“Are regional public budgets associated with renewable energy development? Evidence from Ukraine”

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ARE REGIONAL PUBLIC BUDGETS ASSOCIATED WITH RENEWABLE ENERGY DEVELOPMENT? EVIDENCE FROM UKRAINE

Abstract

The growing importance of renewable energy in ensuring energy security and sustainable development has increased attention to the role of public finance, particularly at the regional level. This study aims to assess whether different categories of regional public expenditure are associated with renewable energy development in Ukraine, distinguishing between installed capacity and electricity generation. The analysis is based on a balanced panel dataset for 25 Ukrainian regions over 2018–2021 and applies two-way fixed effects models with lagged specifications and Driscoll–Kraay standard errors. The results show that expenditures on electric transport exhibit the strongest positive association with installed renewable energy capacity ($\beta \approx 0.078$, $p < 0.001$), followed by SME support ($\beta \approx 0.025$, $p < 0.001$), other environmental activities ($\beta \approx 0.017$, $p < 0.001$), and natural resource management ($\beta \approx 0.013$, $p < 0.001$). In contrast, most general economic expenditures are not statistically significant, suggesting that these expenditure categories are not statistically associated with higher renewable energy development within the analyzed period. For renewable electricity production, contributions to the statutory capital of enterprises are positively associated ($\beta \approx 0.006$, $p < 0.05$), while co-financing of investment projects is negatively associated ($\beta \approx -0.027$, $p < 0.001$), reflecting implementation lags. Additionally, capital investments in environmental protection are negatively associated with renewable electricity production ($\beta \approx -0.072$, $p < 0.001$), suggesting that installed capacity expansion differs from renewable electricity production.

Keywords budgets, expenditures, decentralization, municipalities, regions, renewables

JEL Classification H72, H76, Q42, Q48

INTRODUCTION

The acceleration of renewable energy deployment has become a central priority of global economic policy, driven by the need to enhance energy security, reduce greenhouse gas emissions, and ensure sustainable development. International organizations emphasize that public finance plays a crucial enabling role in energy transitions, particularly in emerging and transition economies where institutional and financial risks constrain private investment. In particular, the World Bank highlights that public expenditure and policy support are essential for de-risking renewable energy investments and mobilizing private capital (World Bank Group, 2021). Similarly, the International Monetary Fund underscores that fiscal policy instruments, including targeted spending and subsidies, are necessary to address market failures and accelerate low-carbon transitions (IMF, 2021). Within the European context, the European Commission stresses the importance of multi-level governance and regional investment mechanisms in achieving climate neutrality and implementing the European Green Deal (Fetting, 2020).

In Ukraine, the relevance of these issues has intensified significantly due to structural energy challenges and the large-scale destruction of energy infrastructure caused by the war. The disruption of centralized power systems has exposed vulnerabilities in traditional energy models and reinforced the need for decentralized, resilient energy systems based on renewable sources. According to the World Bank assessments, Ukraine's recovery strategy prioritizes green reconstruction and the expansion of renewable energy as key components of economic resilience and long-term growth (World Bank Group, 2023). Likewise, the European Commission emphasizes that rebuilding Ukraine's energy system should be aligned with EU climate objectives, focusing on decentralization, energy efficiency, and the deployment of renewable energy (European Commission, 2022). In this context, renewable energy is not only an environmental objective but also a critical element of national security and economic stability.

At the same time, the role of subnational governments in supporting the energy transition is gaining increasing attention. Decentralization reforms implemented in Ukraine since 2014 have expanded the fiscal autonomy of regional and local authorities, allowing them to play a more active role in financing infrastructure, environmental protection, and economic development. The World Bank emphasizes that effective decentralization and well-functioning intergovernmental fiscal systems can enhance the efficiency, responsiveness, and targeting of public spending across regions (Boex et al., 2021). Similarly, the International Monetary Fund notes that fiscal policy plays a critical role in supporting green investment and ensuring efficient allocation of public resources (IMF, 2021). However, empirical evidence on how regional public budgets contribute to renewable energy development remains limited, particularly in transition economies and conflict-affected contexts. This gap is also highlighted in World Bank analyses, which call for more detailed, region-level assessments of public finance effectiveness (World Bank Group, 2021).

Against this background, examining the associations between different categories of regional public expenditure and renewable energy development is both timely and policy-relevant. While national-level instruments such as feed-in tariffs and auctions have been widely studied, significantly less attention has been paid to indirect support mechanisms embedded within regional budget programs. The case of Ukraine provides a unique analytical setting, characterized by decentralization, structural transformation, and external shocks. Therefore, investigating whether and how regional public budgets are associated with renewable energy development contributes not only to the academic literature but also to the design of more effective, decentralized, and resilient energy policies aligned with European integration and post-war reconstruction priorities.

1. LITERATURE REVIEW

The transition toward renewable energy has become a central element of sustainable development strategies, reflecting its multidimensional role in addressing environmental, economic, and social challenges. Renewable energy deployment contributes not only to emissions reduction but also to improvements in public health, particularly through reductions in air pollution and associated health risks (Badreddine & Larbi Cherif, 2024). At the same time, renewable energy is increasingly recognized as a driver of sustainable economic growth and structural transformation, especially in developing and lower-middle-income economies, where it supports both environmental and development objectives (Trinh, 2025). Empirical evidence further confirms that investments in renewable energy are closely linked to broader economic development outcomes, including productivity growth and structural change (Okunevičiūtė Neverauskienė et al., 2025). In the European context, the expansion of renewable energy has also been associated with enhanced energy security, particularly in response to geopolitical shocks such as the war in Ukraine (Kuzior et al., 2025; Vasylieva et al., 2025b).

A growing body of literature emphasizes the importance of public finance and fiscal policy instruments in facilitating the energy transition. Government expenditures and public investment

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programs play a key role in overcoming market failures, reducing investment risks, and mobilizing private capital for renewable energy development (Fernandes et al., 2025; Binh & Nguyen, 2024). Fiscal and policy instruments, including subsidies, public-private partnerships, and targeted financial support, have been shown to influence renewable energy deployment across countries significantly (Raboshuk et al., 2025; Kuzior et al., 2023). At the same time, sustainable finance mechanisms and green investment frameworks are increasingly viewed as critical components of the European green transition, enabling the alignment of financial flows with climate objectives (Streimikiene et al., 2024; Krause et al., 2024). However, the effectiveness of public expenditures depends on their structure, targeting, and institutional context, as different categories of spending may generate heterogeneous outcomes (Filipova et al., 2025; Hedau & Malla, 2024).

Within this broader framework, increasing attention has been paid to the role of decentralization and subnational governance in supporting renewable energy development. The decentralization of energy systems and the growing importance of distributed generation have created new opportunities for regional and local governments to influence energy transitions (Belgibayeva et al., 2025; Kostyuchenko et al., 2025). Empirical evidence suggests that fiscal decentralization can foster renewable electricity generation by improving policy responsiveness and aligning investments with local conditions (Lyeonov et al., 2025). Local governments also play a critical role in shaping renewable energy adoption through their attitudes, policy priorities, and institutional capacity (Rakowska & Ozimek, 2021). At the same time, regional development strategies, including public–private partnerships and governance frameworks, are increasingly recognized as important tools for mobilizing investment and supporting sustainable regional transformation (Oe et al., 2025; Topazly et al., 2025).

Despite these advances, the relationship between public budgets and renewable energy development remains complex and context-dependent. Public expenditures may influence renewable energy both directly, through investment in infrastructure and projects, and indirectly, through support for innovation, entrepreneurship, and enabling institutional environments. For instance, SME development and entrepreneurial orientation are key drivers of innovation and technological adoption, including in the energy sector (Fitriningrum et al., 2025). Similarly, broader governance factors, such as the quality of institutions, financial transparency, and the shadow economy, shape the effectiveness of public spending and investment outcomes (Dobrovolska et al., 2024a, 2024b; Ntuli et al., 2025). Moreover, behavioral and social factors, including information dissemination and social norms, can influence the adoption of sustainable practices and technologies at the local level (Bappayo & Adamu, 2025; Rouillé, 2024).

In addition, the energy transition is increasingly linked to technological innovation and system-level transformation. The development of smart energy systems, including home energy management systems and microgrids, underscores the growing importance of decentralized, digitalized energy solutions (Gualandri & Kuzior, 2023; Wojciechowski et al., 2025; Tomczyk et al., 2025). These technologies enable more efficient energy use and facilitate the integration of renewable energy into local energy systems. At the same time, environmental–economic efficiency analyses demonstrate that renewable energy investments must be evaluated not only in terms of output but also in terms of their broader economic and environmental impacts (Morshed & Khrais, 2026). Historical and regional analyses further confirm that renewable energy development can generate significant regional economic effects, particularly when supported by appropriate policy frameworks (Nakamura et al., 2012).

The Ukrainian context adds further complexity to these dynamics. The war has significantly disrupted economic and energy systems, altering investment patterns and policy priorities (Dobrovolska et al., 2024a). At the same time, Ukraine possesses substantial potential for renewable energy development, particularly in bioenergy and decentralized energy systems, although this potential remains underutilized due to institutional and financial constraints (Pecheniuk et al., 2024). The energy crisis triggered by the war has also accelerated renewable energy deployment and reshaped energy policy across Europe, reinforcing the importance of resilient and decentralized energy systems (Vasylieva et al., 2025a, 2025b). Furthermore, macroeconomic and fiscal conditions, including budget deficits and public expenditure dynamics, may influence environmental outcomes and emissions trajectories, highlighting the broader macro-fiscal context of energy policy (Hennach & Echaoui, 2026).

Finally, the broader literature on public finance and economic policy underscores that the impact of government expenditures depends on their multiplier effects and allocation efficiency. Social and public expenditures can generate significant economic effects when optimally structured, but their effectiveness varies across sectors and policy domains (Yurchyk et al., 2024). At the same time, structural transformation, decarbonization policies, and green industrial strategies may have heterogeneous effects on economic performance and competitiveness (Zábojník & Branch, 2025; Zhu et al., 2026). These findings suggest that understanding the effectiveness of specific categories of public expenditures is crucial for designing efficient policy interventions.

The existing literature provides substantial evidence on the importance of public finance, decentralization, and institutional factors in supporting renewable energy development. However, there remains a significant gap in understanding how different categories of regional public expenditures influence renewable energy outcomes, particularly in transition and conflict-affected economies such as Ukraine. Addressing this gap requires a more granular, program-level analysis of public spending, which forms the core contribution of this study.

This study aims to examine the relationship between regional public expenditure programs and renewable energy development in Ukraine, with particular attention to differences in their associations with installed capacity and electricity generation using panel data analysis.

2. METHOD

This study employs a quantitative panel data approach to examine the relationship between regional public expenditures and renewable energy development across Ukrainian regions. The empirical analysis is based on a balanced panel dataset covering 25 regions of Ukraine over the period 2018–2021, resulting in 100 region-year observations. The dataset integrates information from multiple official and open-access sources to ensure both reliability and comprehensiveness. Data on gross regional product and capital investments in environmental protection were obtained from the State Statistics Service of Ukraine database. Detailed information on regional budget expenditures by functional categories was collected from the Ministry of Finance of Ukraine's "Budget for Citizens" database. Data on renewable energy development, including the volume of electricity generated from renewable energy sources and installed renewable energy capacity, were sourced from the Energy Map database maintained by DiXi Group.

The dependent variables capture two distinct dimensions of renewable energy development: (i) the volume of electricity generated from renewable energy sources (million kWh), representing operational performance, and (ii) installed renewable energy capacity (MW), reflecting investment outcomes. The key independent variables consist of multiple categories of regional public expenditures, including co-financing of investment projects through the State Regional Development Fund, socio-economic development measures, contributions to the statutory capital of enterprises, expenditures financed through local target funds, other economic activity measures, energy-saving programs, support for small and medium-sized enterprises, electric transport initiatives, natural resource management, and other environmental protection activities. These variables allow for a detailed assessment of how different policy instruments contribute to renewable energy development. Control variables include gross regional product, capturing the level of economic development, and capital investments in environmental protection, reflecting broader environmental investment activity.

Given the strong right skew and the presence of zero values across many expenditure categories, all monetary variables were transformed using the natural logarithm of $(x + 1)$. This transformation reduces the influence of outliers, stabilizes vari-

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ance, and enables an elasticity-based interpretation of coefficients. The empirical strategy is based on two-way fixed effects (TWFE) panel regression models, which control for unobserved time-invariant regional heterogeneity and common shocks across years. The baseline specification can be expressed as:

$$\ln\left(Y_{it}\right) = \beta X_{it} + \gamma Z_{it} + \mu_i + \lambda_t + \varepsilon_{it}, \qquad (1)$$

where Y_{it} denotes renewable energy outcomes in the region i at time t, X_{it} represents regional budget expenditures, Z_{it} denotes control variables, μ_i captures region fixed effects, and λ_t captures time fixed effects. To account for potential delayed effects of public investment, the analysis also incorporates a lagged specification in which explanatory variables are included with a one-year lag.

Driscoll–Kraay standard errors were applied as a robustness adjustment for heteroskedasticity, serial correlation, and cross-sectional dependence. However, their finite-sample performance may be constrained by the short time dimension of the panel. The combination of a logarithmic transformation, fixed-effects estimation, and robust standard errors provides a reliable framework for identifying the relationship between regional public spending and renewable energy development in Ukraine.

Given the short panel and the relatively large number of explanatory variables, the estimates are interpreted as conditional associations rather than causal effects. A limitation of the study is related to data availability in the context of the ongoing war. Following Russia's large-scale attacks on Ukraine's energy infrastructure, access to detailed regional data on electricity production and installed capacity has been restricted for security reasons. As a result, consistent and reliable data are available only up to 2021, and the analysis does not include the war period. Consequently, the estimated relationships reflect the pre-war structure of interdependencies between regional public expenditures and renewable energy development. It is important to acknowledge that these relationships may have changed significantly under wartime conditions, as the destruction of centralized energy infrastructure and the growing role of decentralized energy systems are likely to alter both policy priorities and the effectiveness of different budgetary instruments.

All calculations and econometric analyses were conducted using the R statistical software environment.

3. RESULTS

The descriptive statistics (Table A1, Appendix A) indicate substantial cross-regional heterogeneity in both renewable energy outcomes and regional budget expenditures across Ukrainian regions during 2018–2021. The dataset is balanced, comprising 100 observations across all variables and spanning 25 regions over four years. The dependent variables reveal pronounced asymmetry in renewable energy development. The average volume of electricity generated from renewable energy sources is 300.52 million kWh. In comparison, the median is significantly lower at 89.68 million kWh, indicating that renewable generation is concentrated in a limited number of regions. A similar pattern is observed for installed capacity, with a mean of 2,549.56 MW and a median of 1,185.78 MW, alongside high standard deviations, confirming strong dispersion.

A key feature of the dataset is the extreme skewness and kurtosis of budget expenditure variables. For most spending categories, mean values substantially exceed medians, often by several orders of magnitude, reflecting the presence of large outliers and highly uneven allocation of public funds. For example, expenditures on contributions to the statutory capital of enterprises have a mean of 56.06 million UAH, whereas the median is only 1.13 million UAH. At the same time, several categories, such as electric transport measures and activities financed through target funds, show median values of 0. This indicates that many regional-year observations recorded no spending in these categories, suggesting that such programs were implemented selectively rather than systematically.

The distributions of expenditure variables are strongly right-skewed, with skewness coefficients typically ranging from 3 to 7 and extremely high kurtosis values, in some cases exceeding 40. This implies heavy-tailed distributions with a concentration of observations at low levels and a small number of extreme values. Similar, though less pronounced, patterns are observed in the dependent and control variables, including gross regional product and environmental investments, which also exhibit positive skewness and high dispersion.

These descriptive results highlight three important empirical features. First, renewable energy development in Ukraine is highly uneven across regions. Second, regional budget expenditures on economic activity, environmental protection, and energy efficiency exhibit strong asymmetry and concentration. Third, the presence of zero values and extreme outliers justifies the use of logarithmic transformation and panel estimation techniques robust to heterogeneity and non-normality. A detailed summary of all variables is presented in Table A1 in Appendix A.

Given the data's distributional properties, variable transformation is essential for reliable econometric estimation. The descriptive statistics show that most expenditure variables are highly right-skewed, with large differences between mean and median values and very high skewness and kurtosis, indicating the presence of extreme observations. In addition, several budget categories contain a substantial number of zero values, reflecting the absence of spending in certain regions or years. Estimating models in levels under such conditions may lead to biased results, heteroskedastic residuals, and an overemphasis on outliers. To address these issues, all monetary variables are transformed using the natural logarithm of (x + 1), which allows zero observations to be retained while reducing skewness and stabilizing variance. This transformation is also associated with a greater elasticity-based interpretation of coefficients, enabling a consistent and economically meaningful comparison of the effects of different expenditure programs on renewable energy development.

The results of the contemporaneous two-way fixed effects models (Table 1) provide important insights into the relationship between regional budget expenditures and renewable energy development in Ukraine. Two dependent variables are considered: installed renewable energy capacity and renewable electricity production, allowing for a distinction between investment outcomes and actual energy generation.

Table 1. Two-way fixed effects regression results (non-lagged models)

Variables	(1) Capacity	(2) Production
ln_cofin_dfrd	−0.0009	−0.0269**
	(0.0027)	(0.0057)
ln_socioeco_territ	0.0076	0.0069
	(0.0157)	(0.0077)
ln_capital_enterprise	0.0082	0.0063†
	(0.0077)	(0.0029)
ln_target_funds	0.0102	−0.0058
	(0.0075)	(0.0034)
ln_other_econ	0.0194	0.0176
	(0.0171)	(0.0100)
ln_energy_save	−0.0117	−0.0235
	(0.0116)	(0.0130)
ln_sme_support	0.0246**	0.0045
	(0.0065)	(0.0064)
ln_electrotransport	0.0783**	−0.0121
	(0.0124)	(0.0092)
ln_natural_resources	0.0125**	0.0138
	(0.0031)	(0.0077)
ln_eco_target_funds	−0.0821†	−0.0912
	(0.0459)	(0.0550)
ln_other_ecology	0.0172**	0.0022
	(0.0032)	(0.0021)
ln_grp	−2.1503†	−2.4757*
	(1.1774)	(1.0578)
ln_env_invest	0.0140	−0.0721**
	(0.0296)	(0.0125)

Note: Dependent variables: Model (1): ln(Installed RES capacity) and Model (2): ln(RES electricity production). Estimator – Two-way Fixed Effects. Fixed effects – Region and Year. Standard errors –Driscoll-Kraay (HC1). Observations – 100. Standard errors in parentheses. Significance codes: ** p < 0.01, * p < 0.05, † p < 0.1. All variables are in logarithmic form (log(x+1)).

For installed renewable energy capacity, only a limited number of expenditure categories exhibit statistically significant associations. In particular, spending on support for SMEs is positively and significantly associated with renewable capacity (β = 0.0246, $p < 0.001$), suggesting that a 1% increase in SME support is associated with approximately a 0.025% increase in installed RES capacity, ceteris paribus. Expenditure on electric transport shows the largest positive association with installed RES capacity (β = 0.0783, $p < 0.001$), indicating substantial elasticity and a comparatively strong positive association with infrastructure-related expenditure for renewable energy expansion.

Additionally, spending on the protection and rational use of natural resources (β = 0.0125, $p <$ 0.001) and other environmental activities (β =

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0.0172, $p < 0.001$) is positively associated with installed RES capacity. In contrast, most economic and investment-related spending categories, including co-financing through the State Regional Development Fund, socio-economic development programs, and general economic activity expenditures, are not statistically significant, suggesting that their impact on renewable capacity is either weak or indirect.

Among control variables, gross regional product (GRP) exhibits a negative effect at the 10% significance level ($\beta = -2.15$, $p \approx 0.073$), which may reflect structural differences whereby more economically developed regions rely less on expanding installed renewable capacity or have already reached higher levels of infrastructure saturation. Environmental investment is not statistically significantly associated with capacity in this specification.

Turning to renewable electricity production, the results differ notably. Several expenditure categories demonstrate statistically significant or marginally significant effects, although the pattern is less consistent. Most importantly, co-financing of investment projects through the State Regional Development Fund shows a negative and highly significant coefficient ($\beta = -0.0269$, $p < 0.001$), indicating that higher spending in this category is associated with lower contemporaneous renewable electricity production. This may reflect timing issues, where funds are allocated to projects that are not yet operational within the same year.

Contributions to enterprises' statutory capital are positively associated with renewable electricity production ($\beta = 0.0063$, $p < 0.05$), suggesting that direct financial support to firms may be associated with higher renewable energy output. Several other variables, including other economic activity measures, natural resource management, and energy-saving measures, show weak significance at the 10% level, indicating potential but less robust relationships.

Among the control variables, gross regional product again shows a negative, statistically significant association ($\beta = -2.48$, $p < 0.05$), reinforcing the interpretation of structural differences across regions. Notably, capital investments in environmental protection exhibit a statistically significant negative association ($\beta = -0.0721$, $p < 0.001$), which may indicate that such investments are directed toward mitigation or remediation activities rather than immediate increases in renewable energy output, or that their effects materialize with a time lag.

The results suggest that the associations between regional budget programs and renewable energy development vary substantially across expenditure categories and outcomes. Infrastructure-related and environmental expenditures appear to be more relevant for expanding installed capacity, while financial support to enterprises shows a comparatively stronger association with electricity generation. The presence of negative or insignificant coefficients in several categories highlights the importance of accounting for timing effects, reinforcing the need for lagged specifications in subsequent analysis.

The lagged two-way fixed effects specification reported in Table 2 examines whether regional budget expenditure in the year (t − 1) is associated with renewable energy outcomes in the year t, while controlling for time-invariant regional characteristics and common annual shocks. The one-year lag is intended to capture the implementation period required for public programs to influence infrastructure investment, installed renewable energy capacity, and subsequent electricity generation. Given the short time dimension of the panel, however, the coefficients should be interpreted as conditional delayed associations rather than causal effects.

For installed renewable energy capacity, several expenditure categories display statistically significant positive lagged associations. Expenditure on socio-economic development projects is positively associated with subsequent capacity ($\beta = 0.0202$, $p = 0.036$), implying that a 1% increase in this category in the previous year is associated with an approximately 0.020% increase in installed RES capacity. Measures financed through local target funds show a slightly larger positive association ($\beta = 0.0253$, $p < 0.001$), while expenditure on energy-saving programs is also positive and highly significant ($\beta = 0.0208$, $p < 0.001$). SME support remains one of the most consistent predictors ($\beta = 0.0244$, $p < 0.001$), suggesting that local business-support

Table 2. Two-way fixed effects estimates (lagged specification, (t – 1)) with Driscoll–Kraay standard errors

Variables	Installed RES capacity (ln)	Renewable electricity production (ln)
Co-financing of projects (State Regional Development Fund)	–0.0018	–0.0215***
	(0.0022)	(0.0009)
Socio-economic development programs	0.0202*	0.0046†
	(0.0093)	(0.0025)
Contributions to the statutory capital of enterprises	0.0049	0.0021
	(0.0031)	(0.0055)
Local target funds	0.0253***	0.0271†
	(0.0030)	(0.0145)
Other economic activities	0.0017	0.0010
	(0.0052)	(0.0010)
Energy-saving programs	0.0208***	0.0105
	(0.0056)	(0.0068)
SME support	0.0244***	0.0034**
	(0.0040)	(0.0012)
Electric transport	0.0615***	–0.0135
	(0.0094)	(0.0089)
Protection and rational use of natural resources	0.0050	0.0035
	(0.0045)	(0.0059)
Environmental measures financed through target funds	–0.0361†	–0.0886**
	(0.0194)	(0.0316)
Other environmental activities	0.0076	0.0024
	(0.0049)	(0.0040)
Gross regional product	0.5506	–0.1198
	(0.6603)	(0.9993)
Capital investment in environmental protection	0.0666†	0.1106***
	(0.0359)	(0.0215)
Region fixed effects	Yes	Yes
Year fixed effects	Yes	Yes
Model	Two-way Fixed Effects	Two-way Fixed Effects
Observations	75	75

Note: Standard errors are reported in parentheses. All explanatory and control variables are lagged by one year and transformed using ln(x + 1). Region- and year-fixed effects are included in all specifications. Driscoll–Kraay heteroskedasticity- and autocorrelation-consistent standard errors are reported. Significance levels: *** p < 0.001, ** p < 0.01, * p < 0.05, † p < 0.10.

measures may create favorable conditions for decentralized renewable investment and smaller-scale private projects. Expenditure on electric transport exhibits the largest positive estimated association with installed capacity ($\beta = 0.0615$, $p < 0.001$), which may reflect complementarities between electrification infrastructure, electricity demand, and renewable energy integration.

The lagged production model reveals a different pattern. Co-financing through the State Regional Development Fund is negatively associated with renewable electricity production ($\beta = -0.0215$, $p < 0.001$), which may indicate a timing mismatch between budget allocation and project operation. By contrast, SME support is positively associated with subsequent generation ($\beta = 0.0034$, $p = 0.006$), while capital investment in environmental protection shows the largest positive delayed association with production ($\beta = 0.1106$, $p < 0.001$). Socio-economic development expenditure ($\beta = 0.0046$, $p = 0.072$) and local target funds ($\beta = 0.0271$, $p = 0.070$) are positive but only marginally significant. Environmental measures financed through target funds show a statistically significant negative association with production ($\beta = -0.0886$, $p = 0.008$), whereas contributions to statutory capital, other economic activities, energy-saving programs, electric transport, natural resource management, other environmental activities, and GRP are not statistically significant in the lagged production specification.

The comparison between contemporaneous and lagged estimates reveals distinct temporal patterns.

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Electric transport and SME support remain positively associated with installed capacity in both specifications, suggesting relatively persistent relationships. Socio-economic development projects, local target funds, and energy-saving programs become significant only after one year, suggesting that their association with capacity may emerge over time. Conversely, natural resource management and other environmental activities are significant only in the contemporaneous capacity model. For electricity production, the positive contemporaneous association of statutory capital contributions is not sustained after one year, while environmental investment changes from a negative contemporaneous association to a strong positive lagged association. These differences demonstrate that regional expenditure programs operate through different channels and time horizons and should not be treated as a homogeneous group.

The results, therefore, point to a differentiated policy interpretation. Programs related to electric transport, SME development, energy saving, local target funds, and territorial socio-economic development show the clearest positive delayed associations with installed capacity. In contrast, environmental investment is more strongly associated with subsequent electricity production. This pattern is consistent with the indirect nature of regional support for renewable energy in Ukraine, where public budgets may not finance renewable installations directly but instead strengthen complementary infrastructure, improve local investment conditions, support firms, and reduce implementation barriers. At the same time, the negative associations observed for State Regional Development Fund co-financing and environmental target funds indicate that program design, implementation timing, and expenditure compo-

Table 3. Robustness analysis: Lagged two-way fixed effects models with region-clustered standard errors (Arellano HC1)

Variables	Installed RES capacity	Renewable electricity production
Lagged co-financing of State Regional Development Fund projects	–0.0018	–0.0215
	(0.0119)	(0.0146)
Lagged socio-economic development projects	0.0202†	0.0046
	(0.0112)	(0.0121)
Lagged contributions to statutory capital	0.0049	0.0021
	(0.0073)	(0.0074)
Lagged local target funds	0.0253	0.0271
	(0.0218)	(0.0192)
Lagged other economic activities	0.0017	0.0010
	(0.0130)	(0.0145)
Lagged energy-saving programs	0.0208*	0.0105
	(0.0094)	(0.0121)
Lagged SME support	0.0244†	0.0034
	(0.0143)	(0.0115)
Lagged electric transport	0.0615***	–0.0135
	(0.0120)	(0.0127)
Lagged natural resource management	0.0050	0.0035
	(0.0067)	(0.0056)
Lagged environmental target funds	–0.0361*	–0.0886***
	(0.0153)	(0.0126)
Lagged other environmental activities	0.0076	0.0024
	(0.0193)	(0.0154)
Lagged gross regional product	0.5506	–0.1198
	(1.7948)	(2.1077)
Lagged environmental investment	0.0666	0.1106
	(0.0915)	(0.0995)

Note: Two-way fixed effects estimates. Robust standard errors clustered at the regional level (Arellano HC1) are reported in parentheses. Standard errors are clustered by region to account for within-region serial correlation and heteroskedasticity. Significance levels: *** $p < 0.001$; ** $p < 0.01$, * $p < 0.05$, † $p < 0.10$.

sition may be as important as the overall amount allocated.

To examine whether the results are sensitive to the choice of covariance estimator, the lagged two-way fixed effects models were re-estimated using Arellano heteroskedasticity-consistent standard errors clustered at the regional level (Table 3). Compared with the baseline Driscoll–Kraay estimates, the estimated coefficients remain virtually unchanged in both sign and magnitude, indicating that the relationships identified in the main analysis are stable. However, as expected, clustered standard errors are generally larger, leading to lower statistical significance for several expenditure categories. This finding reflects the conservative nature of cluster-robust inference in short regional panels and suggests that some relationships should be interpreted with greater caution.

For installed renewable energy capacity, expenditure on electric transport remains the most robust predictor across specifications (β = 0.0615, $p < 0.001$), indicating that infrastructure-related expenditure retains the strongest positive association with subsequent RES capacity expansion. Energy-saving programs also retain statistical significance (β = 0.0208, $p = 0.033$), while expenditures on socio-economic development projects (β = 0.0202, $p = 0.079$) and SME support (β = 0.0244, $p = 0.098$) remain positively associated at the 10% significance level. By contrast, local target funds, which were highly significant under Driscoll–Kraay estimation, lose statistical significance once regional clustering is introduced, indicating that their estimated relationship is more sensitive to the treatment of within-region error correlation. Environmental measures financed through target funds remain negatively associated with installed capacity (β = –0.0361, $p = 0.024$), representing the only statistically significant negative relationship in the capacity model.

The robustness results for renewable electricity production are more conservative. After clustering standard errors at the regional level, only environmental measures financed through target funds remain statistically significant (β = –0.0886, $p < 0.001$), indicating a persistent negative association with renewable electricity generation in the following year. All remaining expenditure categories, including State Regional Development Fund co-financing, SME support, environmental investment, and electric transport, lose statistical significance despite retaining coefficient signs similar to those obtained in the baseline specification. This suggests that estimated relationships with renewable electricity production are less stable than those observed for installed capacity and may be more sensitive to regional heterogeneity and the limited time dimension of the dataset.

The robustness analysis strengthens confidence in the study's principal conclusions while highlighting the importance of cautious statistical inference. The stability of coefficient signs and magnitudes across covariance estimators suggests that the estimated associations are not driven solely by model specification. At the same time, the reduction in statistical significance for several variables confirms that the evidence should be interpreted as exploratory, particularly given the short panel (2018–2021) and the relatively small number of regional observations.

The reduced lagged model for installed RES capacity (Table 4) confirms that the principal associations are not solely driven by the large number of regressors in the baseline specification. Under Driscoll–Kraay standard errors, socio-economic development expenditure (β = 0.0184, $p = 0.034$), local target funds (β = 0.0353, $p < 0.001$), energy-saving programs (β = 0.0232, $p < 0.001$), SME support (β = 0.0243, $p < 0.001$), and electric transport expenditure (β = 0.0623, $p < 0.001$) remain positively associated with subsequent installed capacity. When standard errors are clustered by region, electric transport, local target funds, and energy-saving expenditure retain conventional statistical significance. At the same time, socio-economic development remains marginally significant, and SME support loses significance. Environmental target funds remain negatively associated with capacity under region-clustered inference (β = –0.0341, $p = 0.030$). Overall, the similarity in coefficient signs and magnitudes across the two covariance estimators indicates that the reduced model preserves the substantive pattern found in the full specification. However, the significance of SME support and environmental investment is sensitive to the treatment of within-region dependence.

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Table 4. Robustness analysis: Reduced lagged two-way fixed effects models

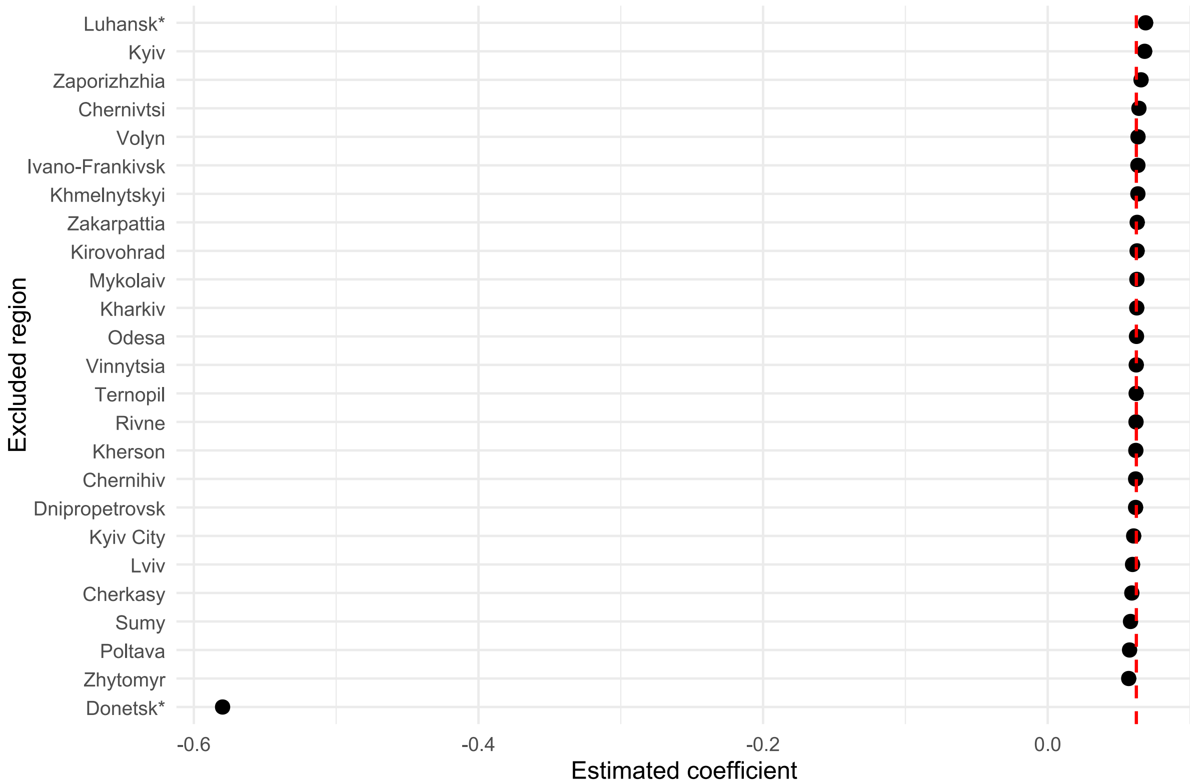
Variables	Capacity: DK SE	Capacity: Clustered SE	Production: DK SE	Production: Clustered SE
Socio-economic development programs	0.0184*	0.0184†	0.0017	0.0017
	(0.0084)	(0.0104)	(0.0012)	(0.0132)
Local target funds	0.0353***	0.0353***	0.0266*	0.0266***
	(0.0037)	(0.0073)	(0.0099)	(0.0074)
Energy-saving programs	0.0232***	0.0232**	0.0077	0.0077
	(0.0060)	(0.0079)	(0.0077)	(0.0107)
SME support	0.0243***	0.0243	0.0057*	0.0057
	(0.0061)	(0.0175)	(0.0025)	(0.0106)
Electric transport	0.0623***	0.0623***	−0.0193**	−0.0193
	(0.0084)	(0.0106)	(0.0071)	(0.0123)
Environmental target funds	−0.0341†	−0.0341*	−0.0876*	−0.0876***
	(0.0198)	(0.0152)	(0.0352)	(0.0133)
Environmental investment	0.0847†	0.0847	0.1114**	0.1114
	(0.0432)	(0.0834)	(0.0335)	(0.0898)
Gross regional product	0.2137	0.2137	0.2306	0.2306
	(0.7240)	(1.7386)	(0.7899)	(1.9611)
Region fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
Observations	75	75	75	75

Note: All explanatory variables and controls are lagged by one year. Continuous variables are transformed using ln(x + 1). Columns labeled "DK SE" report Driscoll-Kraay HC1 standard errors, while columns labeled "Clustered SE" report Arellano HC1 standard errors clustered by region. Standard errors are shown in parentheses. Significance levels: *** p < 0.001, ** p < 0.01, ** p < 0.05, * p < 0.10.

The reduced production model (Table 4) produces a more selective pattern. Under Driscoll–Kraay standard errors, local target funds (β = 0.0266, p = 0.010), SME support (β = 0.0057, p = 0.030), and environmental investment (β = 0.1114, p = 0.002) is positively associated with subsequent renewable electricity production, whereas electric transport (β = −0.0193, p = 0.009) and environmental target funds (β = −0.0876, p = 0.017) are negatively associated. After clustering standard errors by region, only local target funds and environmental target funds remain statistically significant, while the remaining coefficients retain their signs but lose significance. These results suggest that the association between regional expenditures and installed capacity is more stable than the corresponding relationship with electricity production. They also reinforce the need to interpret the production estimates cautiously, as their statistical significance is more sensitive to the covariance estimator and the short time dimension of the panel.

Figure 1 presents a leave-one-region-out sensitivity analysis for the lagged electric-transport coefficient in the installed-capacity model. This coefficient was selected because electric-transport expenditure exhibited the largest positive association with subsequent installed RES capacity and remained statistically significant across the main and robustness specifications, making it one of the study's central empirical findings. The installed-capacity model was examined because the corresponding coefficient in the electricity-production model was not statistically significant, indicating that electric-transport expenditure is more closely associated with capacity expansion than with short-term generation. The model was re-estimated 25 times, excluding one region per iteration, to determine whether the estimated relationship was driven by a particular region. In most cases, the coefficient remained positive and close to the full-sample estimate, though excluding Donetsk produced a substantial change, suggesting this result should be interpreted with caution.

The broader leave-one-region-out analysis also identified several influential regional observations in the remaining model coefficients. Excluding Kherson produced the largest change in the estimated coefficient for local target funds in both



Note: For the Donetsk and Luhansk regions, the data refer only to the territories under the control of the Government of Ukraine during the analyzed period.

Figure 1. Leave-one-region-out sensitivity of the lagged electric-transport coefficient in the installed-capacity model

the installed-capacity and electricity-production models, while Kyiv had the strongest influence on the environmental-investment coefficient. The estimates for environmental target funds and GRP were most sensitive to the exclusion of Chernivtsi. Although most coefficients retained broadly similar signs and magnitudes across the leave-one-region-out specifications, these cases indicate that selected relationships are partly dependent on particular regional observations. Therefore, the estimates for local target funds, electric transport, environmental investment, and environmental target funds should be treated as exploratory and interpreted with appropriate caution.

The baseline, lagged, reduced-model, covariance-estimator, and leave-one-region-out analyses show that the empirical evidence is stronger and more stable for installed renewable energy capacity than for electricity production. Electric transport expenditure emerges as the most consistent positive correlate of subsequent capacity expansion, while energy-saving programmes and, to a lesser extent, socio-economic development and SME support also retain positive associations across several specifications. However, the sensitivity of selected coefficients to the exclusion of Donetsk, Kherson, Kyiv, and Chernivtsi, together with the loss of significance under region-clustered standard errors, indicates that the findings should be interpreted as exploratory regional associations rather than definitive evidence of programme effectiveness.

4. DISCUSSION AND LIMITATIONS

The findings suggest that selected regional budget programs exhibit stronger estimated associations with renewable energy development than broader expenditure categories. However, these relationships should be interpreted as observational rather than causal. Expenditure on electric transport and SME support show the most consistent positive associations with installed renewable energy capacity across the contemporaneous

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and lagged specifications. This is consistent with the broader argument that public finance may be more closely connected to renewable energy expansion when it helps reduce market barriers, strengthen complementary infrastructure, and support innovation ecosystems rather than relying solely on direct project financing (Fernandes et al., 2025; Raboshuk et al., 2025). The positive association between SME support and installed capacity is also consistent with the importance of entrepreneurial and decentralized dynamics in renewable energy development (Fitriningrum et al., 2025; Belgibayeva et al., 2025) and with evidence that fiscal decentralization may improve policy responsiveness and alignment with local conditions (Lyeonov et al., 2025).

The corrected lagged estimates also reveal substantial heterogeneity in the timing and strength of the observed relationships. Socio-economic development projects, expenditures financed through local target funds, and energy-saving programs become statistically significant only in the one-year-lag specification. In contrast, natural resource management and other environmental activities are significant only in the contemporaneous model. This suggests that regional expenditure categories operate through different implementation cycles and should not be treated as homogeneous policy instruments. Most broad economic expenditure categories remain statistically insignificant, indicating that general fiscal measures may be less closely associated with renewable energy outcomes than targeted programs (Filipova et al., 2025; Hedau & Malla, 2024). This interpretation is consistent with evidence that public investment effects may emerge only after planning, construction, and implementation stages, while some expenditures initially support regulatory, preparatory, or enabling activities rather than immediate energy output (Binh & Nguyen, 2024; Hennach & Echaoui, 2026).

A key contribution of the study is therefore the identification of distinct temporal and functional patterns in the relationship between regional budgets and renewable energy development. The strongest delayed associations are observed for electric transport, SME support, energy-saving measures, local target funds, and territorial socio-economic development programs, suggesting that indirect and complementary expenditure channels may be particularly relevant for expanding installed capacity. At the same time, the results should not be interpreted as definitive evidence of program effectiveness, because the short panel, the one-year lag, and the relatively large number of regressors limit causal inference and long-term interpretation. These findings complement earlier research on infrastructure, regional development, and system-level energy transitions (Morshed & Khrais, 2026; Nakamura et al., 2012) and are especially relevant for Ukraine, where wartime destruction and the growing importance of decentralized energy systems may substantially alter the pre-war relationships identified here (Dobrovolska et al., 2024a; Pecheniuk et al., 2024).

This study has several limitations that should be considered when interpreting the results. First, the analysis covers only 2018–2021 because regional data on renewable electricity production and installed capacity have not been publicly available since 2022 due to security restrictions following Russia's attacks on Ukraine's energy infrastructure. Consequently, the study cannot capture wartime structural changes or longer-term relationships. The short time dimension of the panel (T = 4) also reduces statistical power. At the same time, a one-year lag may be insufficient to reflect the full implementation cycle of renewable energy projects. Second, although the two-way fixed effects approach controls for time-invariant regional characteristics and common annual shocks, potential endogeneity, including reverse causality between regional development and renewable energy investment, may remain. Third, including numerous expenditure categories in a sample of 100 region-year observations creates a substantial parameter burden and may increase coefficient instability, particularly when variables are correlated or exhibit limited within-region variation. The use of aggregated budget categories also prevents a detailed assessment of program design, implementation quality, and allocation efficiency. Finally, despite logarithmic transformation and robust standard errors, the estimates may be sensitive to individual regions and extreme expenditure observations. The findings and policy implications should therefore be regarded as exploratory rather than definitive evidence of program effectiveness.

Future research should extend the analysis when post-2021 data become available, examine longer lag structures, apply more parsimonious and causal specifications, conduct sensitivity tests for influential regions and outliers, and use project-level data to identify more precisely how particular budget programs support decentralized and resilient renewable energy systems.

CONCLUSION

This study set out to evaluate how different categories of regional public expenditures shape renewable energy development in Ukraine, with particular attention to the distinction between investment outcomes, reflected in installed capacity, and operational outcomes, captured by electricity generation. The analysis aimed to identify which budget programs exhibit the strongest associations with renewable energy outcomes and to assess whether regional public finance is systematically associated with the energy transition.

The findings provide exploratory evidence that targeted infrastructure, SME-support, and selected environmental programs are more closely associated with renewable energy development than broad expenditure categories. In the contemporaneous capacity model, electric transport expenditure shows the largest positive association with installed RES capacity ($\beta \approx 0.078$, $p < 0.001$), followed by SME support ($\beta \approx 0.025$, $p < 0.001$), other environmental activities ($\beta \approx 0.017$, $p < 0.001$), and natural resource management ($\beta \approx 0.013$, $p < 0.001$). The lagged estimates reveal a different temporal pattern: electric transport ($\beta \approx 0.061$, $p < 0.001$) and SME support ($\beta \approx 0.024$, $p < 0.001$) remain significant, while socio-economic development projects ($\beta \approx 0.020$, $p < 0.05$), local target funds ($\beta \approx 0.025$, $p < 0.001$), and energy-saving measures ($\beta \approx 0.021$, $p < 0.001$) become significant only after one year. For renewable electricity production, the lagged model identifies a strong positive association with environmental investment ($\beta \approx 0.111$, $p < 0.001$) and a smaller positive association with SME support ($\beta \approx 0.003$, $p < 0.01$), whereas State Regional Development Fund co-financing ($\beta \approx -0.022$, $p < 0.001$) and environmental target funds ($\beta \approx -0.089$, $p < 0.01$) are negatively associated with the subsequent generation. Overall, the results indicate that different regional budget programs are associated with installed capacity and electricity production through different channels and time horizons. Given the short panel, the one-year lag, and the substantial parameter burden, these findings should be treated as exploratory rather than definitive evidence of program effectiveness.

From a policy perspective, the findings suggest that regional support for renewable energy in Ukraine may be more strongly associated with indirect and complementary budget programmes than with direct public financing of renewable energy projects. Expenditure on electric transport, SME support, energy-saving measures, local target funds, and territorial development programmes exhibits the strongest positive associations with subsequent installed renewable energy capacity, highlighting the potential importance of integrating renewable energy objectives into broader regional development policies. Nevertheless, these results should be interpreted cautiously and combined with cost-effectiveness analysis, project-level evidence, and longer-term data before informing policy priorities.

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APPENDIX A

Table A1. Descriptive statistics of variables used in the empirical analysis

Variable	N	Mean	SD	Median	Min	Max	Skewness	Kurtosis
Co-financing of investment projects implemented through the State Regional Development Fund	100	41,144,952.74	91,694,547.38	17,296,794.45	0.00	631,034,000.00	4.67	23.17
Environmental measures within socio-economic development programs for specific territories	100	31,680,665.25	53,094,113.77	13,122,518.75	0.00	287,568,700.00	3.06	9.97
Contributions to the statutory capital of business entities	100	56,059,885.05	292,169,860.06	1,131,360.39	0.00	2,125,000,000.00	6.51	41.79
Measures financed through target funds established by the AR Crimea, local self-government bodies, and local executive authorities	100	11,676,873.98	57,884,043.13	0.00	0.00	319,214,300.00	4.72	20.76
Other measures related to economic activity	100	55,824,197.09	248,606,774.15	3,356,578.55	0.00	2,014,610,000.00	6.09	40.16
Energy-saving measures	100	5,861,443.57	16,943,059.14	349,880.54	0.00	138,958,200.00	5.50	36.84
Support for SMEs	100	1,684,669.05	5,379,305.75	645,996.18	0.00	44,285,370.00	6.65	45.65
Other measures in the field of electric transport	100	44,501,984.92	243,436,155.97	0.00	0.00	1,771,289,000.00	5.86	34.86
Protection and rational use of natural resources	100	10,236,205.90	23,367,820.33	893,230.63	0.00	116,201,900.00	3.26	10.49
Environmental measures financed through target funds	100	15,753,694.10	44,919,298.07	173,278.10	0.00	250,019,600.00	4.13	17.12
Other activities in the field of ecology and environmental protection	100	8,555,551.75	32,247,074.70	0.00	0.00	211,742,600.00	4.88	24.58
Volume of electricity generated from RES, million kWh	100	300.52	459.66	89.68	0.00	2,079.96	2.21	4.52
Installed RES capacity, MW	100	2,549.56	3,368.92	1,185.78	2.63	13,987.91	1.80	2.66
Gross regional product, million UAH	100	172,103.75	200,392.15	98,106.00	33,905.00	1,276,376.00	3.42	13.06
Capital investments in environmental protection, current prices, thousand UAH	100	536,833.36	1,170,819.76	78,304.60	6,864.90	6,945,708.00	3.60	14.18

Note: The balanced dataset covers 25 Ukrainian regions over 2018–2021, yielding 100 region-year observations.