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Decarbonisation of energy through the introduction of small modular nuclear reactors and renewable energy sources

Andrii Kapustianskyi[1*], Oksana Yurasova[1], Igor Galyanchuk[1], Kateryna Romanova[2], Tetiana Sheleshei[2]

[1] Department of Heat Power Engineering, Thermal and Nuclear Power Plants, Lviv Polytechnic National University, Lviv, Ukraine
[2] Department of Heat and Alternative Power Engineering, National Technical University of Ukraine “Ihor Sikorsky Kyiv Polytechnic Institute”, Kyiv, Ukraine
* Corresponding author’s e-mail: kapustianskyiandrii@gmail.com

ABSTRACT

The purpose of the study was to quantify the reduction of carbon dioxide emissions in the energy sector of Ukraine under the scenarios of replacing gas and coal-fired power plants with small modular nuclear reactors and renewable energy sources. The methodology was based on the analysis of international regulatory approaches to assessing the carbon intensity of generation, the examination of the actual technical and economic characteristics of Ukrainian power-generating facilities for 2020–2024, and scenario modelling of changes in total emissions within three options for the transformation of the energy system. The results showed that coal-fired power plants have the highest carbon dioxide intensity in the range of 750–1050 gCO_2/kWh, gas stations form 380–510 gCO_2/kWh, while nuclear power plants and small modular reactors provide 8–16 gCO_2/kWh. Calculations have shown that replacing 20–30% of thermal generation provides an 18–27% reduction in emissions, while the scenario of replacing more than 50% of thermal capacity gives more than 45%. Small modular nuclear reactors have been found to stabilise the operating mode of the power grid and reduce the variability of emission indicators, while solar and wind power plants provide an additional potential for reducing thermal generation emissions in the range of 330–1050 gCO_2/kWh, depending on which thermal technology they replace. The results show that the combined use of small modular nuclear reactors, renewable energy sources, and traditional nuclear power plants allows achieving an integral level of carbon intensity of 100–120 gCO_2/kWh, which corresponds to the parameters of low-carbon energy systems of the European Union. The practical value of the study lies in the formation of scientifically based scenarios for the modernisation of the Ukrainian energy system, which can be used for planning investment decisions and strategies for deep decarbonisation.

Keywords: low-carbon generation, carbon intensity, structural transformation, energy load, scenario modelling, technical-operational parameters.

INTRODUCTION

The growing share of renewable energy sources (RES) in the structure of modern energy systems and the tightening of requirements for reducing the carbon intensity of power generation have formed a new configuration of energy balances, in which maintaining load stability and manageability becomes a key challenge. For Ukraine, this process takes place in the context of the transition to a decentralised model with an increased share of solar and wind generation, which is accompanied by an increase in the stochasticity of production and a complication of balancing between demand and generation. In such circumstances, it is important to find technologies that can ensure the predictability of regimes and system stabilisation with the growing role of renewable sources. A study by Cherep et al. (2023) demonstrated that the use of energy-efficient technologies in combination with optimisation models can significantly reduce energy consumption and improve system manageability. The authors stress that automated control systems create the basis for the integration of low-carbon technologies, forming prerequisites for further decarbonisation of the Ukrainian energy sector. Voronenko et al. (2025) noted that energy efficiency is a basic tool for strengthening the state's energy security since a high level of energy intensity limits the possibility of switching to a low-carbon economy. The authors state that an improved monitoring and forecasting system is critical for the formation of stable operating modes of the power system in the context of an increase in the share of renewable energy sources. These results are consistent with the approach of Kharazishvili et al. (2021), which proposes a systematic approach to assessing energy security and analyses the dependence of the level of systemic risks on the transformation of the generation structure. The paper determines that an increase in the share of renewable energy reduces integral risks, while increasing the need for precise balancing of stochastic power flows.

The analysis of Tkalenko et al. (2024) demonstrates that traditional methods for predicting electrical loads do not reflect the complex temporal dynamics of power systems with a high proportion of renewable energy sources. The authors substantiated the feasibility of using machine learning approaches to more accurately reproduce nonlinear generation variability and improve the quality of forecasting. A generalising study by Shafiullah et al. (2023) is aimed at systematising micro-network management strategies and shows that the combination of rule-based, optimisation, and AI-oriented methods can reduce network losses and increase the efficiency of balancing generation and consumption. It is established that the coordinated use of renewable sources, energy storage, and control systems forms configurations with increased structural stability. Khan et al. (2024) investigated the architecture of hybrid micro-networks with the integration of electric vehicles, energy storage systems and artificial intelligence algorithms; it was shown that such systems provide high flexibility and efficient smoothing of peak loads under variable generation conditions. The authors note that such hybrid systems provide high adaptability in variable generation modes.

In the context of Ukrainian energy, Blinov (2025) examined the development of distributed generation and micro-networks as a key factor in the restoration of local energy systems in the context of damage to centralised infrastructure. The author shows that the growth of decentralised capacities creates technical prerequisites for the introduction of adaptive load management algorithms and improving the stability of the power system. A study by Krasnostanova et al. (2024) is devoted to the analysis of the state of energy management at Ukrainian enterprises and the impact of the level of digitalisation on the efficiency of energy use. Researchers have determined that the insufficient development of digital tools limits the possibilities of reducing energy intensity and carbon intensity of production, justifying the need to introduce intelligent consumption analysis systems. The results of the study show that to ensure the stability of energy systems with a high share of renewable energy sources, it is necessary to integrate technologies that can form a predictable and low-carbon basic generation regime. In this context, An et al. (2025) demonstrate that small modular reactors (SMRS), due to their modular architecture, high power management, and low operating carbon intensity, are able to compensate for fluctuations in solar and wind generation. The study proves that these characteristics allow considering SMR as a structural component of the energy transition in systems with a high proportion of renewable energy sources.

A review by Kang et al. (2025) focuses on analysing the evolution of small modular nuclear reactors and related engineering and safety solutions, in particular, at the stages of the final fuel cycle. It is shown that the design diversity of SMRs and the development of safety systems create technical prerequisites for their integration with intelligent load management systems. The authors also note that optimisation of the fuel cycle and thermal parameters expands the possibilities of integrating SMR into low-carbon power systems with increased requirements for stability and predictability of the base mode. Josephs et al. (2025) analysed the regulatory and economic conditions for integrating small modular nuclear reactors into national energy systems. The authors state that the degree of regulatory certainty, the availability of economic incentives, and the availability of financial mechanisms are key factors that determine the real pace of deployment of SMR technologies.

Despite a significant amount of research, the scientific literature lacks comprehensive models that provide for evaluating the efficiency of load management in hybrid power systems with the simultaneous participation of renewable energy sources, storage facilities, and small modular nuclear reactors. Approaches to optimal power balancing under stochastic generation conditions and methods for evaluating the effectiveness of AI-oriented control strategies remain insufficiently developed. This defines a scientific gap that makes it necessary to create an integrated load management model capable of ensuring regime stability, high energy efficiency and minimal carbon intensity (CO_2) in Ukraine's dynamic energy systems. The study aimed to quantify the potential of decarbonisation of the energy sector of Ukraine by scenario replacement of gas and coal-fired power plants with small modular nuclear reactors and renewable energy sources. The following tasks were defined to achieve this goal: analyse the degree of compliance of national approaches to emission assessment with international standards Intergovernmental Panel on Climate Change (IPCC), International Organisation for Standardisation (ISO), and European Union (EU) and determine their impact on the assessment of CO_2-intensity of Ukrainian energy generating technologies; conduct a quantitative comparison of the actual emissions of gas combined heat and power plants (CHPP), coal thermal power plants (TPP), nuclear power plants (NPP), and renewable energy sources and evaluate them potential contribution to the decarbonisation of the energy system; build a model of changes in total CO_2 emissions in various scenarios of transition from thermal generation to small modular nuclear reactors (MNR) and renewable energy sources and determine the integral decarbonisation effect of these technologies for Ukraine.

MATERIALS AND METHODS

The study was conducted in March-April 2025 and was based on a combination of regulatory analysis, technical-statistical assessment of energy generating facilities, and scenario modelling of changes in total CO_2 emissions in the energy sector of Ukraine during 2020–2024, which allowed for covering the period of significant structural changes in the energy system associated with the growth of the share of renewable energy sources, transformation of thermal generation operating modes, and adaptation to new regulatory requirements. The methodological approach was aimed at quantifying the decarbonising potential of replacing gas and coal-fired power plants with MNR and renewable energy sources, in compliance with the requirements of international standards in the field of greenhouse gas monitoring. In the first stage of the study, an analytical method was used, implemented through regulatory-comparative analysis of international standards and regulatory documents that determine the parameters for assessing the carbon intensity of energy-generating technologies. The IPCC guidelines (2006, 2019) were used to form basic calculated dependencies and typical specific emission coefficients (EF), which served as reference indicators for intertechnological comparison. ISO 14064-1:2018 (2018) provided regulation of the organisational level of accounting and traceability of emission data, while ISO 14044:2006 (2006) created a methodological framework for full life cycle assessment (LCA), enabling a clear distinction between the operational and infrastructure components of thermal, nuclear and renewable generation emissions. On the basis of these provisions, a coherent system of analytical indicators was formed – operational specific emissions (gCO_2/kWh), thermal efficiency (η), installed capacity utilisation factor (CUF), and LCA indicators, which were used to determine the regulatory ranges of CO_2 intensity for coal, gas, nuclear, and renewable technologies in a global comparative framework. Directive 2003/87/EC of the European Parliament and of the Council "On Establishing a Scheme for Greenhouse Gas Emission permission Trading within the Community" (2003), Regulation (EU) 2018/1999 of the European Parliament and of the Council "On the Governance of the Energy Union and Climate Action" (2018), and regulations of the European Commission (2021) provided the formation of a regulatory platform for identifying the requirements of the European Union Emissions Trading System (EU ETS), monitoring, reporting, and verification procedures (MRV), in addition to criteria for classifying technologies as low-carbon in accordance with the European taxonomy. The involvement of these documents allowed determining the parameters of potential compliance of Ukrainian generating facilities with the requirements of the European electricity market, forming a system of regulatory reference values, which was used for further quantitative comparisons and to assess the degree of integration of national generation into European decarbonisation mechanisms. During the second stage, a representative sample of power-generating facilities was formed, which included two gas-fired thermal power plants − CHPP-5 and CHPP-6 (Kyiv), three coal-fired thermal power plants − Ladyzhin, Trypillya, and Kryvyi Rih TPPs, along with Rivne, Khmelnitsky, and Pivdennoukrainsk NPPs.

For the Rivne NPP, the features of operation of the mixed fleet of water-water energetic reactor (VVER), in particular VVER-440 and VVER-1000 reactors, are considered. The inclusion criteria were the availability of complete statistical data for 2020–2024 and the stability of operating modes; objects with an incomplete reporting cycle were excluded. For RES, the average annual values of the installed capacity utilisation coefficients of solar and wind power plants (11–17% and 28–35%, respectively) were used, formed on the basis of aggregated statistical data on actual production and installed capacity for 2020–2024 according to the Ukrainian Wind Energy Association (UWEA) (2024).

Based on the collected characteristics, the actual CO_2 intensity ranges were determined: 750–1050 gCO_2/kWh for coal-fired thermal power plants, 380-510 gCO_2/kWh for gas-fired thermal power plants, 8–16 gCO_2/kWh for nuclear power plants, and promising MNRs (including LCA), 10–45 gCO_2/kWh for wind power, and 30–55 gCO_2/kWh for solar generation. The MNR parameters were determined on the basis of generalised technical-operational and LCA indicators (power, CUF, specific CO_2 emissions) given in the report of the International Atomic Energy Agency (2020), and were used as reference values in scenario analysis. Primary statistical data are obtained from open sources using documentary analysis and secondary statistical processing of official reports of Energoatom (2024), UkrEnergo (2026), National Commission for State Regulation in the Energy and Utilities Sectors (2025), and Market Operator (2025).

The third stage involved the construction of a mathematical model of changes in total emissions ΔEmissions – Delta Emissions (ΔEmissions) based on the annual electricity generation by individual technologies and the corresponding specific emission coefficients determined according to the IPCC methodology (2006, 2019) and ISO 14064-1:2018 (2018). The model was calculated using the following Equation 1:

$$\Delta Emissions = \sum(E_i \times EF_i)_{\{baseline\}} - \sum(E_i \times EF_i)_{\{scenario\}} \quad (1)$$

where: E_i – annual output of an individual technology in kWh, EF_i – specific emissions in gCO_2/kWh.

The assessment was performed for three scenarios: basic (preservation of the existing structure), transitional (replacement of 20–30% of thermal capacity), and low-carbon (replacement of more than 50% of gas and coal power plants). For each scenario, a sensitive analysis was performed, taking into account the seasonal variability of renewable energy sources, changes in CUF, the level of NPP load, and the projected operating modes of MNR. The variability of the output data was estimated at intervals of specific emission coefficients and long-term fluctuations in CUF for each process group in accordance with IPCC, ISO, and EU ETS, which ensured the correct determination of deviations between actual and regulatory values in different scenarios.

Statistical processing was performed in the Microsoft Excel 365 environment (Microsoft Corp., USA) using linear and multiple regression, in which integral CO_2 emissions were modelled as a function of the power generation structure. The validity of the model is estimated by confidence intervals and the p-level of statistical significance of α=0.05. During the fourth stage, a comparative analysis of international data was performed – International Energy Agency (2025), World Nuclear Association (2025), and information from the State Agency for Energy Efficiency (2025). This ensured that national indicators were aligned with global dynamics, and structural factors of changes in CO_2 intensity in Ukraine were identified. The combination of these methods provided a reproducible, statistically justified, and legally verified basis for analysing the efficiency of the transition from traditional thermal generation to low-carbon technologies and quantifying the possibilities of deep decarbonisation of the energy sector of Ukraine.

RESULTS

Regulatory parameters for estimating the CO_2 intensity of power-generating technologies

The analysis of international regulatory and methodological documents, in particular, the

IPCC guidelines (2006, 2019), the requirements of the ISO 14064-1:2018 Standard (2018), and the regulatory framework of the European Union in the field of monitoring and reporting on greenhouse gas emissions (Directive 2003/87/EC, 2003; European Commission, 2021; Regulation (EU) 2018/1999, 2018), allowed establishing that these approaches formed a complementary, although not identical, system for assessing the CO_2 intensity of energy generating technologies. The analysis demonstrated that the IPCC structure focused primarily on fuel and energy characteristics and the application of standard emission factors for different fuels, while ISO 14064-1:2018 – on the organisational level and detailed requirements for completeness, accuracy, and traceability of data. The EU regulations integrated into the EU ETS system (Directive 2003/87/EC, 2003) and the Fit for 55 package (Regulation (EU) 2018/1999, 2018) combine elements of both approaches and define mandatory monitoring, reporting, and verification (MRV) procedures within the market mechanism. A generalisation of the provisions of regulatory documents has shown that the common basis for all approaches is the use of specific emission coefficients (EF) as an integral parameter that characterises the volume of CO_2 per unit of electricity. However, they differ in the degree of their detail: the IPCC guidelines offer typical EF values, the ISO 14064-1:2018 standard requires maximum use of object-specific operator data, while the EU regulatory framework within the EU ETS and Regulation (EU) 2018/1999 (2018) provides for regular updating of coefficients based on actual operational parameters. Thus, the degree of variability of EF greatly depended on the adopted regulatory approach.

It was also established that thermal efficiency (η) and installed power utilisation factor (CUF) were considered key technical characteristics in all documents, but their functional purpose differed. In the IPCC guidelines, η affected the calculation of actual fuel costs, but was not defined as an independent regulatory parameter. In ISO 14064-1: 2018 (2018), the η and CUF indicators were considered as components of the organisational inventory of emissions, whereas in the EU regulatory system, they serve as criteria for compliance of technologies with taxonomy requirements and determine their status in the context of climate policy. In the context of Ukrainian energy, these indicators are reflected through the adaptation of national regulation to EU requirements. Analysis of approaches to life cycle assessment (LCA) determined that the greatest methodological differences occurred in this component. IPCC covered mainly operational emissions, ISO formed a complete LCA framework in accordance with ISO 14044:2006 (2006), and EU regulations include LCA as a mandatory element for a number of technologies, in particular, renewable energy and nuclear generation. The results indicate that for thermal generation (coal, gas), the inclusion of LCA changed the integral indicators insignificantly, while for nuclear power plants, MNR and renewable energy sources, the transition to full-life estimates had a substantial impact on the overall CO_2 intensity. It was also revealed that within the EU ETS, any deviation of actual emissions from declared ones without proper justification is accompanied by financial liability, which increases the importance of accounting accuracy and creates conditions for the integration of Ukrainian energy facilities into the European carbon market. A comparison of approaches showed that transparency and traceability of data have different functional status: IPCC formed the framework for public inventory, ISO – the internal accounting level, while the EU combines both levels in a regulatory model with economic execution mechanisms.

A systematic comparison of methods for estimating CO_2 intensity was conducted in accordance with the IPCC (2006, 2019), ISO 14064-1:2018 (2018), and EU standards (Table 1) to summarise the differences.

As presented in Table 1, the analysis demonstrated the consistency of approaches to the basic interpretation of specific emissions as an integral indicator for comparing energy technologies. The revealed discrepancies in the interpretation of LCA and the functional role of CFU formed different mechanisms of sensitivity to changes in the generation structure. Within the IPCC (2006, 2019), such changes were reflected mainly through EF adjustments, in ISO 14064-1:2018 – through refinement of internal energy efficiency and inventory parameters, and the European approach linked them to the regulatory status of the technology and the conditions of participation in the EU ETS. This combination of agreed and variable elements defined the methodological framework for further scenario calculations of the decarbonisation potential of the Ukrainian energy sector.

Summarising the regulatory data of the IPCC (2006, 2019), ISO 14064-1:2018 (2018), and EU

Table 1. Comparative characteristics of regulatory approaches to assessing the CO_2 intensity of energy technologies

Criterion	IPCC	ISO 14064-1:2018	EU (EU ETS, Fit for 55, MRV Regulation)
Purpose of the approach	National emission inventories, basic formulas for calculating CO_2	Organisational accounting and reporting of emissions	Regulatory control of emissions and market mechanisms (quotas, fines)
Type of emission coefficients (EF)	Standard EFs by fuel type and technology; typical values	EFs should be as object-specific as possible; the accuracy requirement	EFs are linked to actual operational data; regulatory-binding MRV procedures with penalties
Interpretation of thermal efficiency (η)	Is used indirectly – through fuel coefficients	Part of the energy efficiency inventory	Regulatory parameter for compliance with the EU taxonomy technology
Capacity Factor role	Is not a regulatory parameter	Can be used for organisational calculations	Is used as one of the parameters of technology classification within the European taxonomy and EU ETS regulatory criteria
Approach to LCA evaluation	Preferably operational emissions; LCA optional	Full LCA frame (ISO 14044)	For nuclear power plants and renewable energy sources, LCA must be accounted for in the taxonomy part
MRV – monitoring, reporting, and verification requirements	General framework; no financial liability	Internal organisation control, traceability	The strictest MRV level in the world; non-compliance penalties
Units of CO_2 intensity	gCO_2/ kWh, tCO_2/year	Any, depending on the size of the organisation	Standardised gCO_2/kWh for technology comparison
Scope of application	State inventories, climate policy scenarios	Companies, power generating facilities, industry	EU ETS participants, energy companies, regulated emission facilities
Features of application to the energy sector of Ukraine	Basic EF for thermal power plants; the need for adaptation	Provides a more accurate accounting structure for TPPs/CHPPs/NPPs	The European approach forms the criteria for entering the EU energy market

Note: Compiled by the authors based on IPCC (2006, 2019), ISO 14064-1:2018 (2018), Directive 2003/87/EC (2003), Regulation (EU) 2018/1999 (2018), European Commission (2021), Energoatom (2024), UkrEnergo (2026), National Commission for State Regulation in the Energy and Utilities Sectors (2025), and Market Operator (2025).

regulatory acts allowed establishing that these approaches formed a common methodological field for estimating CO_2 intensity and determined structured ranges of acceptable values for various energy-generating technologies. A comparison of these ranges clarified differences between the technology groups: coal-fired and gas-fired power plants were characterised by the highest regulatory values, while nuclear generation, small modular reactors, and renewable sources had lower CO_2 intensity indicators. This ratio of regulatory limits outlined the potential role of individual technological groups in the formation of a low-carbon energy balance.

A comparative visualisation is constructed that summarises the standard values given in the relevant international sources to visually display the detected CO_2 intensity ranges (Figure 1).

Source: calculated by the authors based on International Atomic Energy Agency (2020), Energoatom (2024), UkrEnergo (2026), National Commission for State Regulation in the Energy and Utilities Sectors (2025), Market Operator (2025), and International Energy Agency (2025)

As shown in Figure 1, the normative values of CO_2 intensity formed a stratified structure. Coal generation exceeded 900–1100 gCO_2/kWh, forming the highest range. Gas-fired power plants had indicators of mainly 350–500 gCO_2/kWh, which in the EU documents under EU ETS and Regulation (EU) 2018/1999 (2018) belongs to the category of "transitional" technologies. Nuclear power generation, including small modular reactors, was in the range of 5–20 gCO_2/kWh, depending on the fuel cycle. LCA levels for renewable sources were 10–40 gCO_2/kWh, with lower values for wind and higher values for solar technology. Comparative analysis confirmed a stable order of ranking technologies in various methodological systems: coal→gas→RES and nuclear generation (including MNR). This demonstrated the consistency of regulatory approaches and the possibility of their application as an analytical basis for strategic planning of decarbonisation. The data obtained also showed that even the optimised values of thermal technologies significantly differed from the levels typical for nuclear and renewable energy, which determined different scenarios for

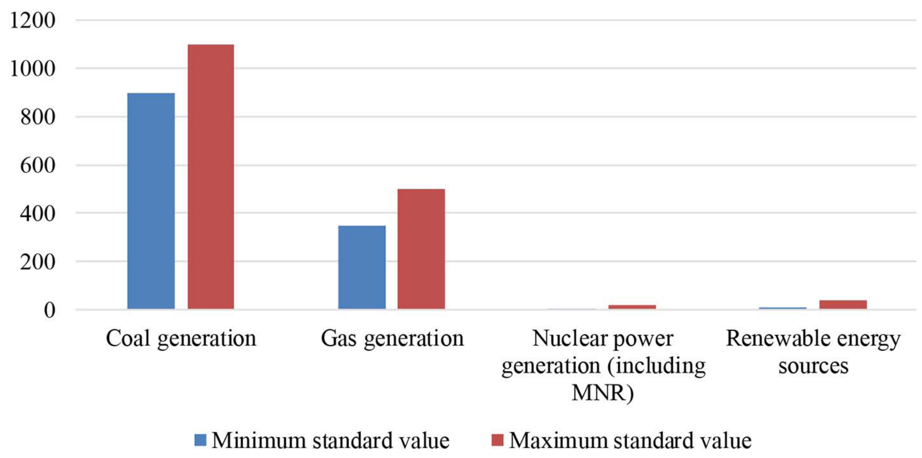

Figure 1. Regulatory CO_2 emission ranges for coal, gas, nuclear (including MNR), and renewable energy generating technologies. These intervals reflect generalised regulatory and methodological estimates, not the results of direct operational measurements of individual power-generating facilities

their involvement in the low-carbon transition. The results confirmed that the regulatory levels of CO_2 intensity for nuclear generation and RES formed the basis for assessing their potential contribution to the achievement of the Fit for 55 goals and other EU strategic frameworks, while thermal technologies, especially coal-fired ones, maintained significantly higher performance in all analysed systems.

Actual emissions and technical and operational parameters of Ukrainian TPPs, CHPPs, and NPPs

Analysis of the technical condition of Ukrainian generating facilities showed a significant heterogeneity of their operational characteristics, which directly affected the structure of CO_2 emissions and formed the initial conditions for decarbonisation scenarios. Within the sample, the parameters of two gas thermal power plants (Kyiv CHPP-5 and CHPP-6), three coal-fired thermal power plants (Ladyzhin, Trypillya, and Kryvyi Rih TPPs), and three nuclear power plants of Ukraine – Rivne, Khmelnitsky, and Pivdennoukrainsk NPPs operating VVER-440 and VVER-1000 power units were summarised. The obtained data helped establish the characteristic load profiles of equipment, thermal efficiency ranges, and actual installed power utilisation coefficients (CUF), which are the determining parameters for estimating CO_2 intensity. Comparison of technical characteristics showed that gas-fired thermal power plants show relatively stable, although lower, CUF values compared to nuclear power plants, which is due to their role in covering peak and intermediate loads. Coal-fired thermal power plants, despite potentially acceptable values of thermal efficiency in individual upgraded units, are characterised by significant technological limitations associated with physical wear of equipment, uneven loading, and a high proportion of downtime (Naumenkova et al., 2024; Redko et al., 2021). In turn, nuclear power plants are characterised by a stable basic mode of operation and a high level of load, which confirms their system-forming role in the national energy balance. The technical-operational parameters of the selected CHPP, TPP, and NPP of Ukraine are summarised to form a representative calculation base (Table 2).

Source: calculated by the authors based on International Atomic Energy Agency (2020), Energoatom (2024), UkrEnergo (2026), National Commission for State Regulation in the Energy and Utilities Sectors (2025), Market Operator (2025), and International Energy Agency (2025).

As can be seen from Table 2, thermal power plants show substantial variability in thermal efficiency – from outdated units with low efficiency to upgraded units capable of operating in optimised modes. The wide range of CUF changes characteristic of TPPs and CHPPs reflects uneven load and demand dependence, which limits their potential in the context of reducing the specific CO_2 intensity. Nuclear power units, for which thermal efficiency was not analysed in this study, instead demonstrated consistently high values of installed capacity utilisation coefficients and uniform operational parameters, which strongly affected the overall structural carbon intensity of

Table 2. Technical parameters of the Kyiv CHPP-5, CHPP-6, Ladyzhin, Trypillya, and Kryvyi Rih TPPs, Rivne, Khmelnitsky, and Pivdennoukrainsk NPPs

Energy facility	Generation type	Rated power, MW	Efficiency (thermal efficiency), %	Capacity factor, %	Fuel/reactor type
Kyiv CHPP-5	Gas CHPP	700	44–46	35–42	Natural gas
Kyiv CHPP-6	Gas CHPP	500	42–45	33–40	Natural gas
Ladyzhin TPP	Coal-fired TPP	1800	30–33	45–60	Coal
Trypillia TPP	Coal-fired TPP	1800	32–34	40–55	Coal
Kryvyi Rih TPP	Coal-fired TPP	2800	30–33	45–60	Coal
Rivne NPP (RNPP)	Nuclear power plant	2835	—	75–85	VVER-440, VVER-1000
Khmelnytskyi NPP (KHNPP)	Nuclear power plant	2000	—	8090	VVER-1000
Pivdennoukrainsk NPP	Nuclear power plant	3000	—	82–90	VVER-1000
MNR (reference, IAEA)	Atomic Energy (MNR)	300 (conditional)	—	85–95	SMR / iPWR

Note: the dash (—) in the "efficiency" column for nuclear power plants and small modular reactors means that the indicator is not used in the study since the CO_2 intensity estimate for nuclear generation is based on life cycle indicators (LCA), and not on direct thermal characteristics. The MNR parameters are given as reference parameters in accordance with the materials of the International Energy Agency.

the power system and confirmed the role of nuclear power plants as the basis of the base load in the low-carbon generation architecture. Based on the available statistical data on the actual annual output and the structure of fuel consumed, specific CO_2 emissions for each type of generation were determined, which allowed forming an integral estimate of the real carbon load of the power system. A comparative visualisation of specific CO_2 emissions is constructed to visually display the obtained values (Figure 2).

As shown in Figure 2, actual specific CO_2 emissions are characterised by a clearly differentiated distribution by generation technology types, in which thermal power plants are concentrated in the upper range of values, while nuclear, reference modular, and renewable generation have lower carbon intensity indicators. Coal-fired power plants are characterised by specific CO_2 emissions in the range of 820–1100 gCO_2/kWh. The recorded values are associated with a combination of low efficiency, high level of equipment wear, uneven loading and a significant share of work in peak modes, which leads to an increased specific carbon intensity even in conditions of partial modernisation of individual power units. Gas-fired thermal power plants and thermal power plants are characterised by lower specific

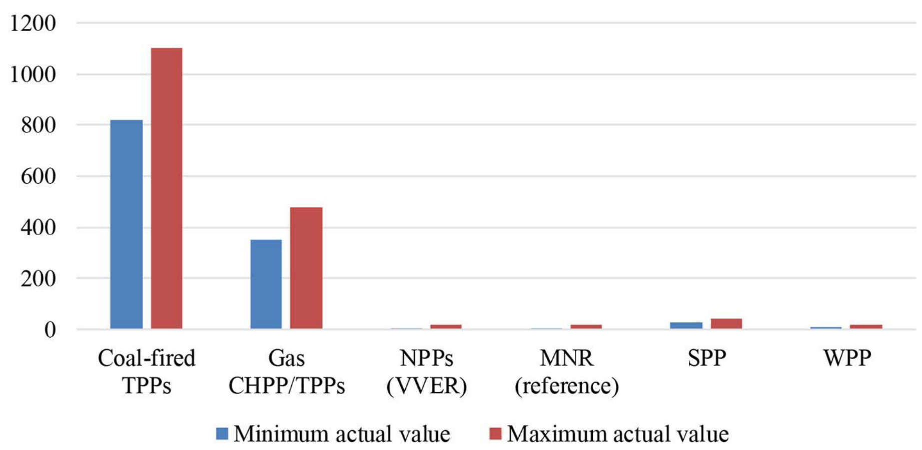

Figure 2. Comparison of actual specific CO_2 emissions from Ukrainian TPPs, CHPPs, NPPs, and RES. Compiled by the authors based on International Atomic Energy Agency (2020), Energoatom (2024), UkrEnergo (2026), National Commission for State Regulation in the Energy and Utilities Sectors (2025), Market Operator (2025), and International Energy Agency (2025)

CO_2 emissions compared to coal, which are in the range of approximately 350–480 gCO_2/kWh (Iskandarov, 2021). However, their combined contribution to the overall emission balance is due to the operating modes of manoeuvrable and peak generation. Frequent starts, stops, and operation under partial load conditions are accompanied by a decrease in energy efficiency, which is reflected in an increase in the average specific CO_2 intensity of gas generation (Sydorets et al., 2017; Panchenko et al., 2019). Ukrainian nuclear power plants and reference small modular reactors show specific CO_2 emissions below 20 gCO_2/kWh, which is consistent with the results of LCA estimates for VVER-type reactors and modern iPWR. High values of the installed capacity utilisation factor and limited sensitivity to daily and seasonal load fluctuations ensure a stable output profile, leading to low variability of CO_2 intensity indicators over time (Huseynov et al., 2021; 2025).

These characteristics are accounted for when forming assumptions in the scenarios for achieving the Fit for 55 climate goals. Renewable energy sources are characterised by low values of specific CO_2 emissions: for solar generation, they are 30–40 gCO_2/kWh, for wind generation – 10–20 gCO_2/kWh. The differences are due to the specifics of the life cycle structure, material consumption, and infrastructure characteristics of the corresponding technologies. Despite dependence on weather conditions and limited participation in ensuring the current structural reliability of the power system, the CO_2 intensity of renewable generation remains notably lower than the values typical for thermal power plants. The totality of the results obtained showed that thermal power plants form the largest contribution to the total emissions of the power system, while nuclear power plants and MNR provide the lowest CO_2 intensity values under conditions of a stable production profile. These characteristics determine their role in modelling three transition scenarios – basic, transitional, and low-carbon.

Model for estimating changes in total CO_2 emissions

The developed ΔEmissions model for estimating changes in total CO_2 emissions allowed quantifying the impact of various decarbonisation scenarios on the carbon balance of the Ukrainian energy system. The application of the model ensured the integration of the actual technical-operational parameters of Ukrainian TPPs, CHPPs, and NPPs with the standard ranges of specific emission coefficients used in international practice. Based on a comparison of annual electricity generation from thermal (coal and gas), nuclear, and renewable sources, along with the reference MNRs with corresponding specific emission coefficients (EF), it was determined that partial replacement of thermal generation at the level of 20–30% provided a reduction in total CO_2 emissions in the range of 18–27%, depending on the replacement structure and installed capacity utilisation rates. The use of the model provided for obtaining indicative quantitative results that reflected the sensitivity of total emissions to changes in the share of individual technologies in the generation structure. The most representative example was the replacement of 1000 GWh of coal generation with equivalent MNR output: at specific coefficients of 820 and 12 gCO_2/kWh, the difference was about 808 thousand tonnes of CO_2. This value was consistent with the ranges given in the materials of the IPCC (2006, 2019), and confirmed the vast potential for reducing emissions during the transition from coal-fired technologies to low-carbon nuclear generation, even in conditions of limited replacement volumes. In addition, it was established that the installed capacity utilisation factor significantly affected the final emissions: stable CUF of nuclear generation and seasonal deviations in renewable energy production increased the contrast between technological groups. Table 3 illustrates a basic example of calculating the reduction in emissions when replacing coal-fired generation with MNR capacities.

As can be seen from Table 3, replacing coal generation with equivalent MNR output provides a reduction of almost 808 thousand tonnes of CO_2, which confirms the high efficiency of small modular nuclear technology in scenarios of structural transformation of the energy balance. The specific emission values obtained for coal-fired power plants (750–1050 gCO_2/kWh) are consistent with the standard range defined in the IPCC materials, which confirms the reliability of the calculated EFS and the correctness of their further interpretation in the ΔEmissions model. The results obtained also indicated that the intensity of emissions is determined not only by the absolute values of specific coefficients but also by the structure of output. In particular, estimates showed that a 10% increase in the share of nuclear generation within the model reduces integral

Table 3. Calculation of the total CO_2 emissions reduction when replacing 1000 GWh of coal generation with MNR

Technology	EF (gCO_2/kWh)	Energy (GWh)	Emissions (kt CO_2)
Coal	820	1000	820
MMR	12	1000	12

Note: calculated by the authors based on International Atomic Energy Agency (2020), Energoatom (2024), UkrEnergo (2026), National Commission for State Regulation in the Energy and Utilities Sectors (2025), Market Operator (2025), and International Energy Agency (2025).

emissions by about 6.5%, while a similar increase in the share of renewable energy sources forms an effect in the range of 4–5%, depending on seasonal variability and power utilisation factors. Gas-fired CHPPs demonstrate an intermediate result: their partial replacement with MNR provides a smaller effect compared to the withdrawal of coal-fired capacities, but twice the efficiency of increasing the share of renewable energy in the inter-peak intervals.

Three scenarios were analysed for an integral assessment of the impact of structural changes on annual CO_2 emissions: basic, transitional, and low-carbon. The results show that the degree of thermal power substitution directly determines the scale of the systemic decarbonisation effect. In the basic scenario, which reflects the preservation of the current generation structure without significant technological transformations, total emissions remain consistently high due to the dominance of coal and gas power plants with lower efficiency values and a wider range of specific EF. In the transitional scenario, which provides for the replacement of 20–30% of thermal capacity by MNR and renewable energy generating units, a reduction in total emissions by an average of 18–27% was recorded. Even partial removal of coal plants provides a marked reduction in CO_2 intensity, as coal technologies result in the highest specific emissions and form the largest part of the systemic carbon profile (Hussain et al., 2022; Iskandarov, 2024). The obtained values are consistent with the EF regulatory limits for different generation types set by IPCC (2006, 2019), ISO 14064-1:2018 (2018), and Directive 2003/87/EC (2003). The most pronounced decarbonisation effect is obtained in the low-carbon scenario, where more than 50% of the country's total thermal capacity is replaced. The reduction in emissions exceeds 45%, which is consistent with the target trajectory of the Fit for 55 package and demonstrates the ability of MNR to act as a basic stabiliser of the power system, compensating for seasonal and weather fluctuations in renewable energy production. The stability of the production characteristics of MNR is confirmed by the reference parameters given by the International Atomic Energy Agency (2020) and the World Nuclear Association (2025).

A comparative graphical interpretation is constructed to visually represent the dynamics of the impact of different scenarios on the volume of annual CO_2 emissions (Figure 3).

A graphical comparison (Figure 3) confirmed that the substitution structure is a key parameter of decarbonisation efficiency: the maximum effect is achieved in the case of priority extraction of coal capacities, while the replacement of gas technologies gives a less pronounced but systemically important result. In addition, it was determined that with an increase in the share of low-carbon generation to 60% or more, there is a transition to accelerated emission reduction, when the cumulative effect becomes the dominant factor in the overall carbon intensity. The totality of the results

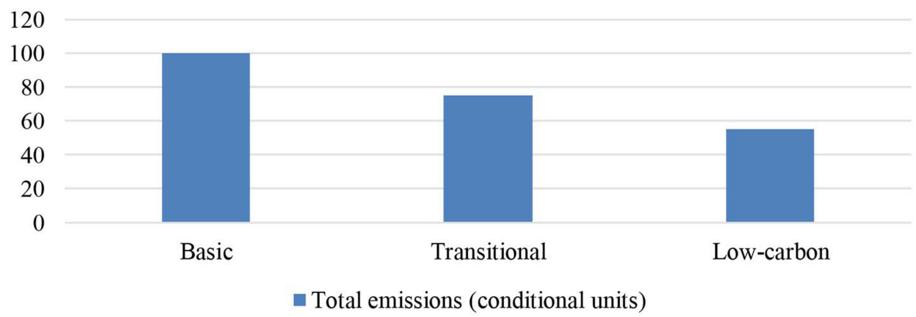

Figure 3. Comparison of three transition scenarios. Calculated by the authors based on International Atomic Energy Agency (2020), Energoatom (2024), UkrEnergo (2026), National Commission for State Regulation in the Energy and Utilities Sectors (2025), Market Operator (2025), and International Energy Agency (2025)

obtained indicates the nonlinear nature of the transition to low-carbon energy: with an increase in the share of nuclear generation and renewable energy, the efficiency of reducing emissions increases, and the sensitivity of the system to peak fluctuations decreases. This determines the prospects of MNR and renewable energy sources as the main technological components of Ukraine's long-term decarbonisation strategy and its integration into the European energy space.

Statistical and trend analysis of international and national data

The analysis of generalised statistical data provided by the IPCC (2006, 2019) and the World Nuclear Association (2025) clarified the main patterns of changes in global and national CO_2 emissions in 2018-2024. Globally, the growth rate of energy emissions slowed during this period: according to the IEA, the average annual growth rate decreased from 1.8–2.0% in 2018–2019 to below 1% after 2021, and in 2023–2024, the dynamics approached a plateau (International Energy Agency, 2025). This trend was accompanied by a steady increase in the share of low-carbon technologies – renewable and nuclear energy, the total contribution of which to global electricity production in 2024 exceeded 39–40% according to the International Energy Agency (2025) and the World Nuclear Association (2025). The national dynamics of Ukraine in 2018–2024 were characterised by greater variability, but remained structurally consistent with global trends in the technological distribution of generation. The analysis showed that the specific indicators of CO_2 intensity formed clearly differentiated intervals depending on the type of generation: nuclear power showed the lowest values (5–20 gCO_2/kWh), while coal and gas power plants were characterised by significantly higher and more variable indicators – 750–1050 gCO_2/kWh and 350–500 gCO_2/kWh, respectively. The obtained ranges are consistent with the standard emission coefficients given in the IPCC guidelines (2006, 2019) and correspond to the calculated logic of the ΔEmissions model based on the comparison of actual output and specific EF for individual technologies. In 2018–2021, the dynamics of Ukrainian emissions were close to European and were accompanied by a gradual decrease in the specific CO_2 intensity, which correlated with the growing role of nuclear generation and the expansion of the share of renewable energy sources.

Since 2022, there has been a deviation from this trend due to military factors, reduced power consumption, and uneven operating modes of thermal generation. Such changes led to increased variability in CO_2 emissions, which distinguished national dynamics from global ones, which were dominated by more stable processes of reducing carbon intensity. The comparative analysis revealed that Ukraine's medium-term trends were consistent with global processes, particularly in terms of an increase in nuclear power generation and a rise in the share of renewable energy sources globally. Ukrainian indicators were influenced by both internal structural restrictions related to the flexibility of thermal generation and dependence on peak gas capacities, along with external factors – transformation of energy infrastructure as a result of military operations, changes in the balance of electricity exports and imports, and restrictions on the operation of individual generating units. A comparative visualisation of the dynamics of CO_2 emissions in the world and in Ukraine was constructed to visually represent certain trends (Figure 4).

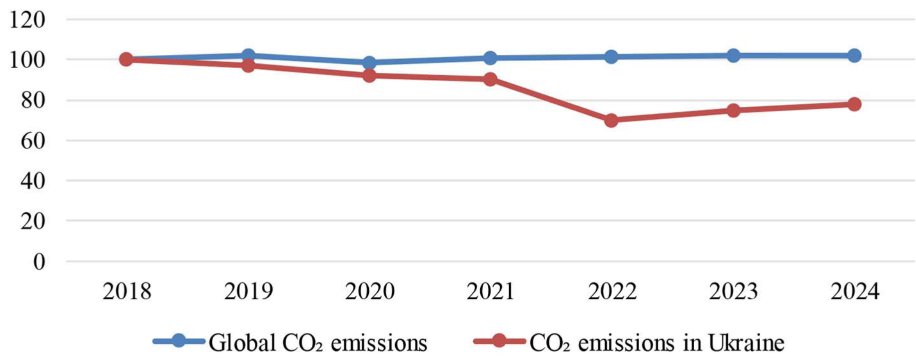

Figure 4. Dynamics of global and Ukrainian CO_2 emissions (2018–2024). Calculated by the authors based on [20–25]

As shown in Figure 4, the global trend was characterised by a gradual slowdown in the growth rate of CO_2 emissions, while the Ukrainian curve was undulating in nature with a sharp decline in 2022 and a subsequent partial equalisation. It was determined that the main differences between the global and Ukrainian trajectories reflected the structural features of the national energy balance: the share of thermal generation in Ukraine remained relatively high in 2023–2024, which limited the rate of reduction in specific emissions. Additionally, the dynamics were influenced by fluctuations in infrastructure operation, increased manoeuvring of gas-fired thermal power plants, and uneven renewable energy production, which formed variable volumes of CO_2 emissions during peak periods. The results showed that, despite the general correlation between Ukrainian and global dynamics, the specifics of Ukrainian trends were determined mainly by system and infrastructure factors. Considering these characteristics, the potential role of MNR and RES as technological directions that could provide more stable trajectories for reducing emissions under conditions of transformation of the generation structure was determined. The analysis of changes in the structure of electricity production in Ukraine allowed identifying the key stages of the transition to a low-carbon model and assessing the contribution of individual technological groups to the formation of the total CO_2 intensity.

During the study period, there was a consistent reduction in thermal generation, an increase in the share of renewable energy sources, and a stable preservation of the role of nuclear power as a basic power source. The results of these changes are summarised in Table 4.

As shown in Table 4, the structure of the Ukrainian energy balance has undergone significant changes during the analysed period. The share of nuclear generation remained consistently dominant and fluctuated between 51–60%, providing the main volume of low-carbon production. The share of coal-fired thermal power plants decreased from 30% in 2018 to approximately 14% in 2024, but their contribution to CO_2 emissions remained disproportionately high due to lower efficiency and uneven operating modes. The increased load on gas-fired CHPPs during peak periods was accompanied by an increase in their contribution to total CO_2 emissions, although the specific indicators for this type of generation remained lower than those of coal-fired ones. Such dynamics reflect their role as shunting power and explain periodic fluctuations in the carbon intensity of the energy balance under conditions of load instability and weather restrictions for renewable energy sources. Renewable sources maintained positive development dynamics, although after 2022, the growth rate slowed due to infrastructure damage and restrictions on connecting new facilities. Even with a moderate increase in the share of RES, their contribution helped to reduce the average CO_2 intensity of the energy balance. Generalisation of the results obtained displayed that the combination of a stable share of nuclear generation and a gradual increase in output from renewable sources formed a tendency to reduce the carbon intensity of the national energy balance. The increased load on gas CHPPs and the

Table 4. Changes in the structure of electricity production in Ukraine, 2018–2024

Year	NPP	TPP (coal)	CHPP (gas)	RES (SES+WPP)	Other
2018	53%	30%	8%	7%	2%
2019	55%	27%	9%	8%	1%
2020	51%	25%	10%	12%	2%
2021	55%	23%	7%	13%	2%
2022	60%	18%	11%	9%	2%
2023	58%	15%	15%	10%	2%
2024*	57%	14%	17%	10%	2%

Note: Data for 2024 is presented as preliminary since, at the time of sampling, complete electricity production figures and verified CO_2 balances for all types of generation were in the process of being officially approved and published in open statistical sources. The final values for 2024 are published with a time lag of 9–12 months after the end of the reporting period, which corresponds to the international practice of energy and climate statistics. Calculated by the authors based on International Atomic Energy Agency (2020), Energoatom (2024), UkrEnergo (2026), National Commission for State Regulation in the Energy and Utilities Sectors (2025), Market Operator (2025), and International Energy Agency (2025).

presence of a residual segment of coal generation kept the system's emissions at the highest level, which justified the need for scenario transitions with a differentiated degree of replacement of thermal technologies.

Integral assessment of the decarbonisation potential of MNR and RES

The analysis of actual emissions, regulatory parameters of CO_2 intensity, and structural features of the Ukrainian energy balance enabled the assessment of the comparative contribution of different types of generation to the formation of decarbonisation potential in the medium and long term. Summarising the results obtained made it clear that the greatest contribution to reducing total emissions was provided by technologies with low specific CO_2 intensity and a stable output structure. This group included nuclear power, including small modular reactors (MNR), and renewable energy sources (RES). Data were summarised to determine the overall impact of technology groups on total CO_2 emissions for three transition scenarios – basic, transitional, and low-carbon. The comparative analysis showed that the greatest reduction in emissions was due to the gradual decommissioning of coal-fired units, modernisation of gas-fired CHPPs with partial replacement of their output with renewable energy sources, and the introduction of MNR to cover basic loads. According to the results obtained, the average decarbonisation effect of MNR administration corresponded to the difference between the specific emissions of thermal generation (750–1050 gCO_2/kWh) and the operational emissions of nuclear units (≈12 gCO_2/kWh), which provided a reduction of 730–1035 gCO_2/kWh with equivalent replacement of output. This was due to low operating emissions and stable operating modes, which reduced the need for peak gas generation. Based on the reference data of the International Atomic Energy Agency (2020), in particular, on the ranges of installed capacity utilisation factors, base load modes, and estimates of operational and full-life CO_2 emissions for SMR technologies, the inclusion of small modular reactors in the generation structure contributed to compensating for fluctuations in renewable energy sources without significantly increasing systemic CO_2 emissions.

Renewable energy sources provided a reduction in emissions in the range of 730–1.050 gCO_2/kWh for the replacement of coal generation and 330–540 gCO_2/kWh for the replacement of gas-fired thermal power plants, which reflected the difference in specific emission coefficients between technological groups (Vincevica-Gaile et al., 2022; Iurchenko et al., 2024). Therewith, their integral contribution depended on the coefficients of installed capacity utilisation and the availability of balancing capacities. In scenarios with a RES share of more than 35%, a major part of the reduction in emissions was achieved only if there was a stable base source; this function could be performed by MNR or traditional nuclear power plants. Reduced thermal generation remained a key factor in decarbonisation. In the transitional scenario, replacing 20–30% of thermal capacity corresponded to a reduction in emissions by 18–27%, while in the low-carbon scenario, replacing 50% or more – by more than 45%. This highlighted the importance of the generation structure for achieving climate policy targets, in particular, the provisions of the European Commission (2021). An integral visualisation (Figure 5) was compiled to visually represent the comparative contribution of technology groups, which reflects the proportional impact of MNR, NPPs, RES, and reduced thermal generation on the overall reduction of CO_2 emissions.

According to the graphical interpretation (Figure 5), the main contribution to the reduction of total emissions was due to the gradual decommissioning of coal generation, while MNR and RES created a cumulative low-carbon effect, which ensured the stabilisation of the system under conditions of minimal operational emissions. Nuclear power plants continued to serve as a stabilising technology with the lowest specific CO_2 intensity among scalable generation solutions. The results obtained showed that MNR and RES were complementary in nature, forming an integrated model of a low-carbon power system. MNRs provided a stable base load with low operating emissions and a high level of manageability, while RES contributed to a decrease in the average CO_2 intensity in variable operating modes of the power system. Analysis of system effects indicated that the lowest ejection rates were achieved in configurations where MNRs served as base and partially half-peak capacities, compensating for fluctuations in solar and wind generation. Under such conditions, dependence on gas-fired thermal power plants was reduced during peak periods, along with the need for redundancy of thermal units, which generated additional emissions. Generalisation of scenario models confirmed that the combined structure of

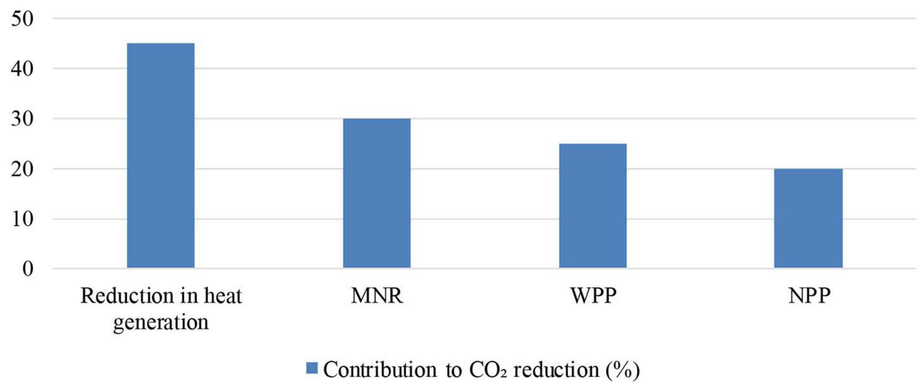

Figure 5. Contribution of MNR, NPPs, RES, and reduced thermal generation to decreasing total CO_2 emissions

"MNR+RES+NPP" provided the lowest level of CO_2 intensity among the considered options. The calculated values showed the possibility of achieving indicators at the level of 100-120 gCO_2/kWh, which corresponded to the parameters defined in the EU climate strategies and benchmarks for achieving climate neutrality by 2050.

Thus, the integral assessment showed that the interaction of MNR and RES formed a decarbonisation configuration, in which MNR provided stability and low-carbon base output, and RES created a flexible low-carbon segment that reduced dependence on thermal generation. Together, these characteristics formed the preconditions for a long-term transition to a sustainable and technologically flexible energy system with low CO_2 intensity.

DISCUSSION

The results obtained demonstrate that the decarbonisation effect of transformation of the Ukrainian energy system is determined not only by the specific characteristics of individual generation technologies, but above all by their ability to form stable and predictable system interactions in conditions of rapid changes in the production structure. The dynamics of CO_2 intensity confirm that the replacement of thermal power plants with low-carbon sources causes nonlinear shifts in the carbon profile, especially pronounced in conditions of increasing the share of renewable energy sources (Paton et al., 2005; Voloshina et al., 2021). This effect is fully consistent with the findings of Asiri et al. (2024), stating that systems with stochastic generation require a stable base power capable of damping peak loads and reducing the amplitude of fluctuations, since the absence of such an element leads to an increase in the frequency of uneven modes and an increase in the need for shunting resources. Similar patterns are described by Choudhary (2023), who notes that an increase in the proportion of RES in the absence of a low-cost component both increases short-term fluctuations and complicates predicting the behaviour of the system, which forms structural constraints to further reduce emissions. The agreement of these provisions with the simulation results shows that key system effects occur at the level of interaction of generation groups, where the combination of sources with different stability characteristics determines the overall dynamics of CO_2 intensity, while the influence of individual installations or their specific coefficients is less significant compared to the effects of structural configuration. An additional structural relationship can be traced to conclusions drawn by Olodu et al. (2025), stressing that the behaviour of hybrid systems largely depends on the availability of technologies with a predictable output profile, as such elements ensure the stability of modes during periods of variable load. An analysis of the results obtained in the ΔEmissions model shows a similar trend: the inclusion of MNR in generation reduces the variability of CO_2 intensity, which is consistent with the approach to optimising the structure of hybrid power systems and reflects the influence of sustainable sources on the overall behaviour of the system. A paper of Hoummadi et al. (2025) displays that power flow control algorithms show higher efficiency in networks with an element with low sensitivity to short-term disturbances, which creates conditions for a more even load distribution. The example of MNR in scenario calculations demonstrates a similar property: maintaining a stable operating mode reduces the impact of non-synchronicity between demand and output and forms a more predictable system profile.

Onteru and Sandeep (2024) point out the importance of stability of technical and operational parameters in the processes of smoothing load fluctuations since such characteristics determine the possibility of generation to maintain uniformity of modes with variable consumption profiles. Comparison of these provisions with data on the behaviour of coal, gas, nuclear power plants, and MNR shows that low-carbon technologies with high power utilisation factors lower the volume of peak imbalances, forming more predictable operating modes. A study by Aslam et al. (2021) also confirms the dependence of the RES system operation on compensatory mechanisms that ensure the equalisation of vibrations and reduce the need for intensive manoeuvring, which is consistent with the scenario in which MNRs perform the function of such an element. In the ΔEmissions model, the correspondence between the proportion of low-carbon generation and the rate of reduction of CO_2 intensity is formed according to a similar principle, reflecting the influence of structural configuration on the overall dynamics of emissions (Tagybayev et al., 2023; Marignetti et al., 2023). A generalisation of Quiñones et al. (2023) demonstrates that the accuracy of predictive models affects the amplitude of imbalances in systems with a high proportion of RES, as it is the errors of short-term forecasts that determine the scale of corrective interventions in generation modes. A similar conclusion is outlined by Wazirali et al. (2023), describing the dependence of the structural stability of microsystems on the ability of the system to respond to predicted load changes and maintain regime parameters within acceptable fluctuations. Kondaiah et al. (2022) clarify the role of peak loads: limiting their frequency and magnitude minimises the need to involve thermal installations for balancing, which correlates with the obtained scenarios, where reducing the share of coal generation reduces specific emissions even if the functional contribution of gas CHPPs to covering intermediate modes is preserved. The analysis of the optimisation properties recorded in the ΔEmissions model shows agreement with the approaches of Faraji et al. (2020), where the stability of the output of individual generating units increases the efficiency of load distribution algorithms since the intended operation profile simplifies parameterisation of optimisation problems. In the MNR implementation scenario, a similar effect is observed: the uniformity of output compensates fluctuations between supply and demand, ensuring smoother transients in the generation structure. Analysis of the optimisation properties recorded in the ΔEmissions model, and the position of Li and Wang (2021) indicate that hybrid configurations with basic generation form a balanced energy flow profile, which correlates with the trends of structural alignment obtained in the study after a decrease in the share of thermal technologies and the transition to low-carbon sources. Conclusions made by Biswal et al. (2024) allow interpreting the recorded effect of accelerated reduction of CO_2 after reaching a certain threshold of thermal capacity substitution, since similar transitions are described in international reviews as a consequence of changes in the load structure and optimisation of modes in networks with a high proportion of low-carbon technologies. System interpretations of Uddin et al. (2023) nature of output, where the aggregate regime is formed not by individual technologies, but by their ability to maintain consistent energy flows. The ΔEmissions model demonstrates a similar logic: the presence of a constant low-carbon base creates conditions for more efficient operation of renewable energy sources since a stable segment reduces the need for frequent corrections of balancing capacities. Conclusions of Kassab et al. (2024) confirm that the combination of PV with sources that provide a constant level of output creates configurations in which the load on shunting installations is reduced and the consistency of power flows is increased. Agreement with the simulation results is manifested in a decrease in the need for thermal peak capacities after an increase in the share of low-carbon generation.

A study by Ahmad et al. (2023) demonstrates that the integration of control and prediction systems in low-carbon configurations contributes to the formation of modes with less variability and a more predictable load profile, which corresponds to the structural behaviour of CO_2 intensity recorded in the studied scenarios. An analysis of the literature on MNRs shows a clear relationship between their technical characteristics and the structural results of the ΔEmissions model. In the study by Mazauric et al. (2022), the operating conditions of nuclear installations in networks with a high proportion of renewable energy sources are described, where the ability of the reactor to operate in a wide range of modes compensates for uneven production and maintains the consistency of energy flows. The correlation of these positions with the obtained calculations shows that the inclusion of MNR in the generation structure is accompanied by a smoother dynamics of CO_2 intensity, since the reactors provide a stable level of base output even under variable load conditions. The publication of Lee (2024) is devoted to the analysis of MNR stability and manageability features, including partial load modes, which are important for interpreting the results of scenario analysis. Comparison of these characteristics with the behaviour of the CO_2 profile in the model demonstrates that an increase in the proportion of MNR correlates with a decrease in the amplitude of structural vibrations and forms a tendency to a more uniform decrease in integral ejection. This comparison allows considering MNR as an element that ensures the stability of the system in configurations with partial or substantial removal of thermal technologies. A study by Tan et al. (2023) focused on the role of MNR in future energy markets, especially in systems with RES dominance and increased balancing requirements. Comparing these positions with the results of scenario modelling shows that the configurations in which MNRs are integrated together with traditional nuclear power plants and renewable sources form the most predictable output structure and stable CO_2-intensity trajectories. These results are consistent with the properties of MNRs described in the literature as sources capable of supporting basic and semi-peak operating modes, which ensures their constructive role in low-carbon energy systems.

Systematisation of the established comparisons shows that the structural interaction of MNR, NPPs, RES, and residual heat capacities results in a complex emission effect, which is manifested in a decrease in the integral CO_2 intensity and the amplitude of regime fluctuations and stabilisation of the generation profile. The obtained dependences demonstrate that the key parameters of decarbonisation – the intensity of changes in ΔEmissions, the variability of the CO_2 profile, and the sensitivity of the system to peak loads – are determined not by individual technologies, but by the configuration properties of the power system (Kravets et al., 2025, Kapustianskyi et al., 2026). The consistency of the identified structural patterns with the results of international studies shows the universal nature of low-carbon stabilisation mechanisms: MNRs provide an inertial damping effect and form a stable basic level of output; nuclear power plants maintain low CO_2 – intensity variability in medium- and long-term modes; renewable energy sources create a flexible generation segment with reduced specific emissions; lowering the share of thermal power plants and thermal power plants minimises the frequency of peak imbalances and the need for reserve high-carbon capacities. The combination of these mechanisms forms an integrated mode circuit, in which a decrease in the structural dependence on thermal generation correlates with a steady drop in CO_2 intensity. The results show that configurations with an increased proportion of MNR and RES reproduce the parameters described in the international literature as characteristic of low-carbon power systems: a decrease in ΔEmissions during the replacement of coal blocks, stabilisation of modes due to inertial nuclear technologies, and the formation of more uniform output structures in scenarios with a share of low-carbon sources of more than 50%. In this combination, a system configuration is formed that meets the principles of decarbonisation models of highly developed energy markets and outlines the practical potential for further transformation of the Ukrainian energy system in the direction of long-term reduction of CO_2 intensity.

CONCLUSIONS

The study allowed for a comprehensive assessment of the decarbonisation potential of the energy sector of Ukraine by combining small modular nuclear reactors and renewable energy sources in the context of structural transformation of the generation mix. It was established that the structural characteristics of the Ukrainian energy balance in the period 2018–2024 had significant differences in the specific CO_2 intensity between technological groups, and it was the configuration of the production structure that determined the systemic nature of emissions.

The lowest rates were provided by nuclear generation, including promising MNRs with operational emissions of 8–16 gCO_2/kWh, which confirms their role as basic low-carbon sources. Instead, coal and gas stations remained the main sources of emissions with ranges of 750–1050 and 380–510 gCO_2/kWh, respectively, forming the main contribution to peak and transient emission regimes. The developed model for estimating total emissions showed that replacing traditional thermal generation by 20–30%

provides a reduction in CO_2 by 18–27%, while in a low-carbon scenario with a replacement share of more than 50%, a reduction of more than 45% is possible. Therewith, the nonlinear nature of the decarbonisation effect was revealed: after reaching a certain threshold of structural changes, the reduction of emissions is accelerated by reducing the frequency of peak imbalances and reducing the need for backup thermal generation.

It is determined that MNRs create a stable basic decarbonisation effect due to their low carbon intensity and ability to compensate for renewable energy fluctuations, providing inertial damping of system fluctuations. In turn, solar and wind stations form the main flexible generation segment with a reduction potential of 330–1050 gCO_2/kWh, depending on the type of technology, but their decarbonisation contribution greatly depends on the availability of stable base capacity. The integral results confirm that the combined configuration of “MNR+RES+NPP” allows achieving system values of 100–120 gCO_2/kWh, which corresponds to the parameters of low-carbon EU energy systems and is consistent with international trajectories of climate neutrality. The obtained dependences indicate that the key parameters of decarbonisation − the intensity of the decrease in ΔEmissions, the variability of the CO_2 profile, and the sensitivity of the system to peak loads-are determined not by individual technologies, but by their ability to form consistent energy flows within a single structural configuration. In this context, MNRs serve as a system-forming element that increases the predictability of operating modes and reduces structural dependence on high-carbon reserves.

The key limitations of the study were the uncertainty of the post-war rate of infrastructure restoration, the variability of the coefficients of use of installed renewable energy capacity, and the dependence of the model on the availability of high-frequency statistics. Further research should be aimed at clarifying the parameters of the MNR system integration, considering partial load modes, modelling hybrid configurations with energy storage devices and flexible demand mechanisms, and developing comprehensive assessments of the economic and regulatory feasibility of various decarbonisation scenarios in the context of the post-war transformation of the Ukrainian energy system.

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