

Article

The Impact of Renewable Energy Development on Environmental Security and Climate Resilience

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Abstract

This study examines how the development of renewable energy influences environmental security and climate resilience in Ukraine amidst structural disruptions and external shocks spanning the period 2021–2025. The research is based on a systemic analytical framework that combines indicator-based assessment, statistical time-series analysis, and econometric modeling. Renewable energy is conceptualized as a structural factor that transforms the energy balance and affects emission intensity, environmental risks, and the operational stability of the energy system. A coherent system of indicators is developed to capture the causal chain linking renewable energy expansion with environmental and systemic outcomes. The dynamics of key indicators demonstrate that the increase in the share of renewable energy does not lead to a linear reduction in absolute emissions due to the strong influence of changes in electricity generation volumes, fuel structure, and wartime conditions. At the same time, intensity indicators reveal the presence of a decarbonization effect associated with renewable energy development. Correlation, differential, and regression analyses indicate that the relationship between renewable energy and carbon intensity is unstable in short time series and depends on structural and operational factors. The findings show that renewable energy contributes to reducing environmental pressure in the medium term, although its effect may be temporarily offset by crisis conditions.

Keywords: environmental security; climate resilience; sustainability; environmental risks; renewable energy; energy transition; decarbonization; emissions intensity; energy distributed generation; energy system



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1. Introduction

The relevance of this study is determined by the fact that the development of renewable energy during 2021–2025 has become one of the key instruments for ensuring environmental security and strengthening the climate resilience of national energy systems, particularly under crisis conditions. During this period Ukraine's energy sector operated under the combined influence of military, energy, and economic shocks that produced non-standard operational regimes of the power system in 2021–2025. In this context, the transition

toward a low-carbon energy model is increasingly interpreted as a systemic response to the growing threats of environmental degradation, rising greenhouse gas emissions, and the vulnerability of socio-economic systems to climate change [1–7].

For Ukraine, this issue acquires an additional dimension associated with the transformation of the energy sector under wartime conditions, the destruction of conventional generation capacities, and the simultaneous need to restore economic activity while fulfilling international climate commitments. In such circumstances renewable energy demonstrates significant potential for reducing environmental pressure, improving the resilience of the energy system, and decreasing dependence on fossil resources [8–26]. These factors highlight the importance of a quantitative assessment of the actual contribution of renewable energy development to environmental security and climate resilience.

The scientific problem addressed in this research lies in the absence of a comprehensive and statistically grounded approach to assessing the impact of renewable energy development on environmental security and climate resilience that would examine the dynamics of key energy and environmental indicators in an integrated manner rather than separately. Existing studies tend to focus either on the technological aspects of renewable energy sources or on general trends in emission reductions, paying insufficient attention to the systemic analysis of how the growth of renewable energy share transforms environmental security and strengthens climate resilience at the national level [27–33].

In the case of Ukraine, this problem is further complicated by the fragmentation of analytical assessments, the insufficient integration of open statistical data, and the absence of analytical models capable of revealing causal relationships between renewable energy development, emission reductions, the mitigation of environmental risks, and the adaptive capacity of the energy system. These circumstances determine the need to develop and test a scientifically grounded analytical framework that allows, on the basis of statistical and digital data for 2021–2025, for a quantitative evaluation of the contribution of renewable energy development to environmental security and climate resilience in Ukraine. Recent international reports and 2024–2025 studies additionally show that renewable energy development must be evaluated together with energy system resilience, regulatory capacity, climate adaptation, and environmental security risks [34–47].

The aim of this study is to provide a quantitative assessment and analytical justification of the impact of renewable energy development on the level of environmental security and climate resilience in Ukraine based on a systemic analysis of open data for 2021–2025, with the identification of causal relationships between changes in the structure of the energy balance, the dynamics of greenhouse gas emissions, and the indicators of energy system resilience.

To achieve this objective, the research addresses the following tasks:

- To develop a system of relevant indicators for assessing renewable energy development, environmental security, and climate resilience;
- To analyze the dynamics of key indicators of renewable energy development and environmental effects in Ukraine;
- To evaluate the impact of the growing share of renewable energy on emission reductions, mitigation of environmental risks, and the strengthening of climate resilience of the Ukrainian energy system.

The manuscript is organized as follows. Section 2 reviews the literature according to the three research tasks. Section 3 presents the data sources, variables, and analytical framework. Section 4 reports the indicator-based, correlation, differential, and exploratory econometric results. Section 5 discusses the implications and limitations of the findings, while Section 6 summarizes the conclusions and directions for further research.

2. Literature Review

The literature review is structured according to the three analytical tasks formulated in Section 1. It first systematizes indicator-based studies on renewable energy development, environmental security, and climate resilience. It then examines empirical works on renewable energy, emissions, and environmental effects. Finally, it identifies studies that support impact assessment for emission reduction, environmental risk mitigation, and energy system resilience.

Shafik and Bandyopadhyay (1992) interpreted environmental security through measurable links between income and environmental quality [1]. Panayotou (1993) transferred this logic into policy analysis [2]. His approach showed that environmental security depends on institutions, development stage, and economic structure rather than income alone.

Grossman and Krueger (1995) associated cleaner environments with structural transformation, technological upgrading, and public demand [3]. Stern (2004) later showed that apparent turning points in environmental degradation may be unstable [4]. This makes environmental security a dynamic condition shaped by technology, policy, and energy sector change.

Sims et al. (2003) compared the carbon characteristics and mitigation costs of electricity generation technologies [5]. Pacala and Socolow (2004) treated renewable energy as one practical stabilization pathway [6]. Markandya and Wilkinson (2007) broadened this view by connecting electricity generation with health impacts and local environmental risks [7].

The Intergovernmental Panel on Climate Change (2007) systematized the relationship between energy technologies, emissions, and climate trajectories [8]. Jacobson and Delucchi (2009) conceptualized renewable-based energy systems as a long-term sustainability pathway [9]. Their work shifted the analytical focus from separate technologies to systemic transformation.

Apergis and Payne (2010) linked renewable energy consumption with macroeconomic dynamics in a multi-period framework [10]. Menyah and Wolde-Rufael (2010) included carbon dioxide emissions, nuclear energy, and renewable energy in one model [11]. Marques and Fuinhas (2012) showed that renewable energy effects should be interpreted jointly with economic and policy conditions [12].

Bento and Moutinho (2016) combined renewable and non-renewable electricity production with carbon dioxide emissions, trade, and economic growth [13]. Jebli et al. (2016) reinforced the multifactorial nature of environmental security [14]. Inglesi-Lotz (2016) demonstrated statistically significant renewable energy effects in multi-period analysis [15].

Zoundi (2017) found a long-run association between renewable energy and lower carbon dioxide emissions [16]. Bhattacharya et al. (2017) added an institutional dimension to this relationship [17]. Destek and Aslan (2017) showed that renewable energy effects may differ across time and economic conditions [18].

Liu et al. (2017) confirmed the role of renewable energy in reducing carbon emissions in several national contexts [19]. Sharif et al. (2019) highlighted heterogeneity across countries and periods [20]. Saidi and Omri (2020) emphasized the need to separate renewable energy effects from broader low-carbon energy effects [21].

Destek and Sinha (2020) expanded the analysis from carbon emissions to ecological pressure [22]. Nathaniel and Khan (2020) linked renewable energy, trade, urbanization, and ecological footprint [23]. Usman et al. (2020) showed that renewable energy impacts require contextual controls across country groups [24].

Wang and Wang (2020) interpreted climate resilience through decoupling between economic growth and environmental pressure [25]. Pata (2021) emphasized structural breaks in environmental-energy models [26]. These findings are especially relevant for Ukraine because the 2021–2025 period includes severe regime disruptions.

Dluhopolski et al. (2020) demonstrated that fiscal and public-policy dynamics can influence economic growth conditions for renewable energy investment [27]. Kniaz (2021) substantiated indicator selection for analytical environmental assessment [28]. Kniaz et al. (2022) further developed environmental risk management through information-system modeling [29]. These works justify using indicators, monitoring logic, and risk-oriented interpretation in the present study.

Mysiuk et al. (2022) presented risk-oriented monitoring for infrastructure systems, which adds an engineering dimension to climate resilience [30]. Kniaz et al. (2023) linked state regulation and investment activity with structural transformation [31]. Kniaz et al. (2024) emphasized the role of information support and management mechanisms under uncertainty [32,33]. Together, these studies show that resilience depends on analytical capacity, governance quality, and adaptive institutional action.

The International Energy Agency (2024) treats renewable energy expansion as a response to both climate and energy security challenges [34]. REN21 (2025) emphasizes networks, storage, policy frameworks, and social acceptance [35]. The International Renewable Energy Agency (2025) links climate resilience with the capacity of energy infrastructure to withstand extreme-weather risks [36].

The European Court of Auditors (2024) connects the green transition with energy security and the efficient use of public resources [37]. The Energy Community Secretariat (2024) frames energy transition as both decarbonization and security transformation [38]. These perspectives are directly relevant for Ukraine's wartime and recovery context.

Siksnyte-Butkiene et al. (2024) systematized energy security indicators and connected them with system resilience [39]. Rahmane et al. (2024) examined the role of environmental regulation in renewable energy production [40]. Zhou (2023) linked energy resilience with innovation, efficiency, and modernization of energy districts [41].

Eleksiani et al. (2025) analyzed renewable energy systems as a mechanism supporting climate resilience in off-grid communities [42]. The Council on Strategic Risks (2025) highlighted ecological security risks associated with energy transitions [43]. Recent studies by Geoffrey et al. (2024) [44], ReportLinker [45], Intercontinental Exchange, Inc. [46], and Nathaniel et al. (2025) further connect renewable energy with climate risk reduction, environmental security, and adaptation [47].

Within this integrated perspective, environmental security denotes a statistically observable reduction in environmental risks achieved through renewable energy development, institutional quality, and risk governance. Its measurability is ensured through carbon dioxide emissions, ecological pressure indicators, health-related effects, and structural energy system parameters.

Climate resilience denotes the capacity of energy systems and economies to maintain functionality under crisis conditions and long-term climate change. It combines decarbonization, resilient infrastructure, flexible networks, investment capacity, and effective governance. This interpretation supports the empirical assessment of Ukraine during 2021–2025.

The literature review reveals four research gaps. First, renewable energy and emission studies rarely combine environmental security and climate resilience within one empirical framework. Second, studies for 2021–2025 insufficiently explain how wartime shocks distort observed energy–emission relationships. Third, many models rely on long stable time series. Fourth, curtailment, balancing reserves, SAIDI, and SAIFI are usually separated from decarbonization indicators.

3. Materials and Methods

The methodological framework is presented as a staged analytical chain: (a) data source identification; (b) harmonization of energy, emission, and reliability indicators;

(c) calculation of intensity indicators; (d) descriptive and correlation diagnostics; (e) exploratory regression estimation; and (f) cautious interpretation of resilience implications. This flow replaces a purely linear causal reading with a reproducible framework that separates structural change from crisis-related disturbances.

The methodological framework of the study is grounded in a systems approach to the analysis of energy transformations, within which the energy system is considered an integrated socio-technical structure shaped by the interaction of technological, economic, and environmental processes. Within this research logic, renewable energy development is interpreted as a structural driver of changes in the energy balance, capable of influencing emission intensity, environmental risks, and the resilience of energy system operations. This approach makes it possible to conceptualize the energy transition as a process of long-term structural transformation, the effects of which can be measured through changes in generation, emission, and system reliability indicators.

The research design is based on a combination of indicator-based analysis, statistical methods for time-series investigation, and econometric modeling. The integration of these methods enables a transition from the descriptive analysis of energy dynamics to the quantitative assessment of causal relationships between renewable energy development and the parameters of environmental security and climate resilience.

The empirical basis of this study consists of open national and international statistical sources. These include official statistics of Ukraine, data from the electricity transmission system operator, national greenhouse gas inventory reports, and international databases on energy and climate statistics. The use of multiple data sources ensures the verifiability of calculations, comparability of the findings with international indicators, and the reproducibility of the study. Appendix A includes the Revised Data Harmonization and Diagnostic Tables.

The analytical procedure of the study is structured into several interrelated stages.

The initial stage involves the development of a system of indicators that allows for the quantitative representation of the relationship between renewable energy development and the environmental as well as systemic effects of energy system performance. The indicator system is constructed according to the logic of the causal chain “scale of renewable energy development—change in the structure of electricity generation—environmental outcomes—parameters of climate resilience.” The selected indicators include renewable energy capacity and electricity generation, the share of renewable energy in the electricity generation mix, CO₂ emission indicators and their intensity, as well as indicators of the integrative and operational resilience of the energy system. The selection of indicators is guided by the principles of statistical consistency, international comparability, and causal interpretability.

The next stage of the study involves a statistical and comparative analysis of the dynamics of key indicators of renewable energy development and environmental effects during 2021–2025. At this stage, time series are constructed for electricity generation, the structure of the energy balance, and greenhouse gas emissions. The analysis of dynamics relies on descriptive statistics, trend analysis, and comparative interpretation of changes in the generation structure. This approach makes it possible to identify structural shifts in the functioning of the energy system and to assess the relationship between changes in the energy balance and the dynamics of environmental indicators.

Particular attention is given to distinguishing the effect of renewable energy development from the influence of external factors that may also affect emission levels. These factors include changes in economic activity, wartime events, regime shifts in the functioning of the energy system, and fluctuations in electricity demand. Accounting for these factors helps avoid a misleading interpretation of environmental change as a direct and isolated consequence of renewable energy expansion.

The final stage of this study involves the application of correlation analysis and econometric modeling in order to quantitatively assess the impact of renewable energy development on the environmental and systemic parameters of the energy system. At the first step, correlation analysis is used to determine the direction and strength of statistical relationships between the share of renewable energy in electricity generation and the dependent indicators. This provides a preliminary assessment of the associations observed in the data and establishes the analytical basis for subsequent econometric modeling.

The subsequent analysis is carried out using multivariate regression models in which the dependent variables are represented by indicators of carbon intensity of electricity generation, the intensity of pollutant emissions, and the operational parameters of the energy system. The explanatory variable is the share of renewable energy in electricity generation. The set of control variables includes total electricity generation, electricity imports, seasonal demand fluctuations, and regime shifts in the operation of the energy system. This model specification makes it possible to estimate the contribution of renewable energy development to changes in the environmental parameters of the energy system while controlling for other relevant influences.

Because only five annual observations are available, conventional robustness tests cannot provide reliable inferential confirmation. The manuscript therefore reports model diagnostics, coefficient instability, and variance inflation factors as warning indicators. The econometric results should be read as exploratory diagnostics that support interpretation of the indicator dynamics, not as a basis for strong causal inference.

The proposed methodological framework combines indicator-based analysis, statistical investigation of time series, and econometric modeling, thereby enabling a transition from the description of renewable energy development dynamics to a quantitative assessment of its impact on the environmental security and climate resilience of Ukraine's energy system. The use of this multi-level methodology provides an analytical basis for drawing well-grounded conclusions regarding the role of renewable energy in decarbonization processes and in strengthening the resilience of the energy sector.

4. Results

4.1. *The Formation of a System of Relevant Indicators for Renewable Energy Development, Environmental Security, and Climate Resilience*

The formation of a system of relevant indicators for renewable energy development, environmental security, and climate resilience is carried out with consideration of the need to quantitatively capture both structural transformations in the energy sector and the resulting environmental and systemic effects of these transformations during 2021–2025.

The methodological starting point is the interpretation of renewable energy development as the primary impulse that, through changes in the structure of generation and consumption, translates into reduced environmental pressure while simultaneously influencing the ability of the energy system to function under conditions of heightened climatic and geopolitical instability. For this reason, the indicator system is structured according to the causal logic “scale and structure of renewable energy → emission and environmental effects → parameters of climate resilience”.

Table 1 presents a coordinated system of indicators grouped into three interrelated blocks. For each indicator, its analytical purpose and the corresponding open data sources are specified, which ensures the reproducibility of calculations and the international comparability of results. The numerical and documentary evidence base combines official international, national, sectoral, and institutional open sources used for indicator construction, harmonization, verification, and 2025 proxy estimates [48–66].

Table 1. System of Relevant Indicators for Renewable Energy Development, Environmental Security, and Climate Resilience.

Blocks	Indicators	Analytical Purpose	Units of Measurement	Main Open Data Sources
Renewable energy development	Total installed renewable energy capacity	Characterizes the investment and technological scale of renewable energy development	MW	IEA [48], State Statistics Service of Ukraine [57], Ministry of Energy of Ukraine [58]
Renewable energy development	Installed capacity by renewable energy type	Allows for an assessment of renewable energy diversification and different sensitivity to seasonality	MW	IEA [48], Ministry of Energy of Ukraine [58], NPC Ukrenergo [60]
Renewable energy development	Electricity generation from renewable sources	Reflects the actual volume of fossil fuel generation substitution	GWh	IEA [48], State Statistics Service of Ukraine [57], NPC Ukrenergo [60]
Renewable energy development	Share of renewable energy in electricity generation	Key structural variable for analyzing the impact on emissions	%	IEA [48], Eurostat [53,54], NPC Ukrenergo [60]
Renewable energy development	Share of renewable energy in gross final energy consumption	Reflects the systemic character of the energy transition	%	World Bank WDI [49,50], Eurostat [54], State Statistics Service of Ukraine [57]
Renewable energy development	Energy intensity of GDP	Control variable used to distinguish renewable energy effects from energy efficiency effects	kg of oil equivalent per USD	World Bank WDI [49], OECD [55], National Bank of Ukraine [61]
Environmental security	Total CO ₂ emissions	Integral indicator of decarbonization outcomes	million t CO ₂	IEA [48], World Bank [49]
Environmental security	CO ₂ emissions of the energy sector	Identifies the energy channel of renewable energy impact	million t CO ₂	IEA [48], UNFCCC [51], National Greenhouse Gas Inventory of Ukraine [59]
Environmental security	CO ₂ emissions and greenhouse gas emissions in CO ₂ equivalent	Ensures consistency with inventory methodology and nationally determined contribution reporting	million t CO ₂ equivalent	UNFCCC [51], National Greenhouse Gas Inventory of Ukraine [59]
Environmental security	Carbon intensity of GDP	Indicates structural decoupling of economic growth and emissions	kg CO ₂ per USD	World Bank WDI [49,50], OECD [55], National Bank of Ukraine [61]
Environmental security	Emission intensity of electricity generation	Directly links the generation structure with emissions	g CO ₂ per kWh	Calculated based on IEA [48] and Ukrenergo [60]
Environmental security	Air pollutant emissions	Reflects local environmental impact beyond climate effects	thousand t	State Statistics Service of Ukraine [57], EEA [52]
Climate resilience	Curtailement of renewable energy generation	Indicator of grid constraints and system flexibility	GWh	NPC Ukrenergo [60]
Climate resilience	Balancing reserves	Characterizes the system's ability to integrate variable renewable energy	MW	NPC Ukrenergo [60]
Climate resilience	Reliability of electricity supply indicators	Reflects the operational resilience of the power system	hours or indices	NPC Ukrenergo [60]
Climate resilience	Climate risk indicators	Provides the context of climate threats and associated losses	index	World Bank WDI [49], OECD [55]

Note: The indicators are used to describe the analytical framework and the structure of the assessment, while the metrics (Tables 2–6) represent their numerical operationalization in time series.

The combination of indicators reflecting installed renewable energy capacity and actual electricity generation makes it possible to avoid a methodological bias in which environmental effects are attributed to the nominal deployment of technologies without accounting for their real utilization. The share of renewable energy in electricity generation serves as the main explanatory variable in models assessing the impact on emissions, while the share of renewable energy in gross final energy consumption extends the analysis to the systemic level of the energy transition. The inclusion of GDP energy intensity as a control variable is particularly important, since emission reductions during crisis periods may result from declining economic activity rather than from the expansion of renewable energy.

The environmental security block is designed to combine absolute and relative indicators. Absolute emissions allow for the evaluation of the overall environmental outcome, whereas emission intensities remove the scale effect and reveal structural shifts that are essential for demonstrating a causal relationship between renewable energy development and decarbonization. The additional inclusion of pollutant emission indicators provides a broader interpretation of environmental security that also encompasses local environmental risks.

The climate resilience indicators presented in Table 1 have a systemic nature and reflect not only the outcome of emission reduction but also the capacity of the energy system to integrate renewable energy without compromising operational reliability. Renewable generation curtailment and the need for balancing reserves capture structural constraints associated with renewable energy integration, while supply reliability indicators make it possible to link the energy transition with the broader socio-economic resilience of the system.

To ensure methodological consistency and international comparability of the data, Table 2 presents a scheme for combining national and international sources, in which national statistics serve as the primary database, while international databases perform the functions of verification and cross-country comparison.

Table 2. Harmonization of National and International Data Sources for Ukraine.

Groups of Indicators	Basic Sources for Ukraine	Sources for Verification and Comparison	Methodological Comments
Electricity generation and structure	NPC Ukrenergo [60], State Statistics Service of Ukraine [57]	IEA [48], Eurostat [53,54]	Ensures comparability of definitions and enables comparisons with the EU
Energy balance and final consumption	State Statistics Service of Ukraine [57], Ministry of Energy of Ukraine [58]	IEA [48], World Bank WDI [49,50]	Avoids inconsistencies in interpreting final energy consumption
CO ₂ emissions and greenhouse gas emissions in CO ₂ equivalent	National Greenhouse Gas Inventory of Ukraine [59]	UNFCCC [51], IEA [48], World Bank [49], EEA [52]	Inventory data are the primary source; international databases are used for comparison
Macroeconomic variables	National Bank of Ukraine [61], State Statistics Service of Ukraine [57]	World Bank WDI [49,50], OECD [55,56]	Harmonization of deflators and the currency base
Indicators of renewable energy integration resilience	NPC Ukrenergo [60]	OECD [55,56]	International indicators are used as conceptual benchmarks

4.2. Analysis of the Dynamics of Key Indicators of Renewable Energy Development and Environmental Effects in Ukraine

The data presented in Table 3 indicate that in 2021 the development of renewable energy in Ukraine was in a phase of relative stability. The installed capacity of renewable

energy sources reached 9650 MW, while electricity generation from renewable sources amounted to 12.8 billion kWh, accounting for 8.2% of total electricity production [57,62].

Table 3. Dynamics of Key Indicators of Renewable Energy Development, Environmental Security, and System Effects of Ukraine’s Electricity Sector.

Indicators	2021	2022	2023	2024	2025
Installed renewable energy capacity, MW	9650	9730	9870	10,020	10,180
Electricity generation from renewable sources, billion kWh	12.8	11.6	12.3	13.1	13.8
Total electricity generation, billion kWh	156.6	146.9	105.8	121.3	128.5
Share of renewable energy in electricity generation, %	8.2	7.9	11.6	10.8	10.7
CO ₂ emissions of the energy sector, million t	93.4	78.1	64.7	69.2	71.0
Carbon intensity of electricity generation, g CO ₂ /kWh	597	531	611	570	553
Electricity imports, billion kWh	0.3	1.7	2.1	4.44	4.8

Sources: calculated based on data from the State Statistics Service of Ukraine, NPC Ukrenergo, the National Inventory Report of Ukraine, IEA, UNFCCC, and the World Bank [49,51,57,62–64].

Under these conditions, CO₂ emissions from the energy sector reached 93.4 million tonnes, and the carbon intensity of electricity generation amounted to 597 g CO₂ per kWh, reflecting the prevailing dominance of coal- and gas-based generation in the energy mix.

In 2022, the reduction in total electricity production to 146.9 billion kWh was accompanied by a decline in renewable energy generation to 11.6 billion kWh. However, the contraction of conventional generation was deeper, which allowed the share of renewable energy to remain close to 7.9% of total electricity production [57,63]. At the same time, CO₂ emissions from the energy sector decreased to 78.1 million tonnes, while carbon intensity declined to 531 g CO₂ per kWh, indicating a combination of structural effects and an overall reduction in electricity demand.

The year 2023 was characterized by the most significant decline in total electricity generation, which dropped to 105.8 billion kWh, while electricity production from renewable sources reached 12.3 billion kWh. As a result, the share of renewable energy increased to 11.6%. However, this increase was largely relative in nature and was not accompanied by a proportional reduction in carbon intensity. On the contrary, carbon intensity rose to 611 g CO₂ per kWh due to changes in the fuel mix and emergency operating regimes of thermal power plants [63,64]. CO₂ emissions declined to 64.7 million tonnes, which was largely explained by the contraction of electricity production rather than exclusively by the expansion of renewable energy.

In 2024, electricity production partially recovered to 121.3 billion kWh, while renewable energy generation increased to 13.1 billion kWh. The share of renewable energy stabilized at 10.8%, reflecting not only the effect of reduced conventional generation but also a real increase in electricity output from renewable sources [51,64]. CO₂ emissions from the energy sector rose to 69.2 million tonnes, although carbon intensity declined to 570 g CO₂ per kWh, indicating the gradual restoration of the environmental effect associated with renewable energy development.

In 2025, according to preliminary consolidated estimates, electricity generation continued to increase to 128.5 billion kWh, while renewable electricity production reached 13.8 billion kWh, with the share of renewable energy stabilizing at approximately 10.7%.

Under these conditions, carbon intensity declined further to 553 g CO₂ per kWh, despite the growth of absolute emissions to 71.0 million tonnes. This reflects a combination of economic recovery and the gradual environmental effect of expanding renewable energy capacity [49,51].

The obtained time series confirm that during 2021–2025 the influence of renewable energy development on environmental security in Ukraine manifested itself in a non-linear manner through a complex interaction with the dynamics of total electricity production, the fuel structure of generation, and systemic constraints. An increase in the share of renewable energy alone does not automatically guarantee a reduction in carbon intensity; however, during the recovery phase of the energy system following crisis conditions, it becomes a key factor in stabilizing environmental indicators. This provides a quantitatively grounded basis for the next stage of the research devoted to econometric modeling of causal relationships between renewable energy development, emissions, and climate resilience.

4.3. Assessment of the Impact of the Increasing Share of Renewable Energy on Emission Reduction, Mitigation of Environmental Risks, and Enhancement of the Climate Resilience of Ukraine's Energy System

The assessment of the impact of renewable energy development on environmental security and the climate resilience of Ukraine's energy system should be conducted within a unified methodological framework in which the growth of the renewable energy share is interpreted as a structural factor transforming the electricity generation balance.

Environmental and systemic effects are captured through intensity indicators (relative indicators normalized to production volumes or economic activity), differential characteristics (changes in indicators between periods reflecting the direction and magnitude of structural shifts), and resilience indicators (measures of the capacity of the energy system to integrate renewable energy sources while maintaining operational reliability). The logic of the assessment is based on the causal chain “increase in the share of renewable energy in electricity generation → change in carbon intensity of generation and emission levels → reduction in environmental pressure and risks → change in parameters of integration and operational resilience of the energy system.”

Given the limited number of annual observations for 2021–2025, the econometric component is treated as exploratory rather than confirmatory. Monthly energy time series would be preferable for statistically stronger estimation, but the present manuscript reports only annual harmonized indicators because complete monthly emission and resilience series are not consistently available for all variables. Therefore, the regression results are used as diagnostic evidence and are not interpreted as definitive causal estimates. At the same time, for emission indicators (CO₂ and air pollutants), inventory-based series are used, including official data from the national greenhouse gas inventory and international climate reporting systems. For incomplete years, the use of intensity-based proxies (emissions or pollution per unit of electricity generated) is permitted, provided that the formulas used for their calculation are formally specified.

Such an approach makes it possible to preserve the causal interpretation of the results even under conditions of structural disruptions and fluctuations in the energy system during crisis periods.

The core variables of the methodology are formalized as follows:

1. The share of renewable energy sources in electricity generation is defined as

$$\text{SRES}_t = 100 \times \text{GRES}_t / \text{GTOT}_t, \quad (1)$$

where GRES_t denotes the volume of electricity generation from renewable sources in period t , and GTOT_t represents total electricity generation in period t .

2. To assess the decarbonization effect, the carbon intensity of electricity generation is used:

$$\text{ICO}_{2t} = \text{ECO}_{2t} / \text{GTOT}_t, \quad (2)$$

where ECO_{2t} is measured in million tonnes of CO_2 and $GTOT_t$ in billion kWh. With this specification, ICO_{2t} is directly interpreted in g CO_2 per kWh, since the ratio of “1 million tonnes CO_2 per 1 billion kWh” equals 1 g CO_2 per kWh. Emission intensity is therefore used as the principal dependent variable because it eliminates the scale effect of production and the sharp demand fluctuations typical of crisis conditions.

3. Environmental risks within the study are operationalized through the intensity of pollutant emissions statistically associated with thermal generation and air quality:

$$IPOLL_t = P_t / GTOT_t, \quad (3)$$

where P_t denotes pollutant emissions in period t . In the absence of monthly time series, the use of annual values is permitted with a transition to models estimated at annual frequency with a limited set of regressors, which is explicitly defined as a limitation of the estimation procedure.

Climate resilience of the energy system in this study is interpreted through the combined perspective of integration and operational components. The integration component reflects the ability of the system to incorporate increasing volumes of renewable energy without excessive losses or imbalances and is represented through renewable generation curtailment C_t (GWh) and the requirement for balancing reserves R_t (MW). The operational component reflects the stability of electricity supply under conditions of increasing weather variability and wartime risks and is represented by the supply continuity indicators $SAIDI_t$ and $SAIFI_t$. The use of these indicators in the context of climate resilience is based on the assumption that extreme weather conditions and structural changes in generation increase pressure on electricity networks and affect the frequency and duration of supply interruptions.

The correlation module is applied to conduct an initial assessment of the direction and strength of relationships between the share of renewable energy and the dependent indicators, as well as to diagnose potential multicollinearity. For approximately normally distributed series, the Pearson correlation coefficient is applied, while for series characterized by structural breaks and outliers, the Spearman rank correlation coefficient is used. For monthly data, autocorrelation and seasonality are explicitly accounted for through the use of differenced variables or seasonal fixed effects.

The econometric module for estimating the impact of renewable energy development on the decarbonization of the energy sector is specified through a multivariate regression framework.

$$ICO_{2t} = \alpha + \beta SRES_t + \gamma_1 \ln(GTOT_t) + \gamma_2 Imp_t + \gamma_3 War_t + \gamma_4 S + \varepsilon_t, \quad (4)$$

where Imp_t denotes electricity imports, War_t represents the wartime regime indicator, and S refers to seasonal fixed effects. The coefficient β is interpreted as the change in the carbon intensity of electricity generation resulting from a one-percentage-point increase in the share of renewable energy, holding other factors constant.

Given the potential endogeneity of $SRES_t$, which may arise from the joint influence of electricity demand, emergency outages, and network constraints, the estimation procedure is complemented by the use of lagged values of the renewable energy share and, where data availability permits, instrumental variables. These may include weather-related factors that influence renewable energy output but do not directly affect emissions outside the electricity generation channel.

The impact of renewable energy on climate resilience is estimated through separate equations for the integration and operational components.

$$C_t = a_0 + a_1 \text{SRES}_t + a_2 \text{Grid}_t + a_3 \text{Wart} + a_4 S + e_t, \quad (5)$$

$$R_t = b_0 + b_1 \text{SRES}_t + b_2 \text{Grid}_t + b_3 \text{War}_t + b_4 S + v_t, \quad (6)$$

$$\text{SAIDI}_t = c_0 + c_1 \text{SRES}_t + c_2 \text{War}_t + c_3 S + \eta_t, \quad (7)$$

where Grid_t denotes a proxy indicator of network constraints. The expected sign of the coefficients associated with SRES_t may vary depending on the condition of the grid infrastructure. This makes it possible to interpret the results either as evidence of increasing systemic risks under conditions of insufficient system flexibility or as an indication of enhanced adaptive capacity when grid management and balancing reserves are adequately developed.

The assessment of the impact of renewable energy development on environmental security and the climate resilience of Ukraine's energy system requires a clearly defined empirical foundation that ensures a continuous causal chain from primary statistical data to the results of econometric modeling. For this purpose, prior to estimating models (5)–(7), a harmonized set of baseline indicators of renewable energy development, emissions, and environmental risks for the period 2021–2025 was constructed, as presented in Table 4.

Table 4. Key Indicators of Renewable Energy Development and Environmental Effects in Ukraine.

Years	GRES_t , TWh	GTOT_t , TWh	SRES_t , %	ECO_{2t} , Million t	ICO_{2t} , g CO_2/kWh	P_t , Thousand t	IPOLL_t , Thousand t/TWh
2021	12.8	156.6	8.2	93.4	597	162	1.03
2022	11.6	146.9	7.9	78.1	531	141	0.96
2023	12.3	105.8	11.6	64.7	611	118	1.12
2024	13.1	121.3	10.8	69.2	570	115	0.95
2025	13.8	128.5	10.7	71.0	553	n.a.	n.a.

Note. Table 4 was harmonized with Table 3. Energy variables are therefore identical in both tables. Pollutant indicators are retained only where reproducible open data are available. n.a. = not applicable.

As shown in Table 4, during 2021–2023 the total volume of electricity generation in Ukraine declined more significantly than electricity generation from renewable energy sources, which resulted in an increase in the share of renewable energy from 8.2% in 2021 to 11.6% in 2023. This indicates that the growth of SRES_t was driven not only by investment factors but also by the relative resilience of renewable generation compared with thermal generation under crisis conditions. A comparison of the dynamics of ECO_{2t} and ICO_{2t} demonstrates that the reduction in absolute CO_2 emissions cannot be explained solely by the contraction of electricity production. The decrease in ICO_{2t} to 527 g CO_2 per kWh in 2022 reflects a structural decarbonization effect, whereas the increase in this indicator to 586 g CO_2 per kWh in 2023 signals a growing role of emergency thermal generation and constraints on renewable integration due to damage to the electricity network.

A similar pattern can also be observed in relation to environmental risks. Despite a reduction in the absolute emissions of pollutants (P_t), the pollution intensity indicator IPOLL_t increased in 2023 to 1.15 thousand tonnes per TWh, indicating a deterioration in the environmental quality of electricity generation during peak periods. This provides methodological justification for the use of intensity indicators as dependent variables in subsequent econometric analysis.

To assess the climate resilience of the energy system within the framework of models (5)–(7), it is necessary to empirically operationalize the variables reflecting operational and integration resilience. In this study, operational reliability is operationalized through the SAIDI indicator, the official values of which are presented in Table 5.

Table 5. SAIDI Indicators for Ukraine.

Years	SAIDI Due to Company Faults, min	SAIDI Planned Outages, min	SAIDI Force Majeure and Other Causes, min	Total SAIDI, min
2021	626	662	444	1732
2022	603	344	18,747	19,694
2023	536	549	12,389	13,474
2024	502	597	29,210	30,309
2025	n.a.	n.a.	n.a.	n.a.

Note: n.a. = not applicable.

The data presented in Table 5 indicate that the SAIDI component associated with company faults demonstrates a downward trend even under crisis conditions. By contrast, force majeure factors dominate total SAIDI in 2022 and 2024. Therefore, the impact of renewable energy development on operational reliability can be identified only with explicit control for the wartime regime.

The indicator of balancing reserve requirements R_t is not available in open sources as a single harmonized annual series for the period 2021–2025. However, for 2024–2025 a reproducible proxy is available in the form of the results of special auctions for the long-term procurement of ancillary services, presented in Table 6. The reported values confirm that the increase in the share of renewable energy is accompanied by a significant rise in the demand for flexible balancing capacities, which provides an empirical basis for estimating model (6) on a limited sample and within the framework of robustness checks.

Regarding the indicator C_t , which reflects renewable energy generation curtailment measured in GWh, open sources do not provide a single harmonized annual series for 2021–2025 suitable for reproducible analysis. For this reason, model (5) may be implemented either through the direct calculation of C_t from hourly dispatch data followed by aggregation, or through the substitution of C_t with an open indicator of supply shortages or losses, with a corresponding adjustment of the economic interpretation of the results.

Table 6. A Proxy of the R_t Indicator Based on the Results of Special Ancillary Services Auctions of NPC Ukrenergo, MW.

Years	R_t , MW	Proxy Description
2024	423	New balancing capacities according to the results of the first special auctions
2025	863	Fast automatic frequency restoration reserves guaranteed for construction

Note: aFRR refers to automatic frequency restoration reserve, which represents the fast-response balancing capacity of the power system that automatically adjusts generation or consumption in order to restore system frequency after deviations.

Thus, the integration of Tables 4–6 ensures the internal completeness of the empirical section of Section 4.3. The key variables $GRES_t$, ECO_{2t} , ICO_{2t} , P_t , $IPOLL_t$, and $SAIDI_t$ have a clearly defined numerical basis, the indicator R_t is represented through a reproducible proxy, and the status of C_t is transparently identified as requiring additional data processing. This provides a sound basis for proceeding to econometric estimation of the impact of renewable energy development on environmental security and the climate resilience of Ukraine’s energy system.

The initial dataset for the econometric analysis includes those indicators presented in Table 3 that provide a complete time series for 2021–2025 for both the share of renewable energy and the carbon intensity of electricity generation. In addition, verification of the identity used for calculating the intensity indicator ICO_{2t} as the ratio of CO_2 emissions from the energy sector to total electricity generation is provided (Table 7).

Table 7. Baseline Series for Assessing the Impact of Renewable Energy.

Years	Share of Renewable Energy in Electricity Generation, %	Total Electricity Generation, Billion kWh	CO_2 Emissions of the Energy Sector, Million t	Carbon Intensity of Electricity Generation, g CO_2 /kWh	Electricity Imports, Billion kWh
2021	8.2	156.6	93.4	597	0.3
2022	7.9	146.9	78.1	531	1.7
2023	11.6	105.8	64.7	611	2.1
2024	10.8	121.3	69.2	570	4.44
2025	10.7	128.5	71.0	553	4.8

Note: Decimal points denote fractional values in this table; thousands are not separated by punctuation marks.

The presented dataset makes it possible to verify the internal consistency between ECO_{2t} , $GTOT_t$, and ICO_{2t} . For this purpose, ICO_{2t} was calculated according to Equation (2), as presented in Table 8.

Table 8. Verification of the Calculation of ICO_{2t} .

Years	ICO_{2t} , g CO_2 /kWh	ICO_{2t} Calculated as $1000 \cdot ECO_2 / GTOT$, g CO_2 /kWh	Difference, g CO_2 /kWh
2021	597.00	596.42	0.58
2022	531.00	531.65	−0.65
2023	611.00	611.53	−0.53
2024	570.00	570.49	−0.49
2025	553.00	552.53	0.47

Note: Decimal points denote fractional values in this table; thousands are not separated by punctuation marks. The equation reference was corrected. The carbon-intensity calculation follows Equation (2), not the regression specification.

The next step is to demonstrate the correlation relationship between the share of renewable energy, emission intensity, absolute emissions, and the scale of electricity generation. Correlation itself does not establish causality; however, it captures the direction and strength of co-variation within the same data series that subsequently form the basis for the regression estimation.

The numerical results provide three important reference points for the argumentation. The share of renewable energy exhibits a strong negative relationship with $GTOT$ at the level of $−0.949$. It also demonstrates a strong negative relationship with absolute emissions ECO_2 at the level of $−0.843$. The positive correlation of 0.410 between $SRES$ and ICO_2 is interpreted as evidence of crisis-period instability rather than as evidence that renewable energy increases carbon intensity.

However, this relationship may be partially influenced by the scale factor of electricity generation, since ECO_2 and $GTOT$ are correlated at the level of 0.930. The emission intensity indicator ICO_2 shows a moderately positive relationship with the share of renewable energy at the level of 0.410. This value reflects a crisis-period structural disruption observed in 2023,

when, despite an increased share of renewable energy, emission intensity rose to 611 g CO₂ per kWh due to the fuel structure and emergency operating regimes of thermal generation.

Following this diagnostic stage, the analysis proceeds to regression specifications while accounting for the limitations of the sample size. For a dataset covering only five annual observations, only very compact models with a minimal number of regressors can be considered methodologically appropriate. For this reason, a baseline model is constructed in which the dependent variable is $ICO_{2,t}$ and the explanatory variable is $SRES_t$, as well as an extended model that includes control variables for the scale of electricity generation and electricity imports, which have been identified as significant factors for interpretation.

These estimates should be interpreted with reference to the numerical evidence presented in Table 7. In 2023, the renewable energy share increased from 7.9% to 11.6%, while $ICO_{2,t}$ rose from 531 to 611 g CO₂ per kWh. Consequently, a simple comparison without control variables produces a positive sign of beta. This sign reflects structural disruptions and regime changes within a short annual series, not a stable causal effect of renewable energy on emission intensity. Model C is retained only as a diagnostic specification because its coefficients are unstable under multicollinearity and five observations.

On this basis, several conclusions can be drawn directly from the constructed tables.

First, the dependent variable $ICO_{2,t}$ is methodologically consistent, since its calculation has been verified with a rounding error not exceeding 0.65 g CO₂ per kWh. Second, the annual data for 2021–2025 demonstrate a strong interaction between the renewable energy effect, the scale of electricity generation, and crisis-related conditions. This is numerically reflected in the correlation between $SRES$ and $GTOT$ at the level of -0.949 and in the increase of $ICO_{2,t}$ to 611 g CO₂ per kWh in 2023 despite the higher renewable energy share of 11.6%. These observations justify the transition from annual to monthly frequency, which has already been proposed in the methodological framework, since monthly data allow for the introduction of seasonal effects and provide better separation of regime disruptions from the structural effect of renewable energy development.

To complete the quantitative analysis and maintain continuity with the previously presented correlation and regression estimates, differential characteristics are introduced that allow for a direct examination of how changes in the share of renewable energy between years correspond to changes in the carbon intensity of electricity generation. Such calculations eliminate the illusion of a linear relationship while providing numerical confirmation of the arguments formulated after Tables 7–10.

Table 9. Correlation Matrix for 2021–2025 Series.

Variables	Share of Renewable Energy, %	ICO_2 , g CO ₂ /kWh	ECO_2 , Million t	Imports, Billion kWh	$GTOT$, Billion kWh
Share of renewable energy, %	1.000	0.410	−0.843	0.650	−0.949
ICO_2 , g CO ₂ /kWh	0.410	1.000	0.013	−0.347	−0.354
ECO_2 , million t	−0.843	0.013	1.000	−0.695	0.930
Imports, billion kWh	0.650	−0.347	−0.695	1.000	−0.545
$GTOT$, billion kWh	−0.949	−0.354	0.930	−0.545	1.000

Note: Decimal points denote fractional values in this table; thousands are not separated by punctuation marks.

Table 10. Estimation of the Impact of the Renewable Energy Share on the Carbon Intensity of Electricity Generation, 2021–2025.

Parameters	Model A: $\text{ICO}_2 \sim \text{SRES}$	Model B: $\text{ICO}_2 \sim \text{SRES} + \ln(\text{GTOT})$	Model C: $\text{ICO}_2 \sim \text{SRES} + \ln(\text{GTOT}) + \text{Import}$
Constant	494.361	628.559	−1052.931
Share of renewable energy, at SRES	7.931	5.882	46.352
$\ln(\text{GTOT}), \gamma$	–	−23.407	252.101
Imports, δ	–	–	−22.101
Coefficient of determination (R-squared)	0.168	0.170	0.952
Number of observations	5	5	5
Econometric status	Exploratory diagnostic specification	Exploratory diagnostic specification	Diagnostic only; unstable because of multicollinearity and five annual observations

Note: Decimal points denote fractional values in this table; thousands are not separated by punctuation marks.

Table 11 presents stepwise differential indicators for the period 2021–2025, constructed exclusively on the basis of previously used values. The change in the share of renewable energy ΔSRES_t is defined as the difference between the renewable energy share in the current and the previous year, while the change in carbon intensity $\Delta\text{ICO}_{2,t}$ is defined as the corresponding difference in the indicator expressed in g CO₂ per kWh. In addition, the ratio $\Delta\text{ICO}_{2,t}$ to ΔSRES_t is calculated and interpreted as the change in carbon intensity associated with a one-percentage-point change in the share of renewable energy.

Table 11. Differential Characteristics of the Impact of Changes in the Share of Renewable Energy on the Carbon Intensity of Electricity Generation.

Parameters	2021 → 2022	2022 → 2023	2023 → 2024	2024 → 2025
SRES_t , previous and current year, %	8.2, 7.9	7.9, 11.6	11.6, 10.8	10.8, 10.7
ΔSRES_t , percentage points	−0.3	3.7	−0.8	−0.1
$\text{ICO}_{2,t}$, previous and current year, g CO ₂ /kWh	597, 531	531, 611	611, 570	570, 553
$\Delta\text{ICO}_{2,t}$, g CO ₂ /kWh	−66	80	−41	−17
$\Delta\text{ICO}_{2,t}/\Delta\text{SRES}_t$, g CO ₂ /kWh per 1 percentage point	220.0	21.6	51.3	170.0
Interpretation	demand contraction effect	crisis-period thermal effect	partial normalization effect	near-stable SRES effect

The numerical values presented in Table 11 are directly consistent with the correlation structure reported in Table 9 and with the regression model behavior shown in Table 10. They demonstrate that the sign and magnitude of the relationship between renewable energy share and carbon intensity depend on the operating regime of the energy system.

The most illustrative case is the transition from 2022 to 2023, where the share of renewable energy increased by 3.7 percentage points, while carbon intensity rose by 80 g CO₂ per kWh. The resulting value of 21.6 g CO₂ per kWh per one percentage point formally indicates a positive relationship. In substantive terms, however, it reflects changes

in the fuel structure and emergency operating regimes of thermal generation in 2023, which is directly consistent with the positive coefficient associated with SRES in the simple regression models presented in Table 10.

During the transition from 2023 to 2024, the decrease in the share of renewable energy by 0.8 percentage points was accompanied by a reduction in carbon intensity of 41 g CO₂ per kWh, corresponding to 51.3 g CO₂ per kWh per one percentage point. This result reflects the partial restoration of normal operating regimes within the energy system and a reduced reliance on emergency thermal generation. A similar pattern is observed for the transition from 2024 to 2025, where carbon intensity declined by a further 17 g CO₂ per kWh despite an almost unchanged share of renewable energy. This numerically confirms the argument that changes in emission intensity are influenced not only by the structure of electricity generation but also by operational factors.

Taken together, Table 11 complements the previous results by demonstrating that the sign and magnitude of the relationship between the share of renewable energy and carbon intensity depend substantially on the operational regime of the energy system and the overall scale of electricity generation. These differential estimates provide quantitative support for the conclusion that the effect of renewable energy cannot be interpreted correctly on the basis of a short annual time series without accounting for structural disruptions. This finding is consistent with both the correlation analysis and the behavior of the regression model parameters.

4.4. Case Insight: The Staryi Sambir Wind Power Plant as a Local Governance Success

The Staryi Sambir Wind Power Plant in Lviv Oblast exemplifies the positive synergy between local governance and renewable energy development in Ukraine. Commissioned in two stages (2015 and 2017), with a total capacity of 20.7 MW, it stands as one of the country's pioneering grid-connected wind farms.

Its success is attributed to strong collaboration between local authorities and private investors, characterized by transparent permitting processes and active community engagement.

The project also benefited significantly from green tariff incentives, which ensured financial viability under the national support scheme. Moreover, Lviv Oblast's commitment to regional energy planning—aligned with national priorities and EU integration frameworks provided a strategic foundation for this initiative. Importantly, public acceptance was high, reflecting the visible economic and environmental advantages the project brought to the local community.

This case underscores how empowered subnational governance and local ownership, supported by clear regulatory frameworks and financial mechanisms, can accelerate renewable energy deployment even amid broader national challenges. Furthermore, it highlights western Ukraine's potential as a testing ground for decentralized energy solutions and post-conflict recovery models.

Lessons from Staryi Sambir suggest the need to strengthen regional and local government capacities in energy planning and permitting, leveraging digital tools and fostering public–private partnerships to diversify Ukraine's energy portfolio and enhance its resilience. In sum, the Staryi Sambir Wind Power Plant demonstrates that focused local governance combined with strategic investment can effectively advance Ukraine's green transition from theory into practice [34,38].

Although this study focuses on a single case, the Staryi Sambir wind power plant provides valuable insight into how local governance capacity can facilitate renewable energy deployment even in the presence of broader national-level regulatory instability. Rather than serving as a statistically representative example, the case illustrates a governance mechanism in practice, highlighting the role of municipal leadership, transparent permit-

ting procedures, and community acceptance in sustaining renewable energy investments under conditions of systemic uncertainty.

5. Discussion

The obtained results allow for a more precise interpretation of the role of renewable energy in ensuring environmental security and climate resilience in Ukraine, taking into account the specific conditions of the period 2021–2025. The analysis of indicator dynamics demonstrates that an increase in the share of renewable energy in electricity generation is not directly associated with a linear reduction in absolute emission volumes. Absolute emissions are significantly influenced by changes in the overall scale of electricity generation, the structure of the fuel balance, and the operational regime of the energy system. Under such conditions, absolute environmental indicators remain sensitive to external shocks and therefore do not directly reflect the structural transformations associated with the development of renewable energy.

The correlation, differential, and econometric estimates obtained in Section 4.3 indicate the presence of a potential inverse relationship between the share of renewable energy and the carbon intensity of electricity generation. However, this relationship appears unstable within the short annual time series and is substantially modified by crisis-related conditions. In particular, the simultaneous increase in the share of renewable energy and the rise in carbon intensity recorded in 2023 reflects the dominant role of emergency operating regimes of thermal generation and changes in the fuel structure, which temporarily offset the expected structural decarbonization effect. This confirms that the interpretation of the impact of renewable energy requires a clear separation between structural transformations and short-term disturbances.

The differential characteristics additionally demonstrate significant variability in the change of carbon intensity per one percentage point change in the share of renewable energy across individual years. Such instability indicates that, without accounting for the scale of electricity generation, electricity import volumes, and the operational features of system functioning, quantitative estimates of the renewable energy effect may remain methodologically vulnerable. This observation justifies the use of intensity indicators as the principal analytical variables, since they reduce the influence of exogenous crisis factors and allow the analysis to focus on the internal structural effects of the energy transition.

The results also clarify the nature of the impact of renewable energy development on the climate resilience of the energy system. An increasing share of renewable energy is associated with higher requirements for balancing capacity, reserves, and grid flexibility, which generates short-term integration pressures and additional systemic challenges. At the same time, as management and infrastructure mechanisms adapt, these challenges do not translate into a persistent deterioration of electricity supply reliability. Instead, in the medium term they create the conditions for strengthening the capacity of the energy system to withstand external disturbances.

Within a broader scientific context, these findings are consistent with approaches that evaluate the effects of renewable energy development dynamically, taking into account the adaptation phases of energy systems. The observed instability of parameters in annual data confirms the relevance of using more detailed time series, particularly monthly data, which allow for a clearer separation of the structural influence of renewable energy development from seasonal fluctuations and emergency operating regimes associated with crisis conditions.

Overall, the discussion results indicate that the empirical estimates do not contradict the decarbonization role of renewable energy. Rather, they reflect the complexity and multi-layered nature of its implementation within the Ukrainian energy system. Environmental

security and climate resilience emerge as interconnected but conceptually distinct outcomes of the energy transition. This necessitates the integration of quantitative analysis with systemic and institutional approaches in the formulation of renewable energy development policies and in the evaluation of their long-term effects.

6. Conclusions

As a result of this study, a coherent and methodologically consistent system of indicators for renewable energy development, environmental security, and the climate resilience of Ukraine's energy system has been developed, based on the integration of national and international open data sources. The proposed system of indicators ensures the reproducibility of calculations and the international comparability of results, while enabling the quantitative identification of both structural transformations in the energy sector and the associated environmental and systemic effects. Particular emphasis is placed on intensity-based indicators that remain robust to changes in the scale of electricity generation.

The analysis of indicator dynamics for the period 2021–2025 demonstrates that renewable energy development in Ukraine occurred under conditions of significant external shocks and structural disruptions, which resulted in a non-linear and uneven trajectory. The increase in the share of renewable energy in electricity generation was largely accompanied by a decline in conventional generation. As a consequence, the rising role of renewable energy often had a relative nature and was not always associated with an increase in absolute generation volumes. Under such circumstances, the environmental effects of the energy transition were manifested primarily through changes in the carbon and ecological intensity of electricity generation, whereas absolute emission volumes remained sensitive to crisis conditions and operational factors.

The correlation, differential, and exploratory econometric analyses show that the impact of renewable energy development on the carbon intensity of electricity generation cannot be estimated as a stable causal effect within the short annual time series. The observed relationship depends strongly on the scale of production, the structure of the fuel mix, electricity imports, and emergency operating regimes of the energy system. The obtained results indicate the presence of a decarbonization potential associated with renewable energy expansion, which in the short term may be masked by crisis conditions and therefore appears inconsistently in the empirical data. This finding supports the methodological justification for the use of intensity-based indicators and for the transition to more detailed time-series data in order to correctly identify the structural effects of renewable energy development.

The assessment of climate resilience of the energy system indicates that the growth of the renewable energy share is accompanied by increasing requirements for system flexibility and balancing capacity, creating short-term integration challenges associated with the variability of renewable generation. At the same time, as management mechanisms adapt and balancing reserves and grid infrastructure develop, these challenges do not translate into a persistent deterioration of electricity supply reliability. In the medium term, they create the conditions for strengthening the resilience of the energy system to external disturbances.

The generalized results suggest that environmental security and climate resilience in the context of renewable energy development should be interpreted as interrelated yet conceptually distinct outcomes of the energy transition. Environmental effects are manifested through the reduction in the intensity of the negative environmental impact of electricity generation, while climate resilience reflects the capacity of the energy system to adapt to structural transformations and crisis conditions. This distinction is of funda-

mental importance for the formulation of long-term renewable energy development policy in Ukraine.

The main limitation of this study lies in the limited availability of complete and methodologically harmonized annual data for several indicators for 2024–2025, which necessitates the use of intensity-based proxies and aggregated estimates. Another limitation arises from the inability to fully incorporate hourly and daily operating regimes of the energy system, which are critically important for analyzing the integration resilience of renewable energy sources.

Future research should focus on the use of high-frequency data provided by the National Power Company Ukrenergo for a deeper examination of balancing processes and grid flexibility. Further work may also involve extending the modeling framework to a multi-period comparative format that includes countries of Central and Eastern Europe. Another promising direction involves combining econometric modeling with scenario analysis of renewable energy development, which would make it possible to evaluate the long-term trajectories of environmental security and climate resilience in the context of the post-war recovery of Ukraine’s energy sector.

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Appendix A. Revised Data Harmonization and Diagnostic Tables

Table A1. Harmonized interpretation of the 2021–2025 empirical sample.

Element	Revision Made in the Manuscript
Sample period	The study period is unified as 2021–2025; 2025 values are treated as preliminary where complete official balances are unavailable.
Table consistency	Official annual balance data are distinguished from harmonized analytical series used for diagnostics.
Regression status	Models A–C are described as exploratory diagnostic specifications, not confirmatory causal models.
Climate resilience indicators	Curtailment, balancing reserves, SAIDI, and SAIFI are interpreted as resilience indicators with limited annual comparability.

Table A2. Variables and operational definitions used in the revised manuscript.

Variable	Full Name	Measurement Unit	Operational Role
$SRES_t$	Share of renewable energy sources in electricity generation	%	Key explanatory indicator
$GRES_t$	Electricity generation from renewable sources	billion kWh	Numerator for $SRES_t$
$GTOT_t$	Total electricity generation	billion kWh	Scale variable and control
ECO_{2t}	Energy sector carbon dioxide emissions	million tonnes CO ₂	Emission variable
ICO_{2t}	Carbon intensity of electricity generation	g CO ₂ /kWh	Main dependent indicator
Imp_t	Electricity imports	billion kWh	Control variable
C_t	Renewable generation curtailment	GWh	Descriptive climate resilience indicator
R_t	Balancing reserve requirement	MW	Descriptive climate resilience indicator
$SAIDI_t$	System Average Interruption Duration Index	minutes per customer	Supply reliability indicator
$SAIFI_t$	System Average Interruption Frequency Index	interruptions per customer	Supply reliability indicator

Table A3. Variance inflation diagnostics for Model C.

Regressor	R-Squared from Auxiliary Regression	Variance Inflation Factor	Interpretation
$SRES_t$	0.9308	14.44	Severe multicollinearity
$\ln(GTOT_t)$	0.9098	11.08	Severe multicollinearity
Imp_t	0.5389	2.17	Moderate and acceptable

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