation, severely impacting their operations and energy output (Dixi Group, 2023).

Prior to the escalation in 2022, renewable energy sources were making significant strides, accounting for about 13.4% of total energy production. However, the war's devastating impact on the operational capabilities of renewable installations nationwide has led to a dramatic reduction in this figure, now standing at about 5-6%. The conflict's repercussions are further evident in the suspension of new projects, including the installation of 800 MW of new wind energy capacities scheduled for 2022 (Конеченков, 2022).

Despite these setbacks, there are signs of recovery and adaptation. In early 2023, the reinstatement of the Trifonivska solar power station (10 MW) and part of the Tylihul wind power plant (114 MW projected capacity) marked significant steps towards restoring renewable energy capacities (Економічна правда, 2023).

Amidst the ongoing conflict, noteworthy changes and investments for recovery and expansion have occurred. In 2022 and 2023, Ukraine introduced over 660 MW of new renewable capacities, showcasing a continued commitment to expanding clean energy production despite significant challenges. This includes a diverse mix of solar, wind, biogas, and small hydro installations, reflecting a strategic shift towards energy independence and sustainability (Міненерго України, 2024). This strategic shift underscores the sector's long-term vision and commitment to a greener future.

Legislative changes have also been significant. On June 30 2023, in Ukraine the Law No. 3220-IX 2023 was adopted, to facilitate the energy system's recovery and "green" transformation. This law introduces mechanisms such as green certificates of origin for renewable energy and contracts for difference, which allow producers to sell electricity directly, enhancing market competition (Міненерго України, 2024). Another crucial addition is the self-generation mechanism, allowing consumers to install generation units and sell excess electricity at market prices, which enhances the resilience of the energy system (Економічна правда, 2023)

These legislative efforts are designed to attract investments and rebuild the infrastructure, emphasizing the government and private sector's collaborative approach to enhancing the renewable sector's contribution to the national energy mix.

Key economic barriers to renewable energy in Ukraine. Despite Ukraine's favourable natural conditions for developing wind, solar, and bioenergy, significant economic barriers impede the accelerated development of renewable energy sources (RES). According to Ukraine's updated energy strategy until 2030, the target is for alternative energy to constitute 25% of the total energy production, aligning with the country's commitments to the European Energy Community (Мінекономіки України, 2024). Achieving this goal is crucial for Ukraine's energy transformation but is challenged by several economic factors.

Ukraine faces several economic barriers hindering the utilization of renewable energy sources. These include high initial investment costs, unstable state policy frameworks, and limited access to affordable financing, jointly creating a challenging investment climate that disappoints domestic and foreign investors. The elevated capital investments required for renewable energy projects and their relatively long payback periods pose significant risks in today's economic landscape.

However, a study (Steffen et al., 2020) offers a deeper understanding of mitigating these obstacles. It sheds light on the dynamics of reducing operations and maintenance (O&M) costs for onshore wind farms and solar photovoltaic (PV) systems. According to the findings, there are significant decreases in O&M costs for both energy systems over time, as indicated by the experience curves. The experience rate for O&M costs ranges from 9.2% to 12.8% for onshore wind farms and 15.7% to 18.2% for solar PV systems. Additionally, the study highlights the mechanisms driving these cost reductions, such as economies of scale, learning by doing, using, and interacting. For instance, scaling up operations, optimizing maintenance processes, and technological advancements contribute to lowering maintenance costs. Moreover, regulatory changes, like introducing auctions for setting tariffs for solar PV electricity, foster competitive pressure to reduce service costs.

Furthermore, while the Ukrainian government has implemented various incentives, such as feed-in tariffs, to promote renewable energy, consistency in policy and regulatory environments has led to uncertainty among investors. This uncertainty is exacerbated by frequent changes in regulations and tariff adjustments, which undermine the financial viability of ongoing and planned projects.

Strategic planning in the renewable energy sector also faces complications from these economic barriers. Effective planning requires clear and consistent policies and robust support mechanisms to mitigate the risks associated with high initial costs and enhance the attractiveness of renewable investments. Transitioning to renewable energy enhances energy security by reducing dependency on imported non-renewable energy sources. For instance, a study on Malaysia’s energy system shows that a higher share of renewable energy improves energy production-to-reserve ratios, decreases energy imports, and supports long-term sustainability, mitigating risks associated with fossil fuel volatility and supply disruptions while enhancing environmental sustainability (Nair et al., 2021).

Review of International Experience. Understanding the global landscape of renewable energy development provides valuable insights that can inform and enhance Ukraine's own renewable energy strategies. An examination of the experiences of countries with the world's cleanest electricity can offer lessons on effective practices and policies that Ukraine might adopt or adapt.

According to a recent study, the ten countries with the cleanest power grids have set exemplary standards in renewable energy adoption (Energy Monitor, 2023). These countries have successfully integrated high percentages of renewable energy sources into their national grids, demonstrating the feasibility and benefits of a clean energy transition. The study highlights the diverse approaches taken by these nations, from technological innovation to regulatory frameworks, which have significantly contributed to their success.

In China, aggressive expansion into renewable energy is driven by substantial state investments and a strong policy push, making the country a world leader in both the production and use of wind and solar energy. The United States' renewable energy development is characterised by a combination of federal incentives and private sector innovation, with mechanisms such as investment tax credits and production tax credits supporting large-scale projects. The European

Union employs a regulatory-driven approach with ambitious targets set through the Green Deal, supporting cross-national grid integration to enhance renewable energy stability and distribution.

Following this broad international overview, Singapore's strategic initiatives serve as an exemplary case study. Singapore's approach focuses on significantly diversifying its energy sources, aiming for over 80% renewable energy by 2050. This ambitious target is supported by the exploration of hydrogen energy, increased solar power capacity, and electricity imports, addressing both energy availability and environmental sustainability. The Singaporean model underscores the importance of adapting to technological advancements and geopolitical shifts to maintain and improve energy security. Ukraine could consider similar diversification strategies, emphasizing renewable sources to reduce dependence on imports and enhance energy resilience (Loh & Bellam, 2024).

Comparing these experiences to Ukraine, it becomes evident that a mix of robust government support, innovative financing mechanisms, and strong regulatory frameworks are key to accelerating renewable energy adoption. Ukraine could benefit from tailoring these strategies to fit its unique economic, geographic, and social context. Enhancing governmental incentives, simplifying regulations for renewable projects, introducing financial mechanisms like feed-in tariffs or green bonds to attract investments, and fostering public-private partnerships could accelerate technology transfer and deployment of renewable energy infrastructure.

Given these insights, Ukraine can draw several key lessons and recommendations:

- *Governmental incentives.* Enhance governmental support through incentives and subsidies to encourage both local and foreign investment in renewable energy;
- *Regulatory framework.* Simplify regulations and provide a stable policy environment to attract and secure long-term investments;
- *Financial mechanisms.* Introduce financial mechanisms such as feed-in tariffs or green bonds to make renewable energy projects more attractive to investors;
- *Infrastructure development.* Invest in the necessary infrastructure to support the growth and integration of renewable energy sources, ensuring energy security and efficiency.

By examining and understanding the international experience, particularly from countries leading in clean energy and investment, Ukraine can design more effective and sustainable energy policies that align with global best practices and address its specific challenges and opportunities in the renewable energy sector. This approach will not only help align with global energy trends but also fulfil the nation's energy needs sustainably and economically.

System Dynamics methodology and RES research. System dynamics simulation concept is a sophisticated tool for understanding and managing the complexities of energy systems for a comprehensive analysis of the problems in deploying renewable energy sources (RES). This methodology allows to develop aggregated simulation models, reflecting cause-and-effect relationships between various factors that influence the development of the RES market and make long-term forecast of RES effectiveness.

There have been a lot of articles coming out lately, where system dynamics concept was successfully applied to provide a comprehensive quantitative assessment of RES effectiveness, including economic scenarios, environmental impacts, and energy security needs. Notably, classic models like T. Fiddaman's (Fiddaman, 1997) and more recent ones (Laimon et al., 2020; Laimon et al., 2022; Kelly et al., 2019) have demonstrated the robust capability of system dynamics to forecast the development of energy sectors and economies globally and locally.

A thorough review of the latest scientific literature and existing reference models was crucial in identifying the most influential variables that shape renewable energy policy and technology diffusion. By examining a range of system dynamics publications, such as those exploring the growth of solar electricity capacity in Singapore (Khoong & Wei Kit, 2021) and Germany's potential movement towards 100% renewable electricity (Mashhadi, 2021), along with integrated climate assessment models like FRIDA (Schoenberg et al., 2023), we've gathered insights into the dynamics of renewable energy systems in different contexts.

In (Bartoszczuk, 2004), it is noted that reliance on non-renewable energy sources can lead to a decrease in population. Specifically, the pessimistic scenario highlighted indicates that as non-renewable resources are depleted, economic output available for consumption decreases, subsequently leading to a reduction in population. This underscores the potential demographic impacts of sustained non-renewable resource use, suggesting a direct link between energy resource management and population dynamics.

The importance of societal support in achieving a climate neutral energy system is highlighted by the findings that effective climate policies depend greatly on public acceptance. These policies deeply impact how citizens live, influencing their lifestyle and consumption habits, and are therefore more likely to succeed when there is strong public backing. Furthermore, the perceived fairness of the transition process – ensuring that benefits and burdens are evenly distributed – also plays a critical role in fostering societal support, as it influences public trust and willingness to endorse and adhere to climate policies (de Gooyert, 2023).

Transitioning to renewable energy (RE) is crucial for energy security as it reduces dependency on imported non-renewable energy sources, enhancing both short-term and long-term energy security. According to a study on Malaysia's energy system, incorporating a higher share of RE leads to better energy production-to-reserve ratios, decreases energy imports, and supports long-term sustainability. This shift not only mitigates the risks associated with fossil fuel volatility and supply disruptions but also contributes to environmental sustainability by lowering greenhouse gas emissions (Nair et al., 2021).

From this extensive review, we derived a set of the main assumptions for the base system dynamic model.

Base model assumptions and structural diagram.

Figure 1 presents a basic cause & effect structural model diagram, which integrates four distinct sectors: Energy production, Economic, Ecological and Social ones, each with specific variables and assumptions to explore the dynamics of renewable energy impacts.

Energy production – focuses on the balance between renewable (RES) and traditional energy sources, analysing such variables as RES share, capacity, energy production, consumption, energy efficiency, and technical progress.

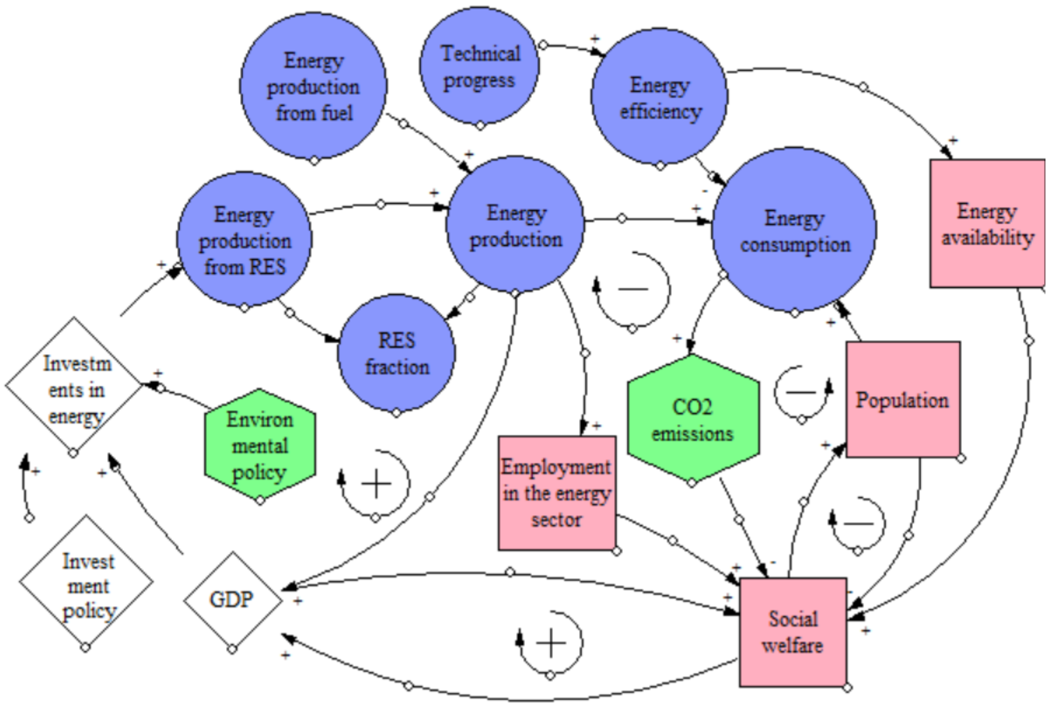

Fig. 1. Base Cause & Effect diagram

Source: authors' development

Economic sector examines renewable energy investments' influence on economic variables such as GDP, profitability, and investment policy. Investing in renewable energy increases the capacity and reliability of energy systems and significantly influences economic growth through job creation. Investments in green energy lead to infrastructure development, create jobs and reduce the need for energy imports, thus enhancing energy security and supporting economic sustainability (Ghezelbash et al., 2023). This supports the hypothesis that renewable energy investments stimulate economic growth by improving energy infrastructure and creating employment opportunities. Investment policy reflects the interplay between state and foreign investments in renewable energy, demonstrating how funding influences the pace of RES capacity expansion.

Ecological sector assesses environmental impacts through variables like CO2 emissions and ecological policy, focusing on air quality and the ecological outcomes of shifting energy paradigms.

Social sector reflects the societal impacts of renewable energy adoption considering such factors as employment rates, energy accessibility, population dynamics and social welfare, social equity etc., which influence policy development and RES expansion. Such variables as job creation rates in the RES sector, public health data linked to environmental quality, and social acceptance of renewable energy technologies are considered.

This comprehensive model structure allows for a holistic assessment of renewable energy's diverse economic, ecological, and social impacts.

Model structure analysis. Feedback loops

Marking of the arrows between pairs of variables / elements in the model diagram (+/-) is based on fairly obvious hypotheses:

- Increased renewable energy share in the energy mix enhances energy efficiency and reduces traditional energy consumption;
- Advances in renewable energy technology boost capacity and decrease energy production costs;
- Effective environmental policies promoting renewable energy reduce CO2 emissions per energy unit;
- Investments in renewable energy drive GDP growth through job creation and reduced energy import dependence;
- GDP growth and energy efficiency gains reduce the economy's energy intensity;
- Enhanced energy accessibility improves social welfare;
- Improved social welfare boosts population growth and GDP.

Marked up Cause & Effect diagram allows to analyze feedback loops in the model structure. Some of the positive (reinforcing) and negative (balancing) loops are marked on fig.1. For example, *Population → Energy consumption → CO2 emissions → Social welfare → Population* (negative feedback) or *Energy production → GDP → Investments in energy → Energy production in RES → Energy production* (positive feedback).

Main feedback loops discussion. Investment dynamics and policy impact loop**.** This loop connects state and foreign investments with policy development. Increased funding boosts renewable energy capacities, influencing energy policies and potentially leading to more supportive legislative acts favouring further RES adoption. Incorporating a 'discount rate' into our model, as discussed by Donges et al. (2020), allows for the exploration of different societal priorities between short-term gains and long-term welfare. This approach enhances our understanding of sustainable policy impacts, providing a methodological link to assess the broader implications of such preferences on environmental and economic health.

Energy production dynamics loop. Increased renewable energy production enhances economic growth through higher export revenues and GDP contributions. This growth supports and is supported by environmental regulations that encourage cleaner energy production methods, even if they might increase operational costs.

Environmental and social feedback loop. Enhanced renewable energy adoption improves air quality and public health, fostering a favourable social response that supports further renewable energy policies. Improved environmental conditions and energy accessibility enhance social welfare, boosting economic growth and spurring ongoing development in the energy sector.

Social dynamics and policy impact loop. The importance of societal support for achieving a climate-neutral energy system cannot be overstated. As de Gooyert (2023) suggests, the success of climate policies hinges significantly on public acceptance and the perceived fairness of the transition process. Ensuring that the benefits and burdens of energy transitions are evenly distributed is crucial for fostering public trust and willingness to support and comply with these policies. This understanding reinforces the need for inclusive policy-making that considers the social implications of energy transitions, thereby enhancing the effectiveness of renewable energy expansion.

External impacts (system boundary):

- World energy dynamics. Global trends and prices for fossil fuels and RES influence domestic energy strategy;
- Technological progress. Global and local achievements in energy technologies affect the efficiency and cost of renewable energy production;
- Geopolitical factors. The influence of geopolitical situation, such as dependence on energy imports and relations with energy exporting countries.

Expansion of assumptions:

- Public and private investment. While previously focusing on state subsidies, the model may also consider the role of private investments, acknowledging the challenges posed by legislative changes, economic instability, and the impact on foreign capital inflow;
- Comprehensive policy impact – may assess not just the direct impacts of policies on energy production but also their indirect effects on economic stability, environmental sustainability, and social well-being.

Structural enhancements. Structural enhancements include the integration of advanced indicators for evaluating the effectiveness of renewable energy. These indicators include energy return on investment (EROI), lifecycle emissions, and socio-economic benefits per unit of energy produced. The model may also feature an endogenous representation of the spread of energy technologies. This involves dynamically representing the dissemination of energy technologies, including nonlinear effects and feedback mechanisms that govern technology adoption and diffusion within the energy system.

Objectives for further development. The model aims to provide insights into potential system behaviour under different policy instruments and investment scenarios. It will measure the nonlinear impacts associated with selected policy tools and investments, helping policymakers and stakeholders optimise renewable energy deployment strategies.

By blending the outlined structure with the detailed feedback loops and interactions, this model will serve as a robust tool for simulating the diverse impacts of renewable energy deployment in Ukraine. It will provide valuable foresight into the interlinked dimensions of economics, ecology, and society. This comprehensive approach will aid in making informed decisions that support sustainable development and energy independence in Ukraine.

Conclusion. This article has outlined the current state and challenges of renewable energy development in Ukraine, drawing on the latest research and reference models to propose enhancements to our system dynamics model. The rapid advancements in solar photovoltaic (PV) technology illustrate the economic viability of renewables, with PV now being the most cost-effective electricity generation method across many countries (Vartiainen et al., 2019). As costs continue to decline, PV technology underscores its strategic importance for Ukraine’s energy sector, offering an economically viable and environmentally responsible way to meet energy needs.

Incorporating comprehensive economic, ecological, and integrated social factors into the model sets a robust framework for forecasting and evaluating the potential impacts of renewable energy policies.

Our future work will focus on refining and expanding this model to provide more precise and actionable insights. The importance of such research cannot be overstated, as it aims to contribute significantly to Ukraine's energy independence and ecological sustainability. Adapting successful strategies from leading renewable energy markets and corresponding model updating in order to reflect the changing dynamics of the energy sector could justify decision making and help meet Ukraine’s energy needs in an economically viable and environmentally responsible way, creating a more sustainable energy landscape.

As demonstrated by successful models – for example, "Optymalny miks energetyczny dla Polski do roku 2060" (Government of Poland, 2015), strategic planning based on comprehensive system dynamics modelling can significantly aid in achieving a balanced and effective energy mix that supports both national security and environmental goals.

In conclusion, the expansion of renewable energy in Ukraine is a technical challenge and a significant strategic opportunity to enhance the nation's energy sovereignty and reduce its environmental footprint. Ongoing SD model development and verification are essential in navigating these complex challenges and forecasting the use of Ukraine's rich renewable energy potential. Diligent research, stakeholder engagement, and adaptive policy-making can ensure that renewable energy plays a pivotal role in Ukraine's sustainable development.

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АЛЬТЕРНАТИВНА ЕНЕРГЕТИКА В УКРАЇНІ. СИСТЕМНО-ДИНАМІЧНИЙ МЕТОДОЛОГІЯ В ДОСЛІДЖЕННІ ВДЕ

Зростаючий попит на електроенергію, який має подвоїтися до 2030 року та збільшитися в чотири рази до 2050 року порівняно з 2000 роком, підтверджує нагальну потребу у широкому впровадженні відновлюваних джерел енергії (ВДЕ), таких як вітер, сонце, біоенергетика, гідро та геотермія. Ініціативи багатьох країн відображають зростаюче визнання необхідності переходу до стійких енергетичних систем. Як відомо, ціль 7 сталого розвитку ООН полягає в «забезпеченні доступу до доступної, надійної, сталої та сучасної енергії для всіх». В роботі розглянуто зарубіжний досвід змішаних стратегій розвитку енергетики та проведено аналіз гіпотез впливу ВДЕ на ключові процеси, що відбуваються у різних сферах життя. В Україні перехід до відновлюваної енергії обумовлений не лише екологічною або економічною, але і стратегічною необхідністю. Згідно з оновленою енергетичною стратегією України до 2030 року, альтернативна енергетика має становити 25% від загального виробництва енергії, що відповідає зобов'язанням країни перед Європейським енергетичним співтовариством. Але Україна стикається з низкою економічних бар'єрів, які перешкоджають використанню відновлюваних джерел енергії. До них належать високі початкові інвестиційні витрати, нестабільні рамки державної політики та обмежений доступ до необхідного фінансування, що разом створює складний інвестиційний клімат, який розчаровує вітчизняних та іноземних інвесторів. До початку війни у 2022 році на відновлювані джерела енергії припадало близько 13,4% від загального виробництва енергії. Однак руйнування по всій країні об'єктів енергетичної інфраструктури, у тому числі у секторі відновлюваної енергетики призвело до різкого зниження цього показника до 5-6%. Окремим фокусом цього дослідження є використання системно-динамічної (СД) концепції імітації у дослідженнях ВДЕ. У роботі проведено аналіз останніх публікацій, які свідчать про ефективність СД методології, та запропоновано базову структурну СД модель для аналізу впровадження відновлюваної енергетики в Україні, враховуючи складну взаємодію економічних, соціальних та екологічних викликів для оцінки довгострокових потенційних наслідків переходу на ВДЕ.

Ключові слова: **відновлювані джерела енергії, енергетична стратегія, економічні бар'єри, системна динаміка, структурна модель, SDG7 ООН.**

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