

РОЗДІЛ I

Економіка та міжнародні економічні відносини

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Alla KRYSAK,
Doctor of Economics,
Associate Professor of the Department of Enterprise Economics and International Business,
National University of Water and Environmental Engineering,
Rivne, Ukraine;
ORCID ID 0000-0002-9834-8712
e-mail: alla_centra@ukr.net

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ENERGY SECURITY OF ENVIRONMENTAL SERVICES IN UKRAINE UNDER MARTIAL LAW

Introduction. The large-scale destruction of Ukraine's energy infrastructure caused by the full-scale war has significantly increased risks to the stable provision of environmental services, agricultural production, and waste management. Under these conditions, strengthening energy security has become a strategic priority for maintaining ecosystem resilience, supporting economic recovery, and fulfilling international commitments related to sustainable development and the European Green Deal. The transition from centralized energy supply to decentralized, low-carbon energy systems requires new conceptual approaches that integrate energy, environmental, and economic dimensions.

The purpose of the article. The purpose of this study is to assess the current state of energy security of environmental services in Ukraine under martial law, determine the contribution of renewable energy technologies to the resilience of ecosystem services, and substantiate strategic directions for the post-war transformation of environmentally oriented energy systems.

Methods. The research employs a comprehensive methodological approach combining comparative, statistical, analytical, and system analysis methods. SWOT analysis is applied to identify the strengths, weaknesses, opportunities, and threats affecting the energy security of environmental services. A conceptual framework is developed to explain the interrelationships among military threats, energy infrastructure resilience, renewable energy deployment, ecosystem services, and sustainable development. Official statistical data, strategic policy documents, and recent scientific publications constitute the empirical basis of the research.

Results. The study demonstrates that the decentralization of energy generation through renewable energy sources substantially enhances the resilience of environmental services during wartime. Bioenergy, agrivoltaic systems, hydrogen technologies, energy-efficient solutions, and waste-to-energy technologies are identified as key instruments for strengthening energy independence while reducing environmental impacts. A comparative assessment of solar and wind energy development during 2023–2026 confirms the faster recovery of the solar energy sector owing to its modularity, shorter implementation period, and higher investment activity. The proposed conceptual framework integrates energy security with ecosystem services, providing a holistic perspective on sustainable energy development under wartime conditions. The SWOT analysis reveals considerable natural resource potential, scientific capacity, and opportunities for European integration, while highlighting infrastructure destruction, investment shortages, and security risks as the principal constraints. The study substantiates strategic priorities for post-war reconstruction, including the expansion of renewable energy, hydrogen technologies, circular economy solutions, digitalization of energy infrastructure, and carbon capture technologies.

Conclusions. Energy security of environmental services should be considered a fundamental component of Ukraine's sustainable economic recovery and environmental resilience. The implementation of decentralized renewable energy systems, together with innovative environmental technologies and integrated energy policy, will strengthen national energy independence, improve ecosystem protection, facilitate compliance with the Sustainable Development Goals, and accelerate Ukraine's transition toward a climate-neutral and resilient economy during the post-war reconstruction period.

Keywords: energy security; environmental services; renewable energy; hydrogen economy; circular economy; sustainable development; martial law; Ukraine.

Алла КРИСАК,
доктор економічних наук,
доцент кафедри економіки підприємства та міжнародного бізнесу,
Національний університет водного господарства та природокористування,
м. Рівне, Україна

ЕНЕРГЕТИЧНА БЕЗПЕКА ЕКОЛОГІЧНИХ ПОСЛУГ В УМОВАХ ВОЄННОГО СТАНУ

Вступ. Повномасштабна війна спричинила масштабні руйнування енергетичної інфраструктури України, що істотно ускладнило безперервне функціонування екологічних послуг, аграрного виробництва та систем управління відходами. За цих умов забезпечення енергетичної безпеки набуває стратегічного значення для збереження екосистемної стійкості, підтримки економічного розвитку та реалізації принципів сталого післявоєнного відновлення держави.

Мета. Метою статті є оцінка сучасного стану енергетичної безпеки екологічних послуг в Україні в умовах воєнного стану, визначення ролі відновлюваних джерел енергії у забезпеченні стійкості екосистемних послуг та обґрунтування пріоритетних напрямів трансформації енергетичного сектору з урахуванням екологічних і соціально-економічних викликів.

Методи. У дослідженні використано комплекс загальнонаукових і спеціальних методів, зокрема системний та порівняльний аналіз, статистичне узагальнення, методи логічного моделювання, SWOT-аналіз і концептуальне моделювання. Інформаційну основу становлять офіційні статистичні матеріали, нормативно-правові документи, стратегічні програми розвитку енергетики України та сучасні наукові публікації з проблем енергетичної безпеки, відновлюваної енергетики, екологічної економіки й сталого розвитку.

Результати. Встановлено, що децентралізація енергетичних систем на основі відновлюваних джерел енергії є одним із ключових чинників забезпечення безперервного функціонування екологічних послуг у воєнний період. Визначено потенціал біоенергетики, агровольтаїки, водневих технологій, енергоефективних рішень і технологій переробки відходів для зміцнення енергетичної незалежності та зниження екологічного навантаження. Проведений порівняльний аналіз розвитку сонячної та вітрової енергетики у 2023–2026 роках засвідчив більш динамічне відновлення сонячної генерації завдяки модульності, швидкому впровадженню та активній участі приватного сектору. Запропоновано концептуальну модель взаємозв'язку енергетичної безпеки й екосистемних послуг, а також виконано SWOT-аналіз, який дозволив визначити сильні та слабкі сторони, можливості й загрози розвитку екологічно орієнтованої енергетики в умовах воєнного стану.

Висновки. Обґрунтовано, що забезпечення енергетичної безпеки екологічних послуг є необхідною передумовою сталого економічного розвитку та післявоєнної відбудови України. Пріоритетними напрямками державної політики визначено розвиток децентралізованої відновлюваної енергетики, впровадження водневих технологій, цифровізацію енергетичної інфраструктури, розширення практик циркулярної економіки та інтеграцію сучасних екологічних технологій, що сприятиме підвищенню енергетичної стійкості, збереженню екосистем і досягненню Цілей сталого розвитку.

Ключові слова: енергетична безпека; екологічні послуги; відновлювана енергетика; воднева економіка; циркулярна економіка; сталий розвиток; воєнний стан; Україна.

Jel Classification: Q40, Q42, Q48, Q56, O13.

Introduction and Problem Statement.

The core problem of this study lies in ensuring the energy security of environmental services under martial law, a period during which a significant portion of Ukraine's energy infrastructure has suffered extensive destruction. This damage poses severe threats to the uninterrupted functioning of the national economy, the agricultural sector, waste management systems, and ecosystem services. Concurrently with the restoration of the energy sector, there arises an urgent imperative to minimize adverse environmental impacts and ensure Ukraine's fulfillment of international commitments regarding the achievement of the Sustainable Development Goals (SDGs), economic decarbonization, and integration into the European energy framework. The practical significance of this research resides in the necessity to identify effective pathways for developing renewable energy, bioenergy, the hydrogen economy, the circular economy, and energy-independent technologies capable of guaranteeing the continuous provision of environmental services even under conditions of elevated wartime risks.

Literature Review and Unresolved Aspects of the Problem.

The theoretical foundation of this study rests on official statistical data provided by the Ministry of Energy of Ukraine, the State Statistics Service of Ukraine, and the Centre for Strategic Communication and Information Security regarding energy sector losses, the provisions of the Energy Strategy of Ukraine until 2050, and fundamental research in the domains of renewable energy, bioenergy, and the hydrogen economy.

Crucial contributions to this field include the research of Paolo Picchi, Davide Geneletti, and Sven Stremke [1] as well as Martina van Lierop [2], who were among the first to systematically synthesize the concepts of renewable energy and ecosystem services. Assessments of the impact of energy systems on regulating ecosystem services have been comprehensively analyzed by Benis N. Egoh and Lacour M. Ayompe [3]. Gerald Kalt [4] developed and introduced the "Energy Service Cascade" concept, which persuasively demonstrates that society requires not energy in its raw form, but rather specific energy services that directly underpin human well-being and sustainable societal development. Benjamin K. Sovacool [5] elaborated on the theoretical and empirical foundations of energy policy, decarbonization, and the socio-economic dimensions of energy transitions, whereas Mark Z. Jacobson [6] devoted his work to modeling transitions toward 100% renewable energy systems. The role of feed-in tariffs ("green" tariffs) in ensuring environmental security and energy independence was examined by A. I. Krysak and M. F. Krysak [7]. Furthermore, this study integrates contemporary publications on solar and wind energy deployment under wartime conditions, studies on natural (geological) hydrogen, and international instruments governing the implementation of the Sustainable Development Goals.

An analysis of existing academic literature reveals that most studies focus on isolated dimensions: national energy security, renewable energy expansion, bioenergy, the hydrogen economy, environmental safety, or waste management. However, several critical areas remain insufficiently investigated:

The comprehensive interrelationship between energy security and environmental services under martial law;

The role of decentralized generation in ensuring the resilience of ecosystem services;

The systemic integration of renewable energy, organic production, waste management, and hydrogen technologies into a unified energy security framework;

Strategic directions for post-war energy reconstruction that explicitly incorporate environmental priorities;

A systematic evaluation of strengths, weaknesses, opportunities, and threats (SWOT) regarding the energy security of environmental services.

Addressing these scientific and practical gaps constitutes the primary object of this research paper.

Objectives of the Article.

The objective of this article is to examine the current state of energy security regarding environmental services in Ukraine under martial law, to determine the role of renewable energy sources in ensuring the sustainable operation of the agricultural sector and waste management, and to substantiate prospective directions for developing environmentally safe energy technologies.

To achieve this stated objective, the following specific tasks were formulated and resolved:

Analyze the current state of Ukraine's energy sector and the consequences of military operations;

Establish the interrelationships between energy security and environmental services;

Investigate the operational potential of renewable energy sources, bioenergy, hydrogen technologies, and waste processing solutions;

Evaluate the development prospects of solar and wind energy over the period of 2023–2026;

Formulate a novel conceptual framework (model) linking energy security and ecosystem services under wartime conditions;

Conduct a SWOT analysis of the energy security of environmental services;

Identify priority directions for the post-war development of environmentally oriented energy systems.

Main Body of Research and Results.

Resolving the challenge of energy security for environmental services constitutes a pivotal priority for economic development under current wartime conditions. The energy sector provides the operational backbone for virtually all branches of the national economy. This dependency has become acutely evident during martial law, as entire regions have experienced rolling blackouts and severe power disruptions as a consequence of military actions within Ukraine.

According to expert assessments, more than 50% of total energy generation capacity was lost as of December 2025 [8]. Data from the Centre for Strategic Communication and Information Security indicates that over four years of full-scale war, Ukraine's energy sector incurred direct losses totaling \$24.8 billion,

representing one of the largest destruction footprints across all economic sectors [9]. The structural distribution of these losses is allocated as follows: \$14.2 billion in power generation, \$2.3 billion in transmission networks, \$0.7 billion in distribution systems, and \$2.4 billion in district heating and thermal generation [9]. Beyond financial damage, Ukraine lost 27 GW of total power generation capacity, of which 15.5 GW was lost due to the temporary military occupation of energy assets [9]. A summary of these losses is presented in Table 1.

Table 1

Energy sector losses in Ukraine over four years of full-scale war

Indicator	Value
Direct losses of the energy sector, USD billion	24.8
Share of total national infrastructure damage, %	12.7
Structure of losses, USD billion:	
Power generation	14.2
Thermal generation / district heating	2.4
Transmission grid	2.3
Distribution grid	0.7
Damaged or destroyed assets:	
Major combined heat and power (CHP) plants, units	18
Boiler houses, units	815
Heating networks, km	354
Capacity losses, GW:	
Destroyed or damaged by military attacks, GW	11.5
Lost due to military occupation of assets, GW	15.5
Total electricity generation capacity lost, GW	27.0

Source: Compiled/generalized by the author based on Ministry of Energy data [9].

Despite this profound energy crisis, Ukraine's energy sector continues to fulfill its critical operational duties. Nevertheless, risks associated with energy security exert a direct impact on the nation's environmental potential, given that all economic activity relies heavily on natural resource consumption. It is vital to recognize that increasing economic activity without strict environmental safeguards can act as an additional stress factor on ecosystems. Higher atmospheric emissions, water pollution, and soil degradation represent severe externalities that impair public health and human well-being as a price paid for economic output.

The integration of renewable energy principles into the global sustainable development paradigm is reflected in the Sustainable Development Goals (SDGs) adopted by the UN General Assembly [7]. The energy security of environmental services aligns closely with SDG 7 ("Affordable and Clean Energy"), which aims to ensure access to affordable, reliable, sustainable, and modern energy for all. Achieving this goal relies directly on harnessing natural resources for diverse energy generation pathways [7].

Such pathways encompass not only wind and solar installations but also agricultural crop and livestock production. The latter generates substantial volumes of agricultural waste, which serve as reliable raw material inputs for renewable energy generation — a practice actively incentivized by the European Union through updated energy indicators [7]. For instance, a necessary prerequisite for rational land resource management under SDG 7 involves maintaining an appropriate degree of energy orientation in agricultural production, specifically the cultivation of energy crops (such as rapeseed, corn, and sugar beet) used as feedstocks for biofuel and bioethanol production [7].

The energy security of environmental services in agriculture is defined as the agricultural sector's capacity to continuously supply itself with necessary energy to sustain ecological processes that yield human benefits without compromising underlying ecosystems.

Within the scope of environmental goods and services in agriculture, organic farming holds a prominent place due to its substantial ecological advantages over conventional farming practices. Prior to the imposition of martial law (February 2022), the agro-industrial complex (agriculture, food, and processing industries) generated 17% of Ukraine's GDP and accounted for nearly 60% of consumer expenditure [10]. Presently, according to the Ministry of Economy, despite adverse climatic conditions and security challenges, the sector remains a primary economic stabilizer and export leader, generating almost

56% of the country's total foreign currency export earnings in 2025 [11]. Goods and services originating from organic production are gaining widespread consumer preference, notwithstanding higher production costs relative to conventional agriculture, because of their positive impact on public health and well-being.

Environmental (ecosystem) services are commonly understood as the benefits provided freely by the natural environment (e.g., natural water filtration by soils, crop pollination by insects, soil fertility formation, and air purification by vegetation). To ensure the uninterrupted provision of these ecosystem services, agricultural producers require guaranteed access to reliable, environmentally benign, and energy-independent power sources.

Traditional fossil fuel energy (oil, coal, natural gas) inflicts severe environmental degradation through air and water pollution and climate disruption. If an agricultural enterprise relies exclusively on fossil-derived energy, it inadvertently degrades the very ecosystem services upon which its productivity depends. Enhancing energy security protects the natural environment through several mechanisms:

Biodiversity preservation: Reducing harmful emissions supports insect pollinator populations and protects aquatic ecosystems;

Operational continuity: Utilizing renewable energy sources (RES) ensures that machinery, irrigation, and processing systems remain operational during grid outages or fuel shortages;

Environmental footprint reduction: Agribusinesses lower their carbon footprint and maintain ecological equilibrium.

In accordance with contemporary research and the Energy Strategy of Ukraine [12], key innovative technological instruments for bolstering energy security include:

Bioenergy and bioresource utilization: Converting agricultural waste (manure, straw, crop residues) into biogas for local electricity and thermal energy generation, simultaneously addressing waste management and reducing reliance on centralized power grids;

Agrivoltaic systems: Installing solar photovoltaic (PV) panels on farm structures, above crop fields, or floating on irrigation reservoirs (where PV panels generate electricity while concurrently mitigating water evaporation losses);

Energy efficiency and waste heat recovery: Capturing and reusing waste heat from industrial boilers and grain dryers for space heating instead of discharging thermal pollution into the atmosphere.

However, an excessive focus on energy crop cultivation can introduce trade-offs regarding food security and environmental conservation [7]. Researchers [1–7] who established the theoretical linkage between energy transitions, RES, ecosystem services, and sustainable development emphasize several operational hurdles:

High capital expenditure (CapEx) required for solar, wind, and biogas installations;

The necessity for long-term strategic planning and risk management;

Susceptibility to climatic variability (droughts, extreme storms), necessitating hybrid energy architectures.

Ultimately, transitioning agricultural enterprises toward self-owned renewable energy sources enhances their operational resilience while conserving soil and water resources, improving ambient air quality, and minimizing negative environmental impacts.

Geothermal energy utilization is similarly tied to the implementation of SDG 7 [7]. Utilizing low-productivity or degraded lands as spatial bases for siting solar and wind power plants helps alleviate socio-economic tensions during periods of high fossil energy prices [7]. Although alternative energy infrastructure can impose localized environmental pressures (e.g., noise and vibrations from wind turbines [7] or land competition from short-rotation coppice cultivation), achieving a balance between socio-economic rationale and ecological priorities is essential. Public adoption of alternative energy solutions can be further accelerated through consumer incentive structures and premium mechanisms [7].

A compelling argument for advancing environmental goods and services involves leveraging alternative energy to address critical regional challenges. A prominent example is the deployment of renewable-powered desalination and water purification systems to supply arid southern regions and the Crimean peninsula, which suffer from acute water scarcity following the destruction of the Kakhovka Hydroelectric Power Plant dam by Russian forces on June 6, 2023.

A vital strategic vector is the implementation of the Hydrogen Strategy of Ukraine, which targets low-carbon hydrogen production of up to 1.3 million tons by 2035 and 3.0 million tons by 2050 [13]. Hydrogen is projected for applications in district heating, heavy transport, and hard-to-abate industrial sectors such as metallurgy and cement manufacturing [13]. Hydrogen production can utilize grid electricity via direct power purchase agreements (PPAs) coupled with Guarantees of Origin, or biomethane via steam methane

reforming (SMR) for subsequent export to the EU [13]. Projected hydrogen export volumes range from 0.8–1.2 million tons by 2035 to 1.5–2.8 million tons by 2050, requiring estimated capital investments of up to \$13.5 billion for a 10 GW electrolysis potential [13].

International cooperation in the hydrogen domain is advancing rapidly. The United Kingdom has initiated grant programs for green hydrogen production facilities in southern Ukraine (the H2U project), while Germany has expressed strong interest in importing Ukrainian green hydrogen, contributing over €100 million to the Ukraine Energy Support Fund [14]. Furthermore, "pink" hydrogen (produced via nuclear power) and "blue" hydrogen (derived from natural gas with Carbon Capture and Storage, CCS) represent viable transitional pathways [13]. Naturally occurring geological ("white") hydrogen has also emerged as a promising zero-carbon mineral resource with potentially low extraction costs; according to the International Energy Agency (IEA), global hydrogen demand reached 100 million tons in 2024 and continues to expand [15].

While feed-in tariffs previously served as the primary market driver for RES investments, wartime realities have shifted private sector motivation toward achieving operational energy autonomy [16]. This driver triggered a doubling of grid-connected residential solar photovoltaic (PV) systems, reaching 87,000 installations [16].

At the end of 2025, the Solar Energy Association of Ukraine (ASEU) reported 1.5 GW of newly constructed solar PV capacity, with sector associations projecting an additional 1.5 GW in 2026 [16]. Should this projection materialize, Ukraine will have added over 4 GW of new solar generation capacity between 2023 and 2026 [16] — a figure exceeding the total solar capacity lost since 2022 due to occupation and military damage. This trend highlights a fundamental structural transformation toward decentralized power generation.

Conversely, the recovery of wind energy has progressed at a more measured pace. Prior to the full-scale invasion, Ukraine's installed wind capacity stood at approximately 2 GW, of which nearly 80% was lost or situated in temporarily occupied southern territories [16]. Nevertheless, data from the Ukrainian Wind Energy Association indicates that 491 MW of new wind capacity was commissioned during 2023–2025, with an additional 130 MW added in the first quarter of 2026 [16]. This cumulative addition of 621 MW represents roughly 31% of pre-war installed capacity, demonstrating steady sector recovery.

A comparative analysis confirms that solar PV adapts more rapidly to wartime conditions due to lower capital requirements, shorter construction timelines, modular deployment options, and active investment from private households and small-to-medium enterprises (SMEs). In contrast, wind power development requires substantial infrastructure investments, complex transport logistics, and a stable security environment.

Decentralized solar and wind expansion serves both an environmental function and a strategic security objective. Siting generation closer to consumption centers enhances grid resilience, safeguards agricultural and waste management operations, and accelerates national decarbonization goals. A complementary prospective avenue includes deploying advanced Carbon Capture, Utilization, and Storage (CCUS) technologies to neutralize CO₂ emissions from remaining thermal generation assets.

In the waste management sector, energy security denotes the capacity of processing plants to maintain continuous environmental purification services using self-generated, independent energy. Waste processing provides direct ecosystem services by preventing soil contamination, groundwater pollution, and hazardous atmospheric emissions. However, processing facilities are inherently energy-intensive. To achieve operational energy self-sufficiency, three primary technological solutions are utilized:

Landfill gas capture (Biogas): Extracting methane-rich gas from municipal solid waste (MSW) landfills via vertical wells and burning it in combined heat and power (CHP) engines to generate off-grid electricity and heat;

Refuse-Derived Fuel (RDF) production: Processing non-recyclable, high-calorific waste fractions into dried RDF pellets for co-incineration in cement kilns and thermal power plants;

Energy-from-Waste (EfW) incineration: Deploying advanced thermal treatment facilities where residual waste is combusted at high temperatures under stringent flue-gas cleaning protocols to drive steam turbines for grid electricity and district heating.

Key operational challenges in waste-to-energy systems involve maintaining rigorous source-sorting standards, financing expensive multi-stage emission filtration systems, and securing stable waste feedstock supplies.

The conceptual framework developed in this study is illustrated in Figure 1, depicting the structural relationships among military threats, infrastructure damage, renewable energy deployment, hydrogen

technologies, circular economy practices, and ecosystem service provision. The proposed framework emphasizes that transitioning toward decentralized, low-carbon energy systems strengthens national energy security while simultaneously supporting ecosystem resilience, environmental protection, and the attainment of the Sustainable Development Goals.

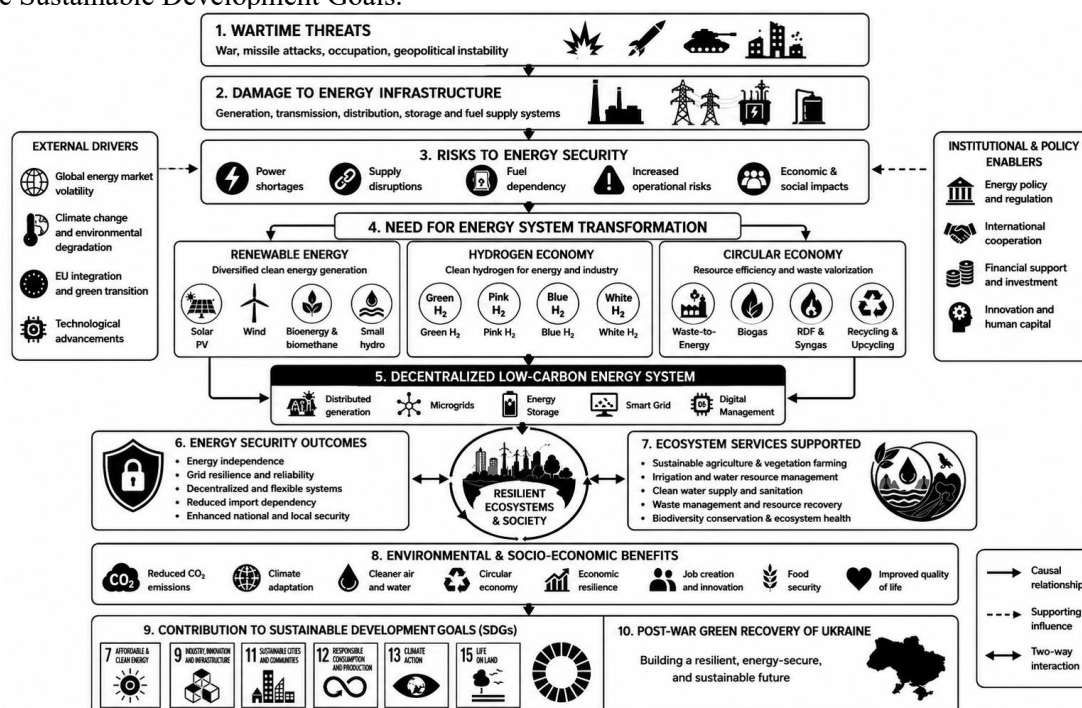


Fig. 1. Conceptual framework of energy security and ecosystem services under wartime conditions. Compiled by the author

Under wartime conditions, renewable energy technologies evolve from basic environmental policy instruments into strategic components of Ukraine's post-war recovery and long-term sustainable development.

Based on the research findings, a comprehensive evaluation of the factors governing the energy security of environmental services was structured using a SWOT analysis (Table 2).

Table 2

SWOT analysis of the energy security of environmental services under martial law

Strengths	Weaknesses
Significant potential for renewable energy development, including solar, wind, bioenergy, biomethane, and hydrogen technologies.	High capital costs associated with renewable energy deployment and advanced energy-efficient technologies.
Strong agricultural resource base supporting biogas and biofuel production.	Extensive destruction of energy infrastructure caused by military operations.
Alignment with the Sustainable Development Goals and the European Green Deal.	Limited access to long-term investment and financial resources.
Increasing energy independence of agricultural enterprises and local communities.	Dependence of certain renewable technologies on weather conditions.
Potential for substantial greenhouse gas emission reductions and environmental improvement.	Insufficient development of energy storage technologies and Smart Grid infrastructure.
Significant scientific and technological capacity in bioenergy, environmental engineering, and sustainable resource management.	Shortage of highly qualified specialists in advanced energy technologies.
Opportunities	Threats

Post-war reconstruction based on the Build Back Better concept, emphasizing resilient, energy-efficient, and climate-adaptive infrastructure.	Continued military attacks on critical energy infrastructure.
Integration into the European electricity market and the ENTSO-E network.	Ongoing occupation of territories resulting in additional generating capacity losses.
Attraction of international investments and green financing mechanisms.	Budget constraints limiting large-scale infrastructure investments.
Development of green and low-carbon hydrogen production.	Climate change impacts, including droughts, floods, and extreme weather events.
Utilization of agricultural residues for renewable energy generation.	Rising equipment costs and dependence on imported technologies.
Expansion of circular economy practices and waste-to-energy technologies.	Volatility of global energy markets and fuel prices.

Source: Compiled by the author

The SWOT analysis demonstrates that the energy security of environmental services in Ukraine is shaped by a combination of substantial internal strengths and severe external threats. The primary strengths include vast natural resource potential, an established agricultural biomass base, and strong strategic alignment with European green integration policies. Conversely, main weaknesses include infrastructure damage, high capital costs, and limited domestic investment capital.

The most promising opportunities reside in post-war reconstruction under the «Build Back Better» paradigm, hydrogen market expansion, international climate finance, and circular waste-to-energy integration. Continued military risks, climate volatility, and macroeconomic instability constitute the principal threats.

Consequently, policy and investment efforts should focus on stimulating economic sectors and technological solutions that minimize social and environmental risks. Ensuring energy security for environmental services requires long-term strategic planning and advanced digital technology integration.

Promising focus areas for stimulating environmental goods and services within the energy security paradigm include:

- Expanding organic farming practices that yield ecological co-benefits;
- Accelerating renewable energy deployment to substitute fossil fuels;
- Developing low-carbon and green hydrogen production infrastructure;
- Modernizing waste management systems to foster resource recovery, composting, and waste-to-energy conversion.

Conclusions and Future Research Prospects

This study concludes that ensuring the energy security of environmental services represents a crucial pillar of Ukraine's sustainable development under martial law and post-war reconstruction. Despite catastrophic physical damage to centralized energy infrastructure, decentralized renewable energy has demonstrated high adaptability. Over the 2023–2026 period, solar generation capacity additions exceeded 4 GW, while wind power additions reached 621 MW.

Integrating renewable energy, bioenergy, hydrogen solutions, and waste-to-energy technologies protects ecosystem service provision, ensures operational autonomy for agriculture, and mitigates environmental pollution.

Promising avenues for future research include:

- Developing organizational and economic mechanisms to attract private investment into decentralized agrivoltaics;

- Modeling the integration of Energy Storage Systems (ESS) and Smart Grid architectures within rural distribution networks;

- Evaluating the geological extraction potential of natural ("white") hydrogen and deploying industrial Carbon Capture and Storage (CCS) systems;

- Advancing digital resource management tools to optimize circular economy and waste-to-energy clusters;

- Formulating comprehensive post-war energy reconstruction models anchored in energy independence, environmental safety, and sustainable development principles.

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