“Macroeconomic drivers of CO_2 emissions reduction in a transition economy: From residential extrapolation to municipal policy scaling”

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MACROECONOMIC DRIVERS OF CO_2 EMISSIONS REDUCTION IN A TRANSITION ECONOMY: FROM RESIDENTIAL EXTRAPOLATION TO MUNICIPAL POLICY SCALING

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Abstract

This study aims to assess a macroeconomic methodological approach for evaluating the impact of investment activity, energy efficiency, energy costs, and renewable energy development on CO_2 emissions in Ukraine, using the model's insights for a conceptual extrapolation to the residential sector with subsequent policy scaling to the municipal building stock. The methodological basis is a top-down approach using econometric modeling (OLS) for 2002–2021, which represents the pre-war period in Ukraine. All estimations are based on aggregated macroeconomic proxy indicators and not on direct residential or municipal emissions measurement data due to a lack of reliable information. The results demonstrate that macroeconomic energy efficiency is the most powerful driver of decarbonization. An analysis of the residential sector indicates that higher household financial burdens associated with higher utility expenditures are statistically connected with lower CO_2 emissions, which may reflect demand-side adjustments in energy consumption, including price-driven savings. However, other factors, such as energy inefficiency or energy poverty, may also add to this relationship. In contrast, traditional investment activity still contributes to growing carbon footprints, with CO_2 emissions rising by 136 kg per 1% increase in gross capital formation as a share of GDP. At the same time, the estimated coefficients for global oil prices and the share of renewable energy exhibit the expected negative signs, suggesting economically meaningful long-term decarbonization tendencies. However, these relationships do not reach conventional statistical significance and should therefore be interpreted as directional trends rather than statistically confirmed effects.

Keywords decarbonization, energy efficiency, renewable energy, residential sector, municipal sector, econometric model, energy policy

JEL Classification Q42, Q43, Q48

INTRODUCTION

Decarbonization of the economy has become critical for modern global environmental and economic policy, directly ensuring sustainable development, energy security, and reducing environmental impacts. Reducing greenhouse gas emissions is necessary to achieve climate neutrality and fulfill international climate commitments, which require transforming energy systems and changing energy consumption patterns (Kurbatova & Khlyap, 2015; Raza et al., 2025; Srivastava et al., 2026).

The residential sector plays an important role in the decarbonization processes. In most countries worldwide, households account for a significant share of final energy consumption, which is associated with substantial greenhouse gas emissions (Wei & Harrison, 2021). For example, in the European Union, households accounted for 26.2% of final energy consumption in 2023 (Eurostat, 2025). The residential sector is also a contributor to greenhouse gas emissions, underlining its relevance for achieving climate and energy policy objectives (Eurostat, 2023). In Ukraine, as of 2021, the residential sector accounted for approximately 33% of final energy consumption, while its contribution to greenhouse gas emissions remained substantial, although the exact share has not been reported in publicly available statistics (SEI, 2023).

Decarbonizing Ukraine's household sector is particularly relevant given the high share of outdated residential buildings characterized by low energy efficiency. The modernization of this housing stock through energy-efficiency measures and renewable energy technologies can not only significantly reduce energy consumption and greenhouse gas emissions but also lower household energy costs, enhance economic resilience, and reduce energy poverty (Li et al., 2022; Smiech et al., 2025). In the long term, these measures will contribute to the comprehensive transformation of the national energy system, enhancing its adaptability and resilience to external economic, political, and climate-related challenges.

At the same time, despite the growing number of studies on residential decarbonization, there remains a lack of macro-level empirical evidence on how household utility expenditures, macroeconomic energy efficiency, investment activity, and renewable energy development jointly relate to CO_2 emissions dynamics in Ukraine. This gap is relevant in the context of the pre-war period, which represents the last consistent time horizon supported by official energy statistics. Addressing this gap is essential for understanding the structural drivers of decarbonization.

1. LITERATURE REVIEW

The majority of modern macroeconomic studies on greenhouse gas emissions are based on an extended STIRPAT (Stochastic Impacts by Regression on Population, Affluence, and Technology) paradigm, which argues that environmental destruction is a derivative of the scale of a system's wealth and its technological maturity (York et al., 2003; Liu et al., 2005a; Li et al., 2025). Within this framework, the decarbonization processes of national economies and their sectors are largely dependent on a complex set of structural and economic factors, including economic development, industrial structure, investment activity, energy prices, and the share of renewable energy sources in total energy consumption (Bilan et al., 2022; Firstová & Vysochyna, 2024; Kongkuah & Alessa, 2025).

Growth in gross domestic product (GDP) per capita, on the one hand, can lead to increased energy consumption and environmental burdens, while, on the other hand, it creates financial opportunities for businesses, individuals, and municipalities to invest in renewable energy, infrastructure modernization, and energy efficiency improvements (Saher et al., 2025). The structure of energy consumption in the economy is also vital, since a high share of production and utilities based on the use of fossil fuels leads to an increase in carbon dioxide emissions into the atmosphere, while renewable energy sources contribute to their reduction (Mentel et al., 2020).

Investment activity and capital accumulation also play distinct roles in shaping emissions dynamics, as they are closely associated with industrialization. An increase in gross capital formation is generally accompanied by the expansion of production capacity and a rise in the energy intensity of the economy, which may lead to higher levels of energy consumption and increased CO_2 emissions, particularly in countries where the energy mix remains heavily dependent on fossil fuels (Rui et al., 2020).

The dynamics of energy prices also constitute an economic driver of the energy transition. Rising oil and natural gas prices can encourage a reduction in consumption of these carriers and accelerate the shift toward renewable energy sources, thereby contributing to lower greenhouse gas emissions. At the same time, increasing energy costs may exacerbate the risk of energy poverty among households, creating additional socioeconomic challenges for decarbonization policies (Knez et al., 2022).

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Within the extended STIRPAT framework, previous evidence consistently identified investment activity, energy prices, renewable energy penetration, and macroeconomic energy efficiency as the principal determinants of CO_2 emissions. These macroeconomic drivers provide the theoretical basis for selecting the explanatory variables used in this study.

A significant amount of research has examined decarbonization in the residential sector, highlighting the importance of energy efficiency improvements, renewable energy deployment, and household energy consumption patterns. However, most of these studies adopt engineering or building-level approaches, focusing on individual technologies or building performance rather than on the macroeconomic drivers of national decarbonization. In particular, Shan et al. (2025) demonstrated that residential building modernization can substantially reduce both energy consumption and CO_2 emissions, confirming the environmental benefits of improving building energy efficiency. Similarly, Liu et al. (2025b) concluded that the residential sector plays a central role in achieving carbon neutrality through improvements in energy efficiency and energy management. These findings underline the importance of the residential sector for decarbonization but provide limited evidence on the macroeconomic mechanisms linking household energy use to national CO_2 emissions.

Renewable energy development is widely recognized as a determinant of long-term emission reduction. Increasing the share of renewable energy contributes to decarbonization, although the degree of this effect depends on national economic and institutional conditions (Kurbatova & Skibina, 2019; Sotnyk et al., 2021; Kurbatova et al., 2025; Rao et al., 2026). While technological studies identify considerable potential for integrating renewable energy into residential buildings, their primary emphasis remains on technology optimization rather than on evaluating renewable energy as a macroeconomic determinant of CO_2 emissions.

In addition to technological factors, household energy consumption is influenced by socioeconomic conditions, particularly energy prices and household expenditure patterns. Zheng et al. (2024) found that rising household income increases total energy consumption while simultaneously improving energy efficiency through technology adoption. Ewald et al. (2021) showed that higher energy prices encourage households to reduce energy consumption, suggesting that household expenditures on energy services can serve as a behavioral proxy in macroeconomic analyses of decarbonization.

Overall, previous studies indicate that residential decarbonization is influenced by technological, economic, and behavioral factors. Nevertheless, existing research predominantly investigates these determinants separately. Limited empirical evidence is available on the joint assessment of macroeconomic determinants, including investment activity, household utility expenditures, renewable energy development, and macroeconomic energy efficiency within a unified econometric framework for transition economies such as Ukraine. Addressing this gap motivates the present study.

Therefore, this study aims to apply and empirically assess a macroeconomic methodological approach to evaluate the impact of investment activity, energy efficiency, energy costs, and renewable energy development on CO_2 emissions in Ukraine, leveraging empirical macro-trends for a conceptual extrapolation to the residential sector and deriving scalable policy implications for municipal buildings.

The development and application of such methodological tools constitute an important prerequisite for achieving Sustainable Development Goals "Affordable and Clean Energy" and "Climate Action," as well as for fostering a more resilient and energy-efficient economic system. The proposed approach provides a scientific basis for evaluating the effectiveness of relevant sectoral policies, optimizing public regulatory and financial incentive instruments, and enhancing the implementation of international climate commitments.

Accordingly, the following hypotheses are empirically tested:

H1: *As gross capital accumulation (% of GDP) increases, reflecting the effect of industrialization, per capita CO_2 emissions rise, slowing down decarbonization.*

H2: As utility costs increase (% of total household costs), CO_2 emissions per capita decrease due to the effect of economic optimization of consumption.

H3: The growth in world crude oil prices has a negative impact on the dynamics of CO_2 emissions per capita, acting as a macroeconomic incentive for energy saving.

H4: An increase in the share of renewable energy in the structure of electricity generation ensures a direct reduction in CO_2 emissions per capita.

H5: The growth in energy efficiency of the national economy depends on economic achievements and has a positive impact on the decarbonization of the national economy.

2. METHOD

To model the level of decarbonization of the national economy and forecast the impact of the residential sector, a top-down methodology was applied. Since countries with transition economies, including Ukraine, lack a long-term, systematic primary accounting system for the carbon footprint of individual residential and municipal buildings, the use of aggregated macroeconomic and structural proxy indicators represents the most scientifically justified approach.

The econometric model used to assess the decarbonization of the national economy is specified as follows:

$$\begin{aligned} CO_{2t} &= \alpha_0 + \alpha_1 GDP\_pc_t + \alpha_2 GFCF_t \\ &+ \alpha_3 EXU_t + \alpha_4 CRO_t + \alpha_5 REN_t \\ &+ \alpha_6 GDPE_t + \upsilon_t, \end{aligned} \tag{1}$$

where CO_{2t} – carbon dioxide (CO_2) emissions, excluding Land Use, Land-Use Change and Forestry (LULUCF), per capita (t CO_2 equivalent /capita) in year t; GDP_pc_t – GDP per capita (USD) in year t; $GFCF_t$ – gross fixed capital formation (% of GDP) in year t (a proxy indicator of investment activity); EXU_t – expenses on utilities (% of total household expenses) in year t; CRO_t – average world crude oil prices (USD/bbl) in year t (a proxy for the overall cost of energy resources); REN_t – electricity generation from renewable energy sources, excluding hydroelectric (% of total), in year t; GDP_E_t – GDP per unit of energy use (constant 2017 PPP USD per kg of oil equivalent) in year t, (a key indicator of macroeconomic energy efficiency); α_0 – constant term (cons); $\alpha_{1,}$ …, α_5 – regression coefficients of the model; υ_t – random regression perturbation.

Conceptually, model (1) integrates indicators that capture both behavioral patterns of consumers at the micro level and structural shifts at the macro level. In particular, the macroeconomic indicator of household expenditure on utility services (*EXU_t*) is used in the model as a key proxy for assessing the level of financial pressure on consumers, which directly shapes their incentives to conserve energy and optimize their carbon footprint.

The information base for modeling was compiled from official statistical data from the State Statistics Service of Ukraine (n.d.) and the World Bank (n.d.). The dataset covers the period 2002–2021 (Kubatko et al., 2025). Data from 2022 onward were excluded from the analysis because public access to energy-related data has been restricted for security reasons during the ongoing Russia–Ukraine war. The econometric estimation of the developed adaptive decarbonization model was conducted using ordinary least squares (OLS) in Stata 18.0.

Equation (1) represents the general conceptual (baseline) functional form of the decarbonization model. Following the fundamental paradigms of ecological economics, in particular the *IPAT* and *STIRPAT* frameworks (York et al., 2003), macroeconomic analysis of CO_2 emissions is theoretically incomplete without simultaneously considering the overall scale of the system's wealth (GDP_pc_t), and its qualitative technological level (GDP_E_t) (Liu et al., 2025b; Li et al., 2025). Deliberately ignoring any of these global dimensions would lead to omitted-variable bias and distort the theoretical basis. At the same time, the transition from a purely theoretical construction to empirical testing requires accounting for objective econometric limitations. Direct empirical testing of all six factors of model (1) within a single calculation is mathematically incorrect due to two strict limita-

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tions caused by the specifics of the available statistical data:

1) limited degrees of freedom – given a short time series (N = 20 observations), the inclusion of an excessive number of independent variables critically reduces the degrees of freedom (20 – k –1), making the regression estimates unstable;

2) multicollinearity trap – the GDP_pc_t (GDP per capita) and GDP_E_t (GDP per unit of energy) have a common macroeconomic basis for formation (GDP volume in the numerator), which creates the risk of strong linear dependence and endogeneity.

Given these empirical limitations, the general (baseline) model (1) was divided into two autonomous specifications, considering the most relevant proxy indicators for the residential sector. In particular, during the testing of Specification 1, GDP_pc_t was removed from the calculation, since its macroeconomic effect was fully accumulated and econometrically more accurately reflected through the housing sector-specific utility expenditure variable (EXU_t), reflecting the level of financial well-being and behavioral responses of households. Instead, the qualitative technological factor of energy efficiency (GDP_E_t) was transferred to a separate Specification 2. Thus, within the framework of Specification 1, four factor variables remained in the model ($GFCF_t$, EXU_t, CRO_t, and REN_t). This approach allowed us to fully preserve the original theoretical logic of the study, while ensuring mathematical stability and robustness of practical estimates.

To provide the reliability of the assessments, the research algorithm included mandatory comprehensive post-regression residual diagnostics. To test the time series for stationarity, the Augmented Dickey–Fuller (ADF) test was applied. Heteroscedasticity of residuals was diagnosed using the Breusch–Pagan/Cook–Weisberg test; serial autocorrelation was tested using the Durbin–Watson statistic; and the level of multicollinearity was controlled using the variance inflation factor (VIF). Upon detection of relevant deformations, the final coefficient calculation was performed using the Robust Standard Errors method.

3. RESULTS AND DISCUSSION

Before estimating the regression model parameters, the time series were subjected to mandatory stationarity testing using the Augmented Dickey–Fuller (ADF) procedure. The results show that most of the examined series are integrated of order one (I(1)) and become stationary after first differencing.

The next step was to analyze the post-regression diagnostic statistics for the OLS model under Specification 1. The variance inflation factor (VIF) confirmed the absence of critical multicollinearity among the four selected explanatory variables. At the same time, initial regression residual diagnostics revealed potential heteroskedasticity and serial autocorrelation, which are commonly observed in short macroeconomic time series for transition economies. To pre-emptively mitigate these distortions and obtain statistically valid t-statistics and p-values under conditions of a limited sample size (N = 20), the final estimation of the model (1) specifications was performed using robust standard errors. The structure, range of variation, and variance of the selected proxy indicators, which form the basis for estimating the two empirical model specifications, are presented in Table 1.

Table 1. Descriptive statistics of the variables for Ukraine (2002–2021)

Variable	Mean	Std.Dev.	Min	Max
CO_{2t}	6.303735	1.332097	4.380606	8.113813
GDP_pc_t	2863.095	1063.984	903.0119	4775.946
$GFCF_t$	18.68264	4.061462	13.20475	27.11947
EXU_t	11.49	2.756791	8.50	17.00
CRO_t	65.69643	25.25673	24.92775	105.0096
REN_t	1.371272	2.095372	0.012663	7.687138
GDP_E_t	6.6645	1.22764	4.34	8.46

The descriptive statistics analysis confirms the validity of the constructed dataset for subsequent econometric modeling. First, all selected variables demonstrate a significant range of dispersion necessary to identify macroeconomic elasticities. The share of electricity from renewable sources (RENt) increases from 0.01% to 7.69%, with the main jump in dispersion occurring only in the last few years of the study period. Such a specific structure of the time series is key for further econometric understanding of the nature and current level of statistical power of renewable energy sources on

```
      Source |       SS            df       MS      Number of obs   =        20
-------------+----------------------------------   F(4, 15)        =     36.21
       Model |   30.550945          4  7.63773624   Prob > F        =    0.0000
    Residual |  3.16423424         15  .21094895    R-squared       =    0.9061
-------------+----------------------------------   Adj R-squared   =    0.8811
       Total |  33.7151792         19  1.77448312   Root MSE        =    .45929
---------------------------------------------------------------------------------
carbondioxideco2emissionsexcludi |CoefficientStd.err.t    P>|t| [95%conf.interval]
---------------------------------+-----------------------------------------------
 grossfixedcapitalformationofgdp |.135816    .03367  4.03   0.001  .06404   .2075
expensesonutilitiesoftotalhouseh |-.2557338 .05625 -4.55   0.000  -.3756   -.1358
              crudeoilaveragebbl |-.0068111 .00447 -1.52   0.148  -.0163   .0027
electricityproductionfromrenewab |-.120086   .07555 -1.59   0.133  -.2811   .04095
                           _cons |7.316848  1.1094   6.59   0.000  4.9520   9.681
---------------------------------------------------------------------------------
```

Figure 1. Modeling the drivers of decarbonization in Ukraine (Specification 1)

decarbonization processes in Ukraine. Second, the number of observations (N = 20) is minimally sufficient for time series analysis, which confirms the validity of the decision to divide the factors into two separate specifications in order to preserve the mathematical degrees of freedom and prevent bias in the estimates.

The econometric evaluation identified statistically significant relationships for several major drivers of carbon neutrality. The results of the evaluation of specification 1 of the model, which focuses on identifying the impact of investment, price, and structural determinants on the level of CO_2 emissions per capita in Ukraine, are presented in Figure 1.

The quality metrics for Specification 1 of the model (1) indicate its extremely high analytical ability: the calculated coefficient of determination (R^2 = 0.9061) shows that the model explains 90.6% of the variation in CO_2 emissions per capita in Ukraine using the selected structural and price factors. The overall adequacy of the regression is confirmed by Fisher's F-test ($F(4,15) = 36.21$; Prob > F = 0.0000). A detailed analysis of the obtained elasticities allowed us to identify the following patterns.

First, a statistically significant positive relationship was found between gross capital formation ($GFCF_t$) and the level of CO_2 emissions per capita (coefficient 0.1358 at p = 0.001). With a 1% increase in gross capital formation, CO_2 emissions per capita (excluding LULUCF) increase by 136 kg per year, which confirms hypothesis *H1*. This indicates that capital investments, particularly in traditional industrial sectors, increase the overall carbon intensity of the economy, as both production and energy consumption rise, including in the residential sector.

Second, a statistically significant negative relationship was found between the share of household expenditures on utilities (EXU_t) and the level of decarbonization (coefficient –0.2557 at p = 0.000). Thus, with a 1% increase in utility costs in household budgets, CO_2 emissions per capita (excluding LULUCF) decrease by 256 kg per year. This is explained by the fact that lower-income households, which allocate a larger share of their income to utility services, tend to reduce energy consumption in order to save financial resources and, consequently, generate lower emissions. This, in turn, verifies hypothesis *H2*.

Third, for the indicator of global oil prices (CRO_t), the estimated coefficient (–0.0068) has the expected negative sign; thus, an increase in oil prices by 10 USD per barrel is associated with a reduction in CO_2 emissions per capita (excluding LULUCF) by 68 kg. However, due to the limited sample size, this relationship does not reach the conventional 5% level of statistical significance (p = 0.148). Nevertheless, the estimated coefficient is consistent with theoretical expectations and suggests an economically meaningful long-term tendency: higher fossil fuel prices encourage more rational energy consumption and support decarbonization. Therefore, hypothesis *H3* cannot be regarded as statistically confirmed at the conventional 5% significance level; instead, the estimated effect should be interpreted as a directional long-term tendency rather than a statistically confirmed relationship.

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```
   Source |       SS           df       MS      Number of obs   =        20
-------------+----------------------------------   F(1, 18)        =     60.30
       Model |  25.9650158         1  25.9650158   Prob > F        =    0.0000
    Residual |  7.75016342        18  .430564635   R-squared       =    0.7701
-------------+----------------------------------   Adj R-squared   =    0.7574
       Total |  33.7151792        19  1.77448312   Root MSE        =    .65617

------------------------------------------------------------------------------------------------
carbondioxideco2emissionsexcludi | Coefficient  Std. err.      t    P>|t|     [95% conf. interval]
---------------------------------+--------------------------------------------------------------
gdpperunitofenergyuseconstant201 |  -.9522402   .1226228    -7.77   0.000    -1.209861   -.6946191
                           _cons |   12.64994   .8302871    15.24   0.000     10.90557    14.39431
```

Figure 2. Modeling the impact of macroeconomic energy efficiency (Specification 2)

Fourth, an increase in the share of electricity generation from renewable energy sources, excluding hydropower (REN_t), by 1% leads to a reduction in CO_2 emissions per capita (excluding LULUCF) by 120 kg per year (coefficient: −0.1201). As with crude oil prices, the estimated coefficient has the expected negative sign but does not reach the conventional 5% level of statistical significance (p = 0.133). Therefore, hypothesis *H4* cannot be regarded as statistically supported at the 5% significance level. Nevertheless, the estimated relationship is consistent with theoretical expectations. It suggests an economically meaningful long-term tendency, indicating that the expansion of renewable electricity generation may contribute to decarbonization as its share in the energy mix continues to increase. The limited statistical significance is explained by the specific characteristics of Ukraine's energy transition: during 2002–2014, the share of renewable electricity generation remained negligible (0.01%–0.1%). It began to increase substantially only in the final years of the study period. Consequently, its systemic macroeconomic effect has not yet accumulated sufficiently to offset the influence of traditional drivers, such as capital formation and household utility expenditures.

To assess the isolated impact of qualitative parameters of energy system modernization and to avoid multicollinearity, Specification 2 of the model was estimated. The results of the modeling are presented in Figure 2.

The integrated indicator of macroeconomic energy efficiency (GDP_E_t) demonstrated the most significant decarbonization effect (coefficient −0.952 at p = 0.000), fully confirming hypothesis *H5*. Specifically, an increase in GDP per unit of energy use by 1 USD per kilogram of oil equivalent leads to a reduction of CO_2 emissions per capita (excluding LULUCF) by 952 kg per year. This demonstrates that increasing energy efficiency is a key driver of decarbonization, enabling economic growth while reducing the carbon intensity of production and consumption. In addition, the modeling results indicate that structural changes in the economy aimed at increasing energy efficiency have a long-term effect on emission decline, reducing the economy's dependence on fossil fuels and increasing its competitiveness in the context of the global energy transition.

The identified regression relationships between gross capital accumulation and CO_2 emissions are supported by a number of empirical studies. In particular, Satrovic et al. (2020) investigated the interconnection between gross capital formation and CO_2 emissions in Turkey and Kuwait. They found a long-term causal relationship between investment activity and environmental indicators. Active investment in production and infrastructure activities is associated with higher energy consumption and, consequently, increased greenhouse gas emissions. Similar conclusions were drawn in studies on Pakistan (Rahman & Ahmad, 2019), which found that changes in gross capital formation have a statistically significant impact on CO_2 emissions dynamics, particularly in the context of the expansion of energy-intensive industries. This supports the fundamental pattern revealed: regardless of a country's level of economic development or geographic location, during the stages of active expansion of traditional infrastructure (industrialization), the growth of energy-intensive industries inevitably increases carbon emissions.

The empirically confirmed phenomenon of demand optimization resulting from increased household expenditures on utility services is fully consistent with behavioral patterns identified in OECD sociological frameworks (OECD, 2014). According to this conceptual framework, consumers are classified into three basic clusters: 1) "altruists" (environmentally motivated individuals, willing to accept voluntary consumption constraints for environmental reasons); 2) "green growth supporters" (technological optimists); and 3) "skeptics" (a broad segment of consumers who ignore environmental threats and are not inclined to save resources for ideological reasons). The econometric results suggest that household expenditures serve as a universal trigger capable of overcoming behavioral barriers. Rising financial pressure from utility tariffs compels even the least environmentally motivated "skeptical" consumer segment to reduce energy consumption primarily for cost-saving reasons, thereby ultimately leading to a large-scale reduction in macroeconomic emissions, as confirmed by the model.

The results on the negative impact of global oil prices on CO_2 emissions are also supported by Sun et al. (2025), who, based on panel data for 119 countries, found that increases in fossil fuel prices are statistically associated with reductions in CO_2 emissions. This can be explained by the fact that rising energy costs encourage businesses and households to improve energy efficiency and switch to renewable energy sources. The observed negative impact of a growing share of renewable energy sources on CO_2 emissions is consistent with the study's results. Sultana et al. (2025) demonstrate that a rising share of renewable energy in the energy mix contributes to long-term reductions in CO_2 emissions as renewable sources gradually replace fossil fuels. The obtained results regarding the effect of increasing energy efficiency on reducing CO_2 emissions are consistent with Tu et al. (2022) and Altın (2024), who confirm that improvements in energy efficiency, together with the development of renewable energy, have a systemic impact on reducing carbon emissions.

Since the proposed econometric model (1) and its two specifications were developed based on aggregated national data, the identified relationships represent broad macroeconomic and structural elasticities rather than micro-level building measurements. However, this top-down approach allows for a conceptual and policy-driven extrapolation of these macroeconomic patterns onto the integrated building stock. While schools, hospitals, and administrative buildings objectively differ from residential housing in occupancy patterns and heating schedules, they are bound by the same macroeconomic environment, energy infrastructure, and budget-driven economic constraints. Therefore, the identified national macro-drivers, such as the demand optimization effect captured by the aggregate utility expenditure variable (EXU_t) and the decarbonization impact of macroeconomic energy efficiency (GDP_E_t), reflect universal economic principles. Whether channeled through household behavioral savings or municipal budgetary procurement, price and efficiency signals operate under similar resource-constrained logics within the transition economy. This justifies translating national macroeconomic empirical trends into scalable conceptual policy instruments for local communities.

The statistically significant decarbonization effect of energy efficiency (a reduction of 952 kg in CO_2 emissions) demonstrates that investments in energy conservation are an essential priority. As a policy implication derived from this macro-coefficient, residential and municipal buildings in Ukraine, due to their high physical deterioration and outdated technical characteristics, represent a primary area for targeted modernization. For the residential sector, this implies a critical need to scale up state and local support programs for associations of multi-apartment building owners and individual homeowners (in particular through the Energy Efficiency Fund of Ukraine) to carry out deep thermal modernization. At the same time, extrapolating this trend to the municipal sector suggests the deployment of energy service company (ESCO) mechanisms, since municipalities, unlike individual households, have the institutional capacity to implement larger-scale grant-funded projects through municipal co-financing programs and attract international assistance. Such institutional capacity enables a more systemic and predictable reduction in energy consumption and emissions.

The revealed long-term decarbonization trend in the development of green power underscores the need to decentralize building energy supply systems, thereby increasing the overall share of clean

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energy in the power mix and reducing dependence on fossil fuels. While the renewable energy coefficient represents a directional trend rather than a micro-level certainty, in the residential sector, this encourages households to transition toward the prosumer model (simultaneously being energy consumers and producers) through the installation of private rooftop solar power plants, small wind turbines, hybrid solar-wind systems, energy storage systems, biomass boilers, and heat pumps. By conceptual extension, implementing these technologies and Net Energy Metering in municipal buildings will not only reduce dependence on fossil fuels but also ensure the autonomous operation of critical community infrastructure.

The model clearly showed that the larger the share of the household budget spent on energy, the lower the CO_2 emissions (a demand-optimization effect of 256 kg). This macroeconomic trend provides a conceptual foundation for scaling financial management tools to both the residential and municipal levels. Since price factors strongly regulate consumption, state and local policy should protect vulnerable populations from energy poverty by shifting the focus from direct consumption subsidies to co-financing energy efficiency measures in the residential sector (for example, through programs such as "Energodim" or local initiatives supporting associations of apartment building owners).

Based on the modeling results, a focused set of policy recommendations is formulated, shifting from national macro-evidence to scalable implications for private households and municipal buildings.

First, we need institutional integration and systemic strategy. To counteract the carbon-intensifying effect of traditional capital accumulation and maximize macroeconomic energy efficiency, energy policy must transition from fragmented local projects to a systemic, integrated institutional framework. This strategy requires aligning national emission-reduction targets directly with the regulatory framework governing the housing and utility sectors, ensuring that capital allocation follows unified low-carbon criteria. Instead of isolated programs, regional and national authorities should establish consolidated support mechanisms, including harmonized concessional lending, pooled grant funding, and public-private co-financing models. By integrating these economic instruments under a single overarching decarbonization strategy, policy frameworks can streamline access to investment resources and effectively scale structural energy transitions from the household level to the municipal sector.

Second is integrated building energy auditing and management systems. To operationalize the high decarbonization potential identified by the macroeconomic energy efficiency driver, local authorities must bridge the macro-to-micro data gap. Governments should implement standardized building energy auditing paired with mandatory energy performance certification. Introducing transparent energy certificates creates necessary financial and legal accountability for both municipal administrators and private housing owners. This data infrastructure must be integrated into automated regional energy management platforms, moving away from intuitive planning toward data-driven targeting of co-financing capital exclusively to facilities with verified environmental returns.

Third is decentralized technical infrastructure modernization. The revealed macroeconomic impact of technological factors (REN_t and GDP_E_t) justifies the comprehensive integration of deep thermal modernization with decentralized renewable energy penetration across the national economy, including the building sector. Thus, public and private investment frameworks should prioritize the cross-sectoral deployment of distributed clean energy technologies within the housing stock and public properties. Shifting the regulatory environment from centralized utility dependency toward decentralized microgeneration allows for the scaling of macro-level renewable trends into local energy self-sufficiency.

Fourth is economic and tariff incentives for demand optimization. Since the model empirically demonstrates that aggregate price signals dictate consumption behavior (EXU_t), energy policy must deploy economic incentives to regulate demand. Instead of non-targeted public consumption subsidies, local regulatory frameworks should apply differentiated tariff systems and financial reward mechanisms for verified energy savings. This approach leverages the price-driven demand-optimization effect to encourage rational resource use across both residential housing and municipal sectors without relying on non-empirical socio-educational measures.

The practical implementation of the developed recommendations provides a foundation for transitioning toward an adaptive, data-driven management concept in local communities. By replacing intuitive planning with standardized energy monitoring and verified primary data collection, public authorities can objectively evaluate the dynamics of energy consumption and the actual CO_2 reductions. Given the econometrically confirmed universality of macroeconomic factors, this framework minimizes investment risks in state and local support programs by directing limited financial resources exclusively toward technological solutions with demonstrated effectiveness. Framed as a conceptual extrapolation, the synchronized execution of these data-driven approaches across both the household and municipal levels will generate a systemic climate effect, strengthening local communities' capacity to build resource-efficient, energy-independent infrastructure.

This study has certain objective limitations. First, the empirical analysis covers the period 2002–2021, representing the pre-war stage of Ukraine's socio-economic and energy development, and deliberately excludes the structural shock to Ukraine's energy sector caused by the full-scale war started in 2022 due to data accessibility constraints. Consequently, the identified relationships should be interpreted as characterizing pre-war conditions rather than the current wartime economy. Furthermore, subsequent geopolitical developments affecting global energy markets, including instability in the Middle East, may further influence energy prices, investment patterns, and the pace of renewable energy deployment. Consequently, the applicability of the reported relationships to the current international context should be interpreted with appropriate caution. Second, the applied econometric model and its specifications rely on aggregated macroeconomic proxy indicators, thereby omitting deeper socio-psychological aspects of energy consumption at the micro level of individual households. In this regard, a promising direction for further research is expanding the database through panel-based sociological surveys. This would make it possible to verify individual behavioral factors in decision-making regarding investments in the modernization of private housing and municipal buildings, and to complement the macroeconomic picture with micro-level insights.

CONCLUSION

Based on OLS econometric modeling for the pre-war period in Ukraine (2002–2021), this study examines the complex set of structural, economic, and energy determinants of decarbonization in Ukraine's national economy and explores their implications for the residential sector with projections for the municipal sector. The application of a top-down approach quantitatively assessed the elasticity of CO_2 emissions per capita with respect to key factors shaping the dynamics of household energy consumption, with subsequent extrapolation of the identified patterns to the municipal buildings sector.

The scientific novelty lies in adapting the classical paradigms of ecological economics to the specific characteristics of transition economies, thereby enabling the distinction between the influence of the scale of national technological modernization and the financial and economic drivers that directly shape demand in energy-intensive sectors.

The results show that macroeconomic energy efficiency, household utility expenditures, and gross fixed capital formation are the main statistically significant drivers of CO_2 emissions in the analyzed period. Higher energy efficiency and a larger share of household spending on utilities are associated with lower CO_2 emissions, while greater gross fixed capital formation is associated with higher emissions. The coefficients for global oil prices and the share of renewable electricity have the expected negative signs, but they are not statistically significant at the conventional 5% level. Therefore, these two results should be interpreted as indicating possible long-term trends rather than statistically confirmed effects.

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The practical value of the study is that it helps identify policy measures for improving energy efficiency in the residential sector and provides a basis for considering similar approaches in municipal buildings. Since the analysis uses aggregated macroeconomic data rather than observations, this multi-sectoral policy scaling should be treated with caution. Nevertheless, the results suggest that targeted co-financing for deep thermal modernization, smart metering, and support for microgeneration may contribute to further decarbonization in both residential and municipal buildings.

The inability to include the period since the start of the full-scale war in the data set shifts the focus to pre-war trends, and the specificity of aggregated proxy variables does not allow for detailed analysis of individual consumer motivation. In this context, future research should focus on a micro-level analysis of household motivations using panel survey data, as well as on applying Data Envelopment Analysis (DEA) to assess the techno-economic efficiency of decentralized energy facilities at the municipal level.

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