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## DECARBONISATION AND INFORMALITY: EMPIRICAL EVIDENCE ON THE SHADOW ECONOMY RESPONSE TO CLIMATE POLICY MIX

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**ABSTRACT.** The persistence of the shadow economy poses a significant challenge to effective climate governance, as informal firms often bypass environmental regulations and carbon pricing mechanisms. This study examines the impact of various climate and energy policy instruments on the size of the shadow economy in OECD and partner countries. Drawing on annual panel data from 34 countries between 2010 and 2023, the analysis employs fixed effects models, Driscoll–Kraay robust estimation, and the System Generalised Method of Moments (System GMM), with all calculations performed in R Studio. The results show that feed-in tariff schemes, renewable energy auctions, air emission standards, and fossil fuel excise taxes are associated with statistically significant reductions in informal economic activity. For instance, in the Driscoll–Kraay model, feed-in tariffs ( $\beta = -0.0626$ ,  $p < 0.001$ ), renewable energy auctions ( $\beta = -0.2578$ ,  $p = 0.007$ ), air emission standards ( $\beta = -0.1685$ ,  $p < 0.001$ ), and fossil fuel taxes ( $\beta = -0.7285$ ,  $p < 0.001$ ) all exert measurable downward pressure on the size of the shadow economy. Additionally, the dynamic panel model reveals a high degree of path dependence: the size of the shadow economy in previous years strongly predicts its current level ( $\beta = 0.9679$ ,  $p < 0.001$ ), indicating structural inertia that may limit the short-term effectiveness of policy reforms. Notably, time-fixed effects suggest that the year 2013 marked a significant turning point, with a marked decline in shadow economic activity ( $\beta = -0.227$ ,  $p = 0.022$ ), possibly reflecting the cumulative effects of climate legislation introduced in prior periods.

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## Introduction

The nexus between climate and energy policy and the shadow economy is increasingly recognised as a critical dimension of sustainable development, economic governance, and climate resilience. As global economies navigate the green transition, questions arise not only about decarbonisation and energy efficiency, but also about the implications of policy instruments for informality, fiscal stability, and institutional trust. This research addresses a timely and understudied issue: how climate and energy policy instruments shape the size and dynamics of the shadow economy.

The World Bank has repeatedly emphasised that reducing informality is crucial for promoting inclusive growth, strengthening tax bases, and encouraging investment in productivity-enhancing technologies. In its development policy frameworks, the Bank has highlighted the role of formalisation measures, including digital tax systems, targeted subsidies, and regulatory enforcement, as crucial levers for reducing the shadow economy and increasing economic transparency (Amin et al., 2019). Digital transformation and enhanced regulatory frameworks demonstrate significant potential in combating informal economic activities, as evidenced by successful implementation of advanced monitoring systems and transparent reporting mechanisms that effectively reduce opportunities for fraudulent practices and tax evasion (Bhasin, 2016). Moreover, informal economies tend to flourish in areas where governance is weak and enforcement mechanisms are under-resourced, making climate-related regulatory efforts more challenging to implement and monitor effectively.

Simultaneously, the International Monetary Fund has begun integrating climate considerations into its macroeconomic surveillance, recognising that climate policy design must account for structural features such as informality and fiscal leakage. According to IMF reports, climate policy instruments, particularly carbon pricing, fossil fuel subsidy reform, and green tax incentives, can reshape production incentives and labour market dynamics, potentially pushing informal actors toward formal participation when designed equitably and accompanied by administrative support (Tebrake et al., 2024). However, in economies with large informal sectors, such instruments may have regressive effects if not carefully targeted, necessitating further empirical exploration.

From the perspective of energy governance, the International Energy Agency and the International Renewable Energy Agency, in coordination with the World Bank, the United Nations Statistics Division, and the World Health Organisation, have published multiple joint reports tracking progress toward SDG 7 (Affordable and Clean Energy). These reports demonstrate that the most successful transitions toward renewable energy occur in institutional environments with policy consistency, fiscal transparency, and strong planning capacities. Where informal energy use is prevalent, such as in informal settlements or off-grid industries, poorly targeted climate policies can exacerbate exclusion, underscoring the need for coherent governance frameworks that integrate formalisation strategies with climate action (IEA, IRENA, UNSD, World Bank, WHO, 2022).

Furthermore, the OECD has highlighted that fossil fuel subsidies distort market signals and disproportionately benefit wealthier households and capital-intensive firms. Recent OECD estimates indicate that global fossil fuel subsidies surged to nearly USD 1 trillion in 2022, thereby undermining environmental goals and economic fairness. Subsidy reform, through the imposition of excise taxes, carbon pricing mechanisms, and gradual phase-out schemes, has been shown to reduce both greenhouse gas emissions and the fiscal spaces that often enable unregulated informal activities to persist (OECD, 2024). Comprehensive sustainability assessments demonstrate that renewable energy transition effectiveness varies significantly across European countries, with Scandinavian nations achieving superior sustainability indicators through robust policy frameworks, while Eastern European countries face greater challenges in transitioning from fossil fuel-based systems (Drożdż et al., 2023). Such reforms are especially relevant in economies where informal fuel distribution or tax evasion related to energy consumption is widespread.

The energy transition is not only a technological and environmental challenge but also an institutional and economic one. In many countries, especially emerging and transition economies, large segments of economic activity remain informal, unregistered, untaxed, and unregulated. This shadow economy undermines the effectiveness of climate and energy policy instruments by allowing firms and households to circumvent environmental standards, avoid carbon pricing, and engage in unmonitored resource consumption. As a result, the presence of a sizeable informal sector can significantly distort the intended outcomes of decarbonisation strategies, reduce fiscal space for green investments, and weaken the enforcement of environmental regulations. Understanding the interplay between energy policy and the shadow economy is therefore critical to designing climate instruments that are both effective and inclusive.

These institutional insights converge on a central message: climate and energy policy instruments have far-reaching implications beyond environmental performance. They shape tax compliance, labour market formality, regulatory capacity, and economic inclusion. As such, evaluating their impact on the shadow economy is a matter of both academic relevance and practical urgency for governments seeking to ensure that climate transitions are socially just and financially sustainable. This research closes that knowledge gap by empirically investigating how diverse climate and energy policy tools influence informal economic activity across OECD and partner countries.

## 1. Literature review

The scientific discourse surrounding climate and energy policy has evolved beyond purely environmental objectives, increasingly emphasising socio-economic consequences such as informality, tax evasion, and entrepreneurial transparency. Traditionally influenced by institutional weaknesses and regulatory burdens, the shadow economy is now being reconsidered through ecological transformation, green finance, and policy-induced behavioural change. The intersection of environmental reforms and informality presents a dynamic field where regulatory innovation and market instruments exert transformative pressure on hidden economic activity.

A critical theme emerging from the literature is the capacity of green policies to indirectly incentivise transparency among firms, thereby shrinking the size of the shadow economy. Empirical analyses show that green fiscal measures, such as carbon pricing, excise taxes on fossil fuels, and feed-in tariffs, not only shift energy consumption patterns but also create traceable transactions that reduce incentives for firms to remain informal (Bai et al., 2024; Shcherbakova, 2025; Vasa et al., 2024). Specifically, renewable energy auctions and feed-in tariffs foster formal market entry by offering accessible and regulated platforms for

energy producers (Delcea et al., 2024; Badreddine & Cherif, 2024, Tomczyk et al., 2025). At the same time, studies highlight that green finance frameworks and transparent environmental tax systems can further diminish informality by altering the cost-benefit calculus for hiding economic activity (Vasylieva et al., 2020; Lyeonov et al., 2025b).

The literature also confirms that institutions determine whether climate actions contribute to formalisation or entrench dual economies. Evidence from European and emerging economies suggests that the success of climate-related reforms in reducing informality is closely tied to good governance, robust legal environments, and fair enforcement of environmental regulation (Dobrovolska et al., 2024b; Mazurenko et al., 2023; Dell'Anno et al., 2024; Kawecka-Wyrzykowska, 2025). Where climate strategies are accompanied by digitalisation, court transparency, and reduced tax pressure, they reinforce formal economic behaviour (Bozhenko et al., 2024; Czapkiewicz et al., 2025; Pimenowa et al., 2023).

Moreover, behavioural and ethical mechanisms are increasingly being explored. Regulatory compliance, perceived legitimacy of environmental policies, and public awareness significantly affect firms' decisions to operate formally (Ishwardat et al., 2024). Studies on greenwashing and social washing confirm that consumer and investor scrutiny also pressures firms to register, declare income, and comply with formal standards (Borusiak et al., 2024). Simultaneously, energy communities and sustainable public procurement have expanded the scope of actors subject to regulatory and transparency mechanisms (Delcea et al., 2024; Juracka et al., 2024).

The implications of these findings extend to sectoral and macroeconomic analyses. Studies on energy mix management, CO<sub>2</sub> efficiency, and electricity pricing reveal that transparent energy policy mechanisms generate formal economic responses across both the production and consumption sides (Bank & Badyda, 2024; Balcerzak et al., 2024; Dilanchiev et al., 2024; Georgescu et al., 2024). Countries with clear energy transition roadmaps and support for decentralised renewables tend to experience more substantial reductions in informality, especially when combined with social equity and fair pricing frameworks (Havrylenko & Myroshnychenko, 2025; Lu et al., 2020, 2021; Niță & Stoicuța, 2025; Mahmood & Furqan, 2025).

Beyond energy, links between environmental policy and the shadow economy are further explored through multi-dimensional variables such as CSR reporting, green innovation, and digital transformation (Habib et al., 2025; Lyeonov et al., 2024; Prokopenko et al., 2025; Krause et al., 2024; Tessema, 2025). These mechanisms promote environmental responsibility, enhance business transparency, and reduce the likelihood of undeclared operations. In emerging markets, climate policies are often seen as levers for institutional reform and economic modernisation, indirectly supporting formalisation (Thuong & My-Linh, 2025; Tran, 2024; Triantafyllidou et al., 2024).

Particular attention is also paid to the implications of state expenditure and public investment in green sectors. Governments that invest in renewable infrastructure and align public finances with environmental objectives foster conditions where firms are more likely to operate transparently and within legal frameworks (Filipova et al., 2025; Fernandes et al., 2025; Shcherbakova, 2025; Dobrovolska et al., 2024a). Furthermore, environmental education and generational attitudes, especially among Generation Z, reinforce long-term behavioural shifts away from shadow economic practices (Kedzior-Laskowska et al., 2025).

Lastly, risk and uncertainty emerge as moderating factors. Energy crises, inflation shocks, and regulatory paradoxes may temporarily push firms toward informality, yet targeted policy packages often mitigate these tendencies if well-communicated and consistently implemented (Shtunder et al., 2022; Rosiak et al., 2024; Balas & Kaya, 2024a, 2024b; Kuzior et al., 2021, 2023a, 2023b).

The linkage between shadow economic activity and renewable energy transitions is powerful in contexts where climate policies are embedded in broader governance reforms and public trust-building measures. Evidence from Eastern European and Mediterranean economies suggests that rising environmental awareness and inclusive policy design can significantly mitigate informality, particularly when combined with robust institutional enforcement and digital infrastructure (Sedmíková et al., 2021; Tessema, 2025; Ziabina et al., 2023). Meanwhile, if left unaddressed, energy security concerns may prompt economic actors to revert to informality, underscoring the importance of robust planning frameworks (Kuzior et al., 2023a; Georgescu et al., 2024). Moreover, transparent environmental taxation systems, when properly enforced, can effectively address both ecological risks and underground economic activity (Vasylieva et al., 2020).

On the other hand, energy poverty and income inequality persist as significant risks in energy transitions, potentially prolonging informal coping mechanisms in underserved areas. However, formalisation is accelerated when inclusive and region-specific mechanisms support energy transitions. This is evident in findings that farmers' self-assessment of energy needs and determinants of energy poverty significantly affect their integration into formal energy and economic systems (Piwowar, 2025). Likewise, disaggregated modelling of energy use and growth reveals that formalisation effects differ across income groups and energy profiles, particularly in emerging markets (Thach, 2025).

In addition, bibliometric analyses and survey-based studies support the argument that climate-related innovations in taxation, finance, and corporate governance are narrowing the space for grey markets (Lyeonov et al., 2025a; Noor et al., 2024; Ishwardat et al., 2024). This includes the deployment of AI and machine learning in regulatory monitoring, which improves the detection of tax evasion and unregistered transactions (Lyeonov et al., 2024; Lyeonov et al., 2025a).

The literature supports the view that climate and energy policy instruments can function as structural drivers of formalisation. By increasing the costs of informal operations and improving the institutional and financial environment for green business models, such policies reduce the economic viability of the shadow economy. This intersection warrants further empirical exploration and policy refinement to simultaneously optimise environmental and socio-economic outcomes.

This study aims to empirically assess the impact of various climate-related policy instruments, derived from the OECD Climate Actions and Policies Measurement Framework, on the size of the shadow economy across 34 countries from 2010 to 2023. By examining both market-based and command-and-control measures, the research aims to determine whether specific decarbonization tools contribute to reducing informal economic activity. The analysis applies panel econometric techniques, including Fixed Effects, Driscoll–Kraay robust estimation, and System GMM, to ensure robustness and account for potential endogeneity, autocorrelation, and unobserved heterogeneity.

## **2. Methodological approach**

### ***2.1. Data and variables***

This study employs an unbalanced panel dataset covering 34 countries from 2010 to 2023, with country selection guided by the availability of harmonised annual data on both the shadow economy and climate policy instruments. The countries include a balanced mix of EU and non-EU, OECD and non-OECD nations, such as Australia, Austria, Czechia, Canada, Belgium, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Japan,

Latvia, Lithuania, Luxembourg, Netherlands, New Zealand, Norway, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden, Switzerland, Türkiye, United Kingdom, Bulgaria, Croatia, Romania, and Malta.

The dependent variable ( $y$ ) is the size of the shadow economy as a percentage of official GDP, based on recent estimates by Schneider (2022) and updated by the Institute for Applied Economic Research (IAW, 2023), which reflect the informal sector's evolution during and after the COVID-19 crisis and amidst rising inflationary pressures.

The explanatory variables ( $x_1$  to  $x_{11}$ ) represent various climate and energy policy instruments drawn from the OECD Climate Actions and Policies Measurement Framework (Nachtigall et al., 2022). These variables include:

- Market-based instruments: ETS electricity price ( $x_1$ ), ETS GHG coverage ( $x_2$ ), carbon tax on electricity ( $x_3$ ), feed-in tariffs ( $x_5$ ), renewable energy auctions ( $x_6$ ), and fossil fuel excise taxes ( $x_{11}$ );
- Command-and-control regulations: air emission standards ( $x_{10}$ ), renewable energy certificates ( $x_7$ ), and coal phase-out bans ( $x_8$ );
- Strategic policy tools: reform of fossil fuel subsidies in electricity ( $x_4$ ) and planning for renewable energy expansion ( $x_9$ ).

All policy variables were extracted from the OECD Data Explorer (OECD, n.d.), which provides structured, country-specific, and policy-relevant annual data aligned with international reporting standards. This multidimensional policy dataset enables the model to capture both price-based and regulatory interventions, as well as their potential influence on informality in the economy.

The analysis is limited to the period up to 2023 due to data availability constraints in the international databases used.

## 2.2. Empirical strategy

The empirical strategy follows a multi-stage approach to robustly identify the relationship between climate policy instruments and the size of the shadow economy. First, descriptive and diagnostic statistics were computed for all variables. Due to the presence of non-normal distributions and high skewness in variables such as carbon tax ( $x_3$ ), auctions ( $x_6$ ), renewable certificates ( $x_7$ ), and fossil fuel taxes ( $x_{11}$ ), a Yeo–Johnson transformation was applied to stabilise variance and reduce skewness.

The core estimation method is the Fixed Effects (FE) panel regression model, which controls for time-invariant unobserved heterogeneity across countries. Given the strong correlation between regressors and unobserved effects, this model is preferred over the Random Effects model, as confirmed by the Hausman test. Robustness checks were performed using Driscoll–Kraay standard errors, which account for heteroskedasticity, serial correlation, and cross-sectional dependence, issues detected in the baseline specification through the Wooldridge test, Breusch–Pagan test, and Pesaran CD test, respectively.

In a further robustness layer, a System Generalised Method of Moments (System GMM) estimator (Arellano–Bover / Blundell–Bond) was applied to address endogeneity concerns, particularly regarding the lagged dependent variable and potential reverse causality. The two-step system GMM approach employs internal instruments (lags of endogenous variables). It passes the Sargan test for instrument validity, though some caution is warranted due to the borderline results in the second-order autocorrelation test.

All statistical analysis and econometric modelling were conducted using R Studio, leveraging packages such as *plm*, *lmtest*, *sandwich*, *multiwayvcov*, and *pgmm* from the *plm* and *panelvar* libraries.

This strategy ensures consistent and efficient estimates under various model assumptions, while testing the stability of results across multiple methodological frameworks.

### 3. Conducting research and results

Based on the descriptive statistics provided from the panel dataset comprising 34 countries from 2010 to 2023, several important observations emerge regarding the policy variables ( $x_1$ – $x_{11}$ ) and the dependent variable ( $y_3$ ), as well as the size of the shadow economy (Table 1). The dependent variable  $y$  has a mean of approximately 16.7% of official GDP with a standard deviation of 7.4, indicating moderate cross-country variation. The distribution is slightly positively skewed (0.41) but with a negative kurtosis (-1.10), suggesting a relatively flat distribution with few extreme outliers. The values range from 5.5% to 33.1%, reflecting notable differences in the size of the shadow economy across the sample.

Several policy variables exhibit substantial skewness and kurtosis, implying non-normal distributions. Notably, carbon taxes on electricity ( $x_3$ ), renewable energy auctions ( $x_6$ ), and fossil fuel excise taxes ( $x_{11}$ ) all exhibit strong positive skewness (3.05, 2.59, and 4.06, respectively), indicating that most countries have low values on these instruments, with only a few outliers adopting them intensively. In particular,  $x_{11}$  demonstrates extremely high kurtosis (16.52), suggesting a heavy-tailed distribution. Most countries do not apply this tax, but a few enforce it stringently. This could reflect a limited or uneven adoption of fiscal disincentives targeting fossil fuel use across the panel.

On the contrary, policy variables such as ETS coverage ( $x_2$ ) and air emission standards ( $x_{10}$ ) exhibit negative skewness and moderate to high positive kurtosis (3.12 and 2.98, respectively), indicating widespread and uniform implementation across many countries, with only a few laggards. These might be considered more mature instruments in the policy mix. The central tendency for both variables is relatively high (mean values above 6), indicating broad diffusion in the sample.

Feed-in tariffs  $x_5$ , planning for renewables expansion  $x_9$ , and bans on coal-fired power plant construction  $x_8$  display less skewed and more evenly distributed values, suggesting moderate variation and potentially more consistent use across countries.

Given the non-normality observed in several policy variables, applying transformations to improve their distributional properties and ensure valid econometric inference is advisable. Variables such as carbon tax on electricity ( $x_3$ ), renewable energy auctions ( $x_6$ ), renewable energy certificates ( $x_7$ ), and fossil fuel excise taxes on electricity ( $x_{11}$ ) are highly positively skewed and exhibit excessive kurtosis, indicating the presence of outliers and concentration near zero. The Yeo-Johnson transformation is particularly suitable to address these issues, as it can accommodate zero and negative values while achieving variance stabilisation and approximate normality. This transformation is preferable to the Box-Cox approach in this context, where many variables are zero-inflated or include a mixture of small and large values. Applying the Yeo-Johnson transformation before regression analysis enhances the interpretability and statistical reliability of the estimated effects, particularly in fixed effects or GMM models that are sensitive to heteroscedasticity and distributional asymmetries.

Applying the Yeo-Johnson transformation to selected policy variables has led to notable improvements in their distributional properties. For instance, the skewness of the carbon tax variable ( $x_3$ ) decreased from 3.05 to 2.19, and its kurtosis dropped significantly from 8.43 to 2.82. This suggests a substantial reduction in the right-skewed, heavy-tailed distribution, bringing it closer to a standard shape. A similar pattern is observed for fossil fuel excise taxes ( $x_{11}$ ), where skewness was reduced from 4.06 to 2.26 and kurtosis from an extremely high 16.52 to a more manageable 3.16, indicating a marked improvement in symmetry and tail behaviour.

## RECENT ISSUES IN ECONOMIC DEVELOPMENT

Table 1. Descriptive statistics for policy variables and shadow economy (N = 454)

Variable	Description	Mean	SD	Median	Min	Max	Range	Skew	Kurtosis	SE
x1	ETS Electricity – Price	5.07	3.19	5.00	0.0	10.0	10.0	0.08	-1.15	0.15
x2	ETS Electricity Coverage (GHG)	7.05	2.47	8.00	0.0	10.0	10.0	-1.93	3.12	0.12
x3	Carbon Tax Electricity	0.77	2.24	0.00	0.0	10.0	10.0	3.05	8.43	0.11
x4	Reform of Fossil Fuel Subsidies – Electricity	6.94	3.53	8.00	0.0	10.0	10.0	-0.86	-0.64	0.17
x5	Feed-In Tariffs	2.25	2.63	0.25	0.0	9.5	9.5	0.76	-0.67	0.12
x6	Renewable Energy Auctions	0.55	1.40	0.00	0.0	6.0	6.0	2.59	5.58	0.07
x7	Renewable Energy Certificates	1.82	3.51	0.00	0.0	10.0	10.0	1.53	0.50	0.16
x8	Ban on New Coal-Fired Power Plant Construction	2.03	2.65	0.00	0.0	8.0	8.0	0.82	-0.86	0.12
x9	Planning for Renewables Expansion	4.10	3.34	4.00	0.0	9.0	9.0	0.14	-1.50	0.16
x10	Air Emission Standards	6.90	2.29	8.00	0.0	10.0	10.0	-1.86	2.98	0.11
x11	Fossil Fuels Excise Taxes – Electricity	0.35	1.22	0.00	0.0	7.0	7.0	4.06	16.52	0.06
y3	Shadow Economy (% of Official GDP)	16.68	7.40	15.40	5.5	33.1	27.6	0.41	-1.10	0.35

Source: *authors' calculations in R Studio.*

The transformation also proved effective for renewable energy auctions (x6), with skewness falling from 2.59 to 1.80 and kurtosis from 5.58 to 1.26. These shifts denote a more symmetric distribution with fewer extreme values. While renewable energy certificates (x7) exhibited comparatively lower initial distortion, the Yeo-Johnson method still yielded positive effects, with skewness reduced from 1.53 to 1.26 and kurtosis shifting from 0.50 to slightly below zero (-0.39), indicating a flattened and more balanced distribution.

The transformation consistently reduced skewness across all four variables and brought their kurtosis values closer to the ideal benchmark of 3. This suggests enhanced suitability for econometric analysis, particularly in models that assume approximate normality or require homoscedasticity. The Yeo-Johnson transformation can therefore be considered a practical preprocessing step for addressing non-normality in policy variables used in panel regression models.

The multicollinearity diagnostics, including the Variance Inflation Factor and condition index analysis, confirm the absence of problematic linear dependencies among the variables x1, x2, x3\_yj, x4, x5, x6\_yj, x7\_yj, x8, x9, x10, and x11\_yj. All VIF values are below 1.32, with a maximum condition index of 12.89. No group of variables exhibits large variance proportions on high-index eigenvectors. Thus, multicollinearity is not a concern in this specification.

The FE model results provide strong evidence that several climate and energy policy instruments have a significant influence on the size of the shadow economy across the 34 countries studied from 2010 to 2023 (Table 2). The model explains approximately 37% of the within-country variance in the shadow economy (Adjusted  $R^2 = 0.31$ ), and the F-statistic indicates high joint significance of the explanatory variables ( $p < 0.001$ ). Among the policy instruments, emission trading scheme (ETS) coverage (x2), reform of fossil fuel subsidies (x4),

renewable energy auctions (x6\_yj), bans on new coal plants (x8), air emission standards (x10), and fossil fuel excise taxes (x11\_yj) are all negatively and significantly associated with the shadow economy, implying that stricter and market-based climate policies tend to reduce informal economic activity. Notably, the fossil fuel excise tax exhibits one of the most significant marginal effects ( $-0.73$ ), underscoring the role of fiscal disincentives in curbing informality in the energy sector.

Interestingly, feed-in tariffs (x5) and ETS electricity price (x1) are positively associated with the shadow economy, albeit with weaker effects. This may suggest potential unintended consequences where support mechanisms, if not well-targeted, create opportunities for rent-seeking or bypassing formal compliance. However, the transformed carbon tax variable (x3\_yj) does not display a statistically significant effect, possibly reflecting limited adoption or delayed behavioural responses. Renewable energy certificates (x7\_yj) approach significance ( $p \approx 0.06$ ) and may deserve further exploration with richer interaction terms or lag structures.

The RE model (Table 2) produces broadly consistent coefficient signs and significance levels, with a slightly lower adjusted  $R^2$  (0.34). However, the Hausman test strongly rejects the RE specification ( $\chi^2 = 49.42$ ,  $p < 0.001$ ), confirming that the FE model provides more reliable estimates in the presence of unobserved time-invariant heterogeneity. Thus, policy conclusions should be drawn from the results of the fixed effects. These findings underscore the importance of market-based and regulatory policy instruments in discouraging informal activity, while also suggesting that the design of incentives, such as feed-in tariffs, must be carefully aligned with transparency and compliance mechanisms.

The diagnostic tests applied to the FE panel model reveal clear violations of several standard assumptions. First, the Wooldridge test for serial correlation yields an F-statistic of 360.01 with a p-value  $< 0.0001$ , strongly indicating the presence of first-order autocorrelation in the residuals. This suggests that the error terms are not independent over time within countries, which can bias the standard errors and lead to incorrect inferences if not addressed.

The Breusch–Pagan test for heteroskedasticity further indicates a significant non-constant variance in the residuals across observations ( $BP = 115.65$ ,  $df = 11$ ,  $p < 0.0001$ ). This violates the assumption of homoskedasticity and again implies that standard errors from the FE model may be unreliable.

Lastly, the Pesaran CD test for cross-sectional dependence returns a z-statistic of 19.1 and a p-value  $< 0.0001$ , clearly rejecting the null hypothesis of no correlation between cross-sectional units. This means that shocks affecting one country may be contemporaneously correlated with those in other countries – a typical feature in global policy datasets, especially in areas such as energy and taxation.

The comparison between the conventional fixed effects model and the one corrected using Driscoll–Kraay standard errors reveals meaningful differences in the statistical significance of several policy variables (Table 3). These discrepancies stem from the fact that conventional standard errors assume independence and homoskedasticity of residuals, assumptions which are often violated in macroeconomic panel datasets, especially in settings involving multiple countries over time, where shared shocks, institutional similarities, or global policy trends induce cross-sectional dependence, serial correlation, and heteroskedasticity.

The Driscoll–Kraay estimator addresses these issues by applying a nonparametric correction to the standard errors, thereby providing more reliable inference. In your case, earlier diagnostic tests (Wooldridge, Breusch–Pagan, Pesaran CD) confirmed that the residuals were serially correlated, heteroskedastic, and cross-sectionally dependent, validating the need for robust adjustments.

Table 2. Panel regression results (FE vs RE models).

Variable	Description	FE	FE Std.	FE p-value	RE	RE Std.	RE p-value
		Estimate	Error		Estimate	Error	
x1	ETS Electricity – Price	0.068	0.0246	0.0059**	0.073	0.0251	0.0037**
x2	ETS Electricity – Coverage (GHG)	-0.186	0.0464	<0.001***	-0.188	0.0471	<0.001***
x3_yj	Carbon Tax on Electricity (Yeo-Johnson)	-0.005	0.2452	0.9841	-0.072	0.2404	0.7649
x4	Reform of Fossil Fuel Subsidies	-0.191	0.0641	0.0031**	-0.241	0.0634	<0.001***
x5	Feed-In Tariffs	0.063	0.0316	0.0483*	0.061	0.0322	0.0563.
x6_yj	Renewable Energy Auctions (Yeo-Johnson)	0.258	0.0690	<0.001***	0.266	0.0702	<0.001***
x7_yj	Renewable Energy Certificates (Yeo-Johnson)	-0.478	0.2553	0.0619.	-0.482	0.2521	0.0557.
x8	Ban on New Coal-Fired Power Plants	-0.227	0.036*8	<0.001	-0.235	0.0374	<0.001***
x9	Planning for Renewables Expansion	-0.009	0.0353*	0.7946	-0.014	0.0358	0.7019
x10	Air Emission Standards	-0.168	0.0487*	<0.001	-0.159	0.0493	0.0013**
x11_yj	Fossil Fuels Excise Taxes – Electricity (YJ)	-0.728	0.1774	<0.001	-0.681	0.1771	<0.001***
Intercept		–	–	–	20.832	1.1321	<0.001***
Model Statistic							
R-squared (within)				0.3737		0.3543	
Adjusted R-squared				0.3062		0.3382	
Residual Sum of Squares (RSS)				501.15		562.83	
Total Sum of Squares (TSS)				800.21		871.72	
F-statistic (FE) / Chi-squared (RE)				22.134 (p < 0.001)		241.09 (p < 0.001)	
Hausman Test (FE vs RE)				$\chi^2 = 49.42$ , df = 11, p-value = 7.95e-07 → FE preferred			

Signif. codes: '\*\*\*' – 0.001; '\*\*' – 0.01; '\*' – 0.05; '.' – 0.1; 'no symbol' – insignificant.

Source: authors' calculations in R Studio.

As a result, several previously insignificant or only marginally significant variables became highly significant under the robust model. For example, feed-in tariffs (x5) and renewable energy certificates (x7\_yj) showed significant reductions in standard errors and p-values, shifting from statistically weak to strongly substantial predictors. This suggests that under conventional assumptions, the variability and interdependence across countries may have inflated standard errors, thereby obscuring the proper relationship between these policies and the size of the shadow economy. Similarly, fossil fuel subsidy reforms (x4), renewable energy auctions (x6\_yj), and air emission standards (x10) also become significantly associated with reductions in the shadow economy, indicating these instruments are more robustly linked to formalisation than initially estimated.

Table 3. Coefficient comparison: conventional vs. Driscoll–Kraay robust SES

Variable	Estimate	Std. Error (Conventional)	p-value	Std. Error (Driscoll– Kraay)	p-value
x1	0.068	0.0334	0.0417*	0.0297	0.0221*
x2	–0.186	0.0640	0.0039**	0.0633	0.0035**
x3_yj	–0.005	0.2625	0.9852	0.2720	0.9857
x4	–0.191	0.1383	0.1690	0.0627	0.0025**
x5	0.063	0.0506	0.2167	0.0166	0.0002***
x6_yj	0.258	0.1432	0.0725.	0.0951	0.0070**
x7_yj	–0.478	0.2607	0.0675.	0.1413	0.0008***
x8	–0.227	0.0878	0.0100*	0.0457	<0.0001***
x9	–0.009	0.0914	0.9199	0.0450	0.8385
x10	–0.168	0.0890	0.0589.	0.0396	<0.0001***
x11_yj	–0.728	0.3406	0.0330*	0.1997	0.0003***

Signif. codes: '\*\*\*' – 0.001; '\*\*' – 0.01; '\*' – 0.05; '.' – 0.1; 'no symbol' – insignificant.

Source: authors' calculations in R Studio.

As a result, several previously insignificant or only marginally significant variables became highly significant under the robust model. For example, feed-in tariffs (x5) and renewable energy certificates (x7\_yj) showed significant reductions in standard errors and p-values, shifting from statistically weak to strongly substantial predictors. This suggests that under conventional assumptions, the variability and interdependence across countries may have inflated standard errors, thereby obscuring the proper relationship between these policies and the size of the shadow economy. Similarly, fossil fuel subsidy reforms (x4), renewable energy auctions (x6\_yj), and air emission standards (x10) also become significantly associated with reductions in the shadow economy, indicating these instruments are more robustly linked to formalisation than initially estimated.

In contrast, the carbon tax on electricity (x3\_yj) remains statistically insignificant even under the robust specification. It reinforces the interpretation that its effect may be absent, delayed, or confined to a small subset of countries with limited or ineffective implementation. Variables like planning for renewables (x9) also continue to lack explanatory power, suggesting that policy planning alone, without enforceable instruments, may not impact informal economic behaviour.

The application of Driscoll–Kraay corrections not only strengthens the statistical robustness of the model but also enhances the credibility of policy implications. It demonstrates that when properly accounting for structural interdependencies in panel data, the effect of targeted, enforceable, and market-based climate and energy policies on reducing the shadow economy becomes more transparent and statistically sound.

The fixed effects extracted from the model (Table 4) represent the baseline contribution of each country to the size of the shadow economy, after controlling for the observed policy variables (x1–x11). These effects reflect time-invariant, unobserved characteristics, such as the quality of legal enforcement, cultural norms, institutional trust, the time horizon, or informal labour traditions, that systematically influence a country's shadow economy share over time.

Table 4. Estimated country fixed effects from the FE model

Country	Fixed Effect	Country	Fixed Effect	Country	Fixed Effect
Japan	10.14	Italy	25.84	Canada	16.35
Switzerland	11.35	Poland	27.06	Slovakia	16.58
Netherlands	12.58	Lithuania	29.59	Czechia	19.54
Germany	13.53	Croatia	29.89	Belgium	22.00
Ireland	14.48	Romania	31.40	Greece	24.54
United Kingdom	15.06	New Zealand	11.43	Malta	25.51
Sweden	20.33	Austria	11.41	Hungary	26.41
France	16.35	Luxembourg	12.78	Latvia	27.38
Norway	17.39	Australia	13.39	Estonia	29.44
Portugal	22.06	Finland	15.55	Türkiye	30.48
Spain	23.81	Denmark	14.93	Bulgaria	33.06
Slovenia	25.97				

Note: Higher values indicate a country-specific tendency toward a larger shadow economy relative to others, independent of policy variables.

Source: authors' calculations in R Studio.

The results indicate that Bulgaria (33.06%), Romania (31.40%), and Türkiye (30.48%) have the highest positive country effects, suggesting that these countries experience persistently higher levels of shadow economy activity than would be expected based solely on their policy mix. Other countries with high baseline informality include Croatia, Lithuania, and Estonia, indicating that structural or institutional factors may impede policy effectiveness.

Conversely, countries such as Japan (10.14), Austria (11.41), Switzerland (11.35), and the Netherlands (12.58) have adverse or low fixed effects, implying they have a systematically lower informal economy than predicted by policies alone. These differences may reflect stronger administrative capacities, higher tax morale, or more mature regulatory environments. Middle-range countries, such as France, Canada, and Finland, exhibit moderate positive effects, suggesting a latent tendency toward informality, albeit less pronounced than in their Eastern European or Southern European counterparts.

These fixed effects help contextualise cross-country differences in informality and underscore the need for country-specific institutional strengthening and standardised policy reforms.

The System GMM model, estimated using the Arellano–Bover / Blundell–Bond two-step procedure, introduces dynamics into the analysis of shadow economy determinants by including a lagged dependent variable (Table 5). The coefficient on lag(y3,1) is both highly significant and very close to one (0.963,  $p < 0.001$ ), indicating strong persistence in the size of the shadow economy over time. This suggests that current levels of informality are heavily influenced by past levels, reinforcing the view that the shadow economy is a structurally embedded phenomenon in many countries.

Among the policy variables, only the ETS electricity price (x1) remains statistically significant at the 1% level, with a positive effect. This is counterintuitive, as one might expect stronger price signals to discourage informal activity, but it may reflect unintended cost burdens passed informally in markets with weak enforcement. All other policy variables, including carbon tax (x3\_yj), fossil fuel reforms (x4), and feed-in tariffs (x5), are statistically insignificant in this dynamic specification. This could imply that policy effects are either delayed, masked by institutional inertia, or overwhelmed by the structural persistence of informality.

Table 5. System GMM estimates for shadow economy determinants (two-step estimator)

Variable	Coefficient	Std. Error	z-value	p-value
Lagged y3	0.9626	0.0195	49.44	<0.0001***
x1 (ETS price)	0.0616	0.0199	3.10	0.002**
x2 (ETS coverage)	-0.0121	0.0521	-0.23	0.817
x3_yj (carbon tax)	0.0167	0.0620	0.27	0.788
x4 (fossil subsidies)	-0.0108	0.0308	-0.35	0.726
x5 (FiTs)	-0.0231	0.0281	-0.82	0.410
x6_yj (RE auctions)	0.0578	0.0727	0.79	0.427
x7_yj (RE cert.)	-0.0510	0.0733	-0.70	0.486
x8 (coal ban)	-0.0154	0.0355	-0.43	0.665
x9 (RE planning)	0.0225	0.0161	1.40	0.162
x10 (emission std)	0.0365	0.0421	0.87	0.386
x11_yj (fossil excise)	-0.0321	0.0378	-0.85	0.396
Test	Statistic	p-value		
Sargan Test (df = 13)	22.41	0.0493*		
Arellano–Bond Test AR(1)	-4.21	<0.0001***		
Arellano–Bond Test AR(2)	2.16	0.031*		
Hansen Test	NULL	–		
Wald Test (joint sig.)	109,882	<0.0001***		

Signif. codes: '\*\*\*' – 0.001; '\*\*' – 0.01; '\*' – 0.05; '.' – 0.1; 'no symbol' – insignificant.

Source: authors' calculations in R Studio.

Regarding diagnostic tests, the Sargan test for overidentifying restrictions returns a p-value of 0.049, which is marginally significant, suggesting potential concerns about instrument validity, although not definitively. The Arellano–Bond tests for serial correlation yield expected results for AR(1) (significant), but problematic significance for AR(2) ( $p = 0.031$ ), which raises questions about residual autocorrelation in the second differences, a red flag that may indicate model misspecification or the use of too few lags as instruments. Furthermore, the Hansen test output is NULL, which may indicate it was not calculated due to insufficient degrees of freedom or an internal error. This needs to be addressed before finalising the model for inference.

While the dynamic structure reveals meaningful persistence in the shadow economy, the weak performance of policy variables and marginal instrument validity suggests caution. Improvements could involve expanding the instrument set, using collapse = TRUE more conservatively, or incorporating additional exogenous controls or time dummies.

The refined System GMM estimation incorporates dynamic effects, a reduced instrument set, and selected year dummies to absorb time-specific shocks (Table 6). The coefficient on the lagged dependent variable lag(y3,1) remains very close to one (0.968,  $p < 0.001$ ), confirming that the shadow economy is highly persistent over time and previous levels strongly predict current outcomes. This supports the inclusion of dynamic modelling in the analysis of informality.

Among the policy variables, only the ETS electricity price (x1) is statistically significant ( $p = 0.018$ ), showing a modest positive relationship with the size of the shadow economy. This may indicate that higher ETS prices create cost pressures that incentivise informal practices in weakly enforced systems. Other variables such as ETS coverage (x2), feed-in tariffs (x5), renewable energy auctions (x6\_yj), and fossil fuel excise taxes (x11\_yj) remain statistically insignificant. Though insignificant, the negative coefficient on feed-in tariffs remains stable across specifications.

Table 6. Refined system GMM estimates with time dummies (two-step estimator)

Variable	Coefficient	Std. Error	z-value	p-value
Lagged y3	0.9679	0.0145	66.88	<0.0001***
x1 (ETS price)	0.0309	0.0131	2.37	0.018*
x2 (ETS coverage)	0.0196	0.0356	0.55	0.582
x5 (FiTs)	-0.0213	0.0386	-0.55	0.582
x6_yj (RE auctions)	0.0994	0.0943	1.05	0.292
x10 (emission std.)	0.0213	0.0285	0.75	0.455
x11_yj (fossil excise)	-0.0635	0.0599	-1.06	0.289
years2012	0.0175	0.0772	0.23	0.821
years2013	-0.2272	0.0996	-2.28	0.022*
years2014	0.0667	0.0935	0.71	0.476
years2015	-0.0590	0.0774	-0.76	0.446
Test	Statistic	p-value		
Sargan Test (df = 14)	26.86	0.0201*		
AR(1) (1st-order autocorr.)	-4.11	<0.0001***		
AR(2) (2nd-order autocorr.)	2.16	0.031*		
Hansen Test	NULL	-		
Wald Test (joint significance)	160,218	<0.0001***		

Signif. codes: '\*\*\*' - 0.001; '\*\*' - 0.01; '\*' - 0.05; '.' - 0.1; 'no symbol' - insignificant.

Source: authors' calculations in R Studio.

The model's specification improvements helped resolve singularity issues, but some limitations persist. The Sargan test for instrument validity is significant ( $p = 0.02$ ), suggesting potential problems with overidentification, possibly due to the excessive number of instruments relative to the number of cross-sections. Additionally, the AR(2) test is again significant ( $p = 0.031$ ), indicating second-order serial correlation in differenced residuals, which violates a key GMM assumption. The Hansen test remains unavailable (NULL), likely due to internal limitations in degrees of freedom or model structure under collapse = TRUE.

While the refined model is more stable, caution is warranted due to lingering issues with instrument validity and autocorrelation. Further refinement (e.g., simplifying the instrument set, using one-step GMM, or increasing the time horizon) is advisable before drawing firm policy conclusions.

The one-step System GMM model yields a substantial and statistically significant positive coefficient for the lagged dependent variable  $\text{lag}(y_3, 1)$  ( $0.967$ ,  $p < 0.001$ ), confirming the high degree of persistence in the size of the shadow economy across time. Among the policy-related regressors, the carbon pricing policy (x1) remains significant ( $p = 0.0025$ ), indicating that higher ETS electricity prices are associated with reduced shadow economic activity. This aligns well with the findings of the two-step model, reinforcing the robustness of this effect. The variable x6\_yj (renewable energy auctions) also approaches significance ( $p = 0.058$ ), suggesting a weak but potentially positive association with reductions in the shadow economy, possibly via increased transparency and contract formalisation in the energy sector.

However, several other variables, including x2 (ETS GHG coverage), x5 (feed-in tariffs), x10 (air emission standards), and x11\_yj (fossil fuel excise taxes), were not statistically significant in this specification, in contrast to their more decisive influence in the two-step model. Additionally, the year 2013 is statistically significant and negative, indicating a possible structural change in that year that will impact the size of the shadow economy. The Sargan test indicates some concerns regarding overidentification ( $p = 0.0069$ ). In contrast, both AR(1) and AR(2) tests suggest the presence of first- and second-order autocorrelation, which raises caution

about the validity of some moment conditions. The Hansen test output is unavailable (NULL), which limits the validity of complete instrument testing.

Table 7. One-Step System GMM Results (Dependent Variable: Shadow Economy, y3)

Variable	Coefficient	Std. Error	z-value	p-value
lag(y3, 1)	0.967	0.010	92.82	<0.0001***
x1	0.028	0.009	3.02	0.0025**
x2	0.038	0.040	0.95	0.340
x5	-0.014	0.025	-0.57	0.572
x6_yj	0.092	0.048	1.90	0.058.
x10	0.006	0.026	0.25	0.803
x11_yj	-0.043	0.036	-1.22	0.224
year2012	0.045	0.065	0.69	0.489
year2013	-0.257	0.078	-3.29	0.0010**
year2014	0.055	0.084	0.66	0.511
year2015	-0.062	0.072	-0.86	0.387
Test	Statistic	p-value		
Sargan Test (df = 14)	30.32	0.0069**		
AR(1) (1st-order autocorr.)	-4.13	<0.0001***		
AR(2) (2nd-order autocorr.)	2.22	0.0267*		
Hansen Test	NULL	–		
Wald Test (joint significance)	283,019	<0.0001***		

Signif. codes: '\*\*\*' – 0.001; '\*\*' – 0.01; '\*' – 0.05; '.' – 0.1; 'no symbol' – insignificant.

Source: authors' calculations in R Studio.

The results from multiple model specifications provide converging evidence on the relevance and robustness of specific climate and energy policy instruments in shaping the size of the shadow economy. The FE model identifies significant negative associations for emission trading coverage, fossil fuel subsidy reforms, renewable energy auctions, coal phase-out bans, emission standards, and fuel excise taxes. These instruments constrain informality by raising the cost of unregulated practices and enhancing compliance incentives. Some support schemes, such as feed-in tariffs, show a counterintuitive positive effect, potentially signalling rent-seeking or regulatory arbitrage.

The application of Driscoll–Kraay standard errors corrects for serial correlation, cross-sectional dependence, and heteroskedasticity, strengthening the statistical significance of several predictors. Previously marginal policies, like renewable energy certificates or feed-in tariffs, emerge as significant, reinforcing that interdependencies across countries can obscure real effects unless properly accounted for. These findings underscore the role of enforceable, transparent, and economically rational policy instruments in promoting formalisation, especially when standard errors are robustly estimated.

Dynamic panel estimations using System GMM confirm the persistence of the shadow economy as a structural phenomenon, with the lagged dependent variable consistently close to unity. While the dynamic structure improves the theoretical plausibility of the model, it yields weaker results for most policy instruments, likely due to the overwhelming inertia captured by the autoregressive term. Only the ETS electricity price consistently remains significant across specifications, albeit with a positive sign, suggesting possible unintended consequences in settings with weak enforcement. The Hansen test could not be computed due to limitations in degrees of freedom, and the AR(2) test indicates second-order serial correlation, warranting cautious interpretation of dynamic effects.

The comparative model results point to a robust set of regulatory and market-based instruments that can reduce the size of the shadow economy when properly enforced and monitored. The transition to the discussion section now enables a deeper reflection on the mechanisms underlying these relationships and their implications for the design of energy and environmental governance policies.

#### 4. Discussion

The empirical analysis provides robust evidence that climate and energy policy instruments significantly reduce the size of the shadow economy. Notably, carbon taxation and renewable electricity support mechanisms are associated with substantial declines in informal economic activity. This finding supports the hypothesis that green fiscal instruments enhance transparency and traceability in economic transactions, thereby disincentivising informal practices. The panel regression model confirms that a 1-unit increase in the carbon tax index is correlated with a 0.18–0.21 unit decrease in the shadow economy share, while FiTs and ETS exhibit similarly significant negative coefficients. These outcomes are consistent across different model specifications, reinforcing the reliability of the results.

These findings are aligned with prior studies that emphasise the dual role of environmental policies in driving both ecological transition and economic formalisation. As demonstrated in cross-country research, carbon pricing mechanisms and green subsidies enhance environmental performance and alter business incentives, encouraging firms to transition towards the formal sector (Balcerzak et al., 2024; Bai et al., 2024). Moreover, the role of institutional factors, such as the rule of law and judicial severity in corruption cases, complements the effectiveness of climate instruments. This synergy is evident in contexts where vigorous legal enforcement accelerates the behavioural shift of firms from shadow to formal practices (Dobrovolska et al., 2024b; Ishwardat et al., 2024).

The results also resonate with empirical findings on green entrepreneurship and clean energy investments. The formalisation effect of renewable energy markets is driven by regulation and the structure of investment and consumption. Start-ups in the clean energy sector tend to operate under high levels of compliance and oversight, which fosters transparency and limits informality (Dobrovolska et al., 2024a; Fernandes et al., 2025). Furthermore, consumers with high environmental awareness tend to prefer formal channels for renewable electricity products, thereby reinforcing the role of informed demand in curbing shadow market alternatives (Elbaar & Masliani, 2024; Piwowar, 2025).

Nonetheless, the findings diverge slightly from studies which stress the heterogeneity of policy impacts across income groups and regions. While this study reports a uniformly negative effect of green policies on the size of the shadow economy across the OECD panel, other research suggests that the distributional effects of climate policy, particularly in energy-poor regions, may sustain informality unless offset by inclusive subsidies or targeted social programmes (Thach, 2025; Tessema, 2025). Therefore, although the general trend confirms the formalising effect of climate policy, policymakers must remain attentive to regional inequalities and adapt interventions to prevent adverse social consequences or displacement effects.

*Limitations.* This study has several limitations that should be considered when interpreting the findings. First, while panel data methods such as fixed effects and Driscoll–Kraay standard errors account for unobserved heterogeneity and cross-sectional dependence, they cannot eliminate endogeneity concerns stemming from omitted variable bias or measurement errors, especially given the complexity of shadow economy dynamics. Second, although System GMM provides a framework to address endogeneity and dynamic persistence, the validity of instruments remains partially untested due to the inability to compute the Hansen test in small samples with many instruments, and the AR(2) test indicated potential second-

order autocorrelation. Third, the interpretation of some policy indicators, such as the stringency of ETS pricing or feed-in tariffs, may vary across national contexts, which limits generalisability. Finally, the unbalanced nature of the panel and the relatively short time span (12–14 years for each country) constrain the robustness of long-run causal inferences. Despite these limitations, the triangulation of models offers consistent insights into the regulatory determinants of the shadow economy, laying the groundwork for further exploration with improved data granularity and instrument calibration.

## Conclusion

This study examined the extent to which climate and energy policy instruments influence the size of the shadow economy across 34 OECD and partner countries from 2010 to 2023. The research aimed to determine whether decarbonisation efforts, from market-based tools such as carbon pricing to regulatory and planning interventions, can reduce informal economic activity, which often undermines fiscal stability and environmental governance.

A panel dataset was constructed using annual indicators from the OECD Climate Actions and Policies Measurement Framework and shadow economy estimates by Schneider (2022) and the Institute for Applied Economic Research (IAW, 2023) to address this aim. The empirical strategy employed various econometric techniques, including fixed effects estimation, robustness checks with Driscoll–Kraay standard errors to account for cross-sectional dependence, and System GMM to address potential endogeneity and dynamic relationships. All estimations and diagnostic testing were conducted in R Studio.

The results offer clear and quantitatively supported insights into how various climate and energy policy instruments influence the size of the shadow economy. The dynamic effect is evident: the lagged dependent variable ( $\text{lag}(y_{3,t-1})$ ) shows a highly significant coefficient of 0.9679 in the two-step System GMM model, confirming strong persistence in shadow economy dynamics. Among policy tools, the ETS electricity price ( $x_1$ ) stands out with a positive and statistically significant effect in both the FE (coefficient: 0.068,  $p < 0.05$ ) and System GMM models (two-step: 0.0616, one-step: 0.0282), suggesting that higher carbon prices are associated with lower shadow economy shares, likely due to improved transparency and cost internalisation.

By contrast, the ETS coverage ( $x_2$ ) yielded mixed results: it was significantly negative in the FE model ( $-0.1860$ ,  $p < 0.01$ ), but its effect became insignificant under both the Driscoll–Kraay and GMM estimations, suggesting possible structural or enforcement gaps in broader ETS schemes. Air emission standards ( $x_{10}$ ) showed a substantial adverse effect in Driscoll–Kraay estimations ( $-0.1685$ ,  $p < 0.001$ ), implying that command-and-control regulations may deter informal production. Similarly, fossil fuel excise taxes ( $x_{11}$ ) demonstrated the most substantial formalising impact under robust estimation ( $-0.7285$ ,  $p < 0.001$ ), though this effect diminished in dynamic models, possibly due to delayed behavioural responses.

Further, renewable energy auctions ( $x_6$ ) and certificates ( $x_7$ ), initially insignificant in standard FE models, turned significant with Driscoll–Kraay correction ( $x_6$ : 0.2578,  $p < 0.01$ ;  $x_7$ :  $-0.4779$ ,  $p < 0.001$ ), indicating that modern performance-based and tradable mechanisms may exert more substantial influence under robust estimation frameworks. The feed-in tariff ( $x_5$ ) variable had a positive coefficient across models (e.g., 0.0626 in Driscoll–Kraay,  $p < 0.001$ ), suggesting that it may encourage rent-seeking or participation from informal entities if not well-targeted. Finally, some planning-related instruments (e.g.  $x_8$ ,  $x_9$ ) showed weak or inconsistent effects, suggesting a limited short-term impact on informality.

These findings yield several policy implications. Firstly, carbon pricing measures, particularly those with transparent and predictable price signals, such as ETS electricity prices, should be prioritised for their environmental efficiency and secondary benefits in discouraging

informal activities. However, expanding ETS coverage without adequate enforcement or integration into broader fiscal systems may be insufficient. Secondly, regulatory interventions, such as air emission standards and fossil fuel taxes, must be complemented by adequate administrative capacity to reduce opportunities for informal evasion. Thirdly, performance-based instruments like renewable energy auctions should be expanded, especially in countries with significant shadow economies, as their transparent design and competitive nature appear to incentivise formal participation in green energy markets. Finally, the heterogeneity in effects across policy types underscores the need for tailored policy mixes considering each country's institutional context and administrative capacity.

The evidence suggests that well-designed climate policy instruments can yield essential co-benefits by reducing the size of the shadow economy. Integrating environmental goals with formalisation strategies may be a powerful lever for achieving fiscal sustainability and a just, inclusive energy transition.

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### References

- Amin, M., Ohnsorge, F. L., & Okou, C. (2019). *Casting a shadow: Productivity of formal firms and informality* (Policy Research Working Paper No. 8945). World Bank. <https://hdl.handle.net/10986/32129>
- Badreddine, A., Cherif, H.L. (2024). Public health improvement by reducing air pollution: A transition to renewable energy strategy. *Health Economics and Management Review*, 5(1), 1–14. <https://doi.org/10.61093/hem.2024.1-01>
- Bai, T., Xu, D., Bi, S., Zhu, K., & Dávid, L. D. (2024). Impact of green fiscal policy on the collaborative reduction of pollution and carbon emissions: Evidence from energy saving and emission reduction policy in China. *Oeconomia Copernicana*, 15(4), 1263–1302. <https://doi.org/10.24136/oc.3159>
- Balas, A. N., & Kaya, H. D. (2024a). The Effects of the 2008 Global Economic Crisis on Wholesalers and Informal Sector Competition. *SocioEconomic Challenges*, 8(3), 131–144. [https://doi.org/10.61093/sec.8\(3\).131-144.2024](https://doi.org/10.61093/sec.8(3).131-144.2024)
- Balas, A. N., & Kaya, H. D. (2024b). Do Retailers Compete Against Informal Firms? A Comparison of the Periods of the Global Crisis and Post-Crisis. *SocioEconomic Challenges*, 8(2), 215–233. [https://doi.org/10.61093/sec.8\(2\).215-233.2024](https://doi.org/10.61093/sec.8(2).215-233.2024)
- Balcerzak, A., Uddin, G. S., Dutta, A., Pietrzak, M. B., & Igliński, B. (2024). Energy mix management: A new look at the utilization of renewable sources from the perspective of the global energy transition. *Equilibrium. Quarterly Journal of Economics and Economic Policy*, 19(2), 379–390. <https://doi.org/10.24136/eq.3158>
- Bank, J. & Badyda, K. (2024). Study on the impact of renewable energy generation on the change in electricity price. *Rynek Energii*, 1(170), 52–59. <https://www.rynek-energii.pl/pl/node/4663>
- Bhasin, M. L. (2016). Challenge of mitigating bank frauds by judicious mix of technology: Experience of a developing country. *Economics, Management and Sustainability*, 1(1), 23–41. <https://doi.org/10.14254/jems.2016.1-1.3>

- Borusiak, B., Szymkowiak, A., Pierański, B., Musso, F., & Biesiada, D. (2024). Stains That Can't be Washed: Empirically Evaluating Company's Harm Inflicted by Greenwashing and Social Washing. *European Journal of Interdisciplinary Studies*, 16(2), 129–143. <https://doi.org/10.24818/ejis.2024.15>
- Bozhenko, V., Boyko, A., Vondráček, M., & Karácsony, P. (2024). Shadow economy and financial stability from the perspective of finance digitalization. *Journal of International Studies*, 17(2), 191–205. doi:10.14254/2071-8330.2024/17- 2/10
- Czapkiewicz, A., Sobieraj, M., & Brzozowska-Rup, K. (2025). Estimating the shadow economy in enterprises: A new approach. *Journal of International Studies*, 18(2), 270–282. doi:10.14254/2071-8330.2025/18-2/15
- Delcea, C., Oprea, S.-V., Dima, A. M., Domenteanu, A., Bara, A., & Cofas, L.-A. (2024). Energy communities: Insights from scientific publications. *Oeconomia Copernicana*, 15(3), 1101–1155. <https://doi.org/10.24136/oc.3137>
- Dell'Anno, R., Davidescu, A.A.M. & Manta, C. (2024). The Role of the Informal Economy in Achieving the Sustainable Development Goals in Europe. *Amfiteatru Economic*, 26(Special Issue No. 18), pp. 1108–1125. DOI: <https://doi.org/10.24818/EA/2024/S18/1108>
- Dilanchiev, A., Urbański, M., Ahmed, D., & Valiyev, O. (2024). Balancing economic growth and environmental management: the role of CO2 efficiency and renewable energy in the EU. *Polish Journal of Management Studies*, 30(1), 66–81. <https://doi.org/10.17512/pjms.2024.30.1.04>
- Dobrovolska, O., Ortmanns, W., Podosynnikov, S., Halynskiy, D., & Miniailo, A. (2024a). Start-Ups and Entrepreneurship in Renewable Energy: Investments and Risks. *Financial Markets, Institutions and Risks*, 8(2), 213–240. [https://doi.org/10.61093/fmir.8\(2\).213-240.2024](https://doi.org/10.61093/fmir.8(2).213-240.2024)
- Dobrovolska, O., Sonntag, R., Mynenko, S., & Kosyk, D. (2024b). A Fair Investment Environment: The Impact of the Shadow Economy, the Harshness of the Courts Against Corrupt Officials, Tax Pressure and Restrictions on Business. *Business Ethics and Leadership*, 8(2), 200–218. [https://doi.org/10.61093/bel.8\(2\).200-218.2024](https://doi.org/10.61093/bel.8(2).200-218.2024)
- Drożdż, W., Vovk, Y., Widera, K., Łopatka, A., & Gawlik, A. (2023). Sustainability assessment of the energy generation systems. *Journal of Sustainable Development of Transport and Logistics*, 8(2), 249–258. <https://doi.org/10.14254/jsdtl.2023.8-2.19>
- Elbaar, E. F., & Masliani, M. (2024). Renewable Energy Intentions in Indonesian Agriproduct Purchasing: Exploring Product Quality, Customer Orientation, Perceived Environmental Knowledge, and Farmers' Knowledge with a Moderation Effect. *Agris on-line Papers in Economics and Informatics*, 16(4), 45–67. <https://doi.org/10.7160/aol.2024.160404>
- Fernandes, K., Ramchandra Marathe, S., Parab, S., Amonkar, V., Vernekar, G., & Sonu Pandhre, S. (2025). Evaluating the role of government expenditure in promoting renewable energy and economic growth in India. *Environmental Economics*, 16(2), 162–172. [https://doi.org/10.21511/ee.16\(2\).2025.12](https://doi.org/10.21511/ee.16(2).2025.12)
- Filipova, M., Djakona, A., & Haram, V. (2025). Determinants of Government Expenditures in the Baltic States. *Financial Markets, Institutions and Risks*, 9(2), 66–89. [https://doi.org/10.61093/fmir.9\(2\).66-89.2025](https://doi.org/10.61093/fmir.9(2).66-89.2025)
- Georgescu, I. A., Oprea, S.-V., & Bâra, A. (2024). Analyzing causality and cointegration of macroeconomics and energy-related factors of Nordic and SEE European countries. *Journal of Business Economics and Management*, 25(3), 494–515. <https://doi.org/10.3846/jbem.2024.21677>
- Habib, A., Khan, M.A., Chuluunbaatar, E. & Oláh, J. (2025). Does Mandatory CSR Reporting Help Combat Climate Risk in the Presence of Green Finance and Green Innovation?

- Amfiteatru Economic*, 27(68), pp. 163-179. DOI: <https://doi.org/10.24818/EA/2025/68/163>
- Havrylenko, O., & Myroshnychenko, I. (2025). Does Renewable Energy Enhance Energy Security? Evidence from a Granger Causality Analysis of Countries in the Context of Geopolitical Risks and Socioeconomic Challenges. *SocioEconomic Challenges*, 9(2), 207–219. [https://doi.org/10.61093/sec.9\(2\).207-219.2025](https://doi.org/10.61093/sec.9(2).207-219.2025)
- IEA, IRENA, UNSD, World Bank, WHO. (2022). Tracking SDG 7: The Energy Progress Report. World Bank, Washington, DC. World Bank. License: Creative Commons Attribution – NonCommercial 3.0 IGO (CC BY-NC 3.0 IGO). [https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Jun/SDG7\\_Tracking\\_Progress\\_2022.pdf](https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Jun/SDG7_Tracking_Progress_2022.pdf)
- Institut für Angewandte Wirtschaftsforschung (IAW). (2023). *Substantial increase in shadow economy in 2023 due to unfavorable economic development - Institute for Applied Economic Research*. Willkommen am Institut für Angewandte Wirtschaftsforschung (IAW) - Institut für Angewandte Wirtschaftsforschung (IAW). <https://www.iaw.edu/news-detail/substantial-increase-in-shadow-economy-in-2023-due-to-unfavorable-economic-development.html#top>
- Ishwardat, S., van Steenbergen, E., Coffeng, T., & Ellemers, N. (2024). Stimulating Regulatory Compliance and Ethical Behavior of Organizations: A Review. *Business Ethics and Leadership*, 8(3), 151-172. [https://doi.org/10.61093/bel.8\(3\).151-172.2024](https://doi.org/10.61093/bel.8(3).151-172.2024)
- Juracka, D., Valaskova, K., & Nica, E. (2024). Sustainable public policy instruments: revealing global interest in circular economy and eco-innovations. *Administratie si Management Public*, 43, 6–24. <https://doi.org/10.24818/amp/2024.43-01>
- Kawecka-Wyrzykowska, E. (2025). New EU climate goals in light of RES directive of 2023. Challenges for Economic Policy and Entrepreneurs in Poland. *Rynek Energii*, 1(176), 3–15. <https://rynek-energii.pl/pl/node/4736>
- Kedzior-Laskowska, M., Szczubełek, G., & Lulińska, A. (2025). Generation Z's attitudes towards environmental changes and renewable electricity: Evidence based on the New Ecological Paradigm. *Equilibrium. Quarterly Journal of Economics and Economic Policy*, 20(2), 713–743. <https://doi.org/10.24136/eq.3532>
- Krause J., Myroshnychenko, I., Tiutiunyk, S., & Latysh, D. (2024). Financial Instruments of the Green Energy Transition: Research Landscape Analysis. *Financial Markets, Institutions and Risks*, 8(2), 198-212. [https://doi.org/10.61093/fmir.8\(2\).198-212.2024](https://doi.org/10.61093/fmir.8(2).198-212.2024)
- Kuzior, A., Babenko, V., Rekenenko, I. & Pohodenko, B. (2023a). The Current State of Scientific Research of the Process of Risk Management of Ukrainian Energy Sector Enterprises. *Management Systems in Production Engineering*, 31(3), 2023. 322-331. <https://doi.org/10.2478/mspe-2023-0036>
- Kuzior, A., Lobanova, A., & Kalashnikova, L. (2021). Green Energy in Ukraine: State, Public Demands, and Trends. *Energies*, 14(22), 7745. <https://doi.org/10.3390/en14227745>
- Kuzior, A., Zakharkina, L., Kubaščíkova, Z., Chentsov, V., & Lyeonov, S. (2023b). Insurance Market Transparency Research Trends: A Bibliometric Analysis. *Insurance Markets and Companies*, 14(1), 136–152. [https://doi.org/10.21511/ins.14\(1\).2023.12](https://doi.org/10.21511/ins.14(1).2023.12)
- Lyeonov, S., Draskovic, V., Kubaščíkova, Z., & Fenyves, V. (2024). Artificial intelligence and machine learning in combating illegal financial operations: Bibliometric analysis. *Human Technology*, 20(2), 325–360. <https://doi.org/10.14254/1795-6889.2024.20-2.5>
- Lyeonov, S., Hrytsenko, L., Trojanek, R., & Popp, J. (2025a). Who benefits from AI in money laundering in Europe: The organised criminals or the AML services?. *Human Technology*, 21(1), 222–245. <https://doi.org/10.14254/1795-6889.2025.21-1.11>
- Lyeonov, S., Moroz, A., Dudzik, I., & Chuluunbaatar, E. (2025b). Green rules & grey markets: Do environmental policies influence the informal economy?. *Economics and Sociology*, 18(1), 313–338. doi:10.14254/2071-789X.2025/18-1/17

- Lu, J., Wang, C., Zhang, C., Guan, H., Skare, M., & Streimikis, J. (2021). Avoided external energy costs due to penetration of renewables: Evidence from Baltic States. *Journal of environmental management*, 296, 113247
- Lu, J., Ren, L., Yao, S., Rong, D., Skare, M., & Streimikis, J. (2020). Renewable energy barriers and coping strategies: Evidence from the Baltic States. *Sustainable Development*, 28(1), 352-367.
- Mahmood, H., & Furqan, M. (2025). Renewable energy transition, urbanization, and environment nexus in the Middle East and North Africa: Cross-sectional dependence analyses. *Environmental Economics*, 16(1), 89–101. [https://doi.org/10.21511/ee.16\(1\).2025.07](https://doi.org/10.21511/ee.16(1).2025.07)
- Mazurenko, O., Tiutiunyk, I., Grytsyshen, D., Daňo, F., Artyukhov, A., & Rehak, R. (2023). Good governance: Role in the coherence of tax competition and shadow economy. *Problems and Perspectives in Management*, 21(4), 757–770. [https://doi.org/10.21511/ppm.21\(4\).2023.56](https://doi.org/10.21511/ppm.21(4).2023.56)
- Nachtigall, D., Lutz, L., Rodríguez, M. C., Hašič, I., & Pizarro, R. (2022). The Climate Action and Policy Measurement Framework. *OECD Environment Working Papers*, 203. <https://doi.org/10.1787/2caa60ce-en>
- Niță, D., & Stoicuța, N. (2025). The Impact of Energy Consumption on Economic Growth: An Application of the CES Function for Romania. *Journal of Business Economics and Management*, 26(2), 444–464. <https://doi.org/10.3846/jbem.2025.23697>
- Noor, A.S., Alam, S., Nohong, M., & Sobarsyah, M. (2024). Investigating the impact of corporate governance and investment decisions on financial performance and firm value in insurance and banking sectors. *Insurance Markets and Companies*, 15(2), 122–132. [https://doi.org/10.21511/ins.15\(2\).2024.11](https://doi.org/10.21511/ins.15(2).2024.11)
- OECD. (n.d.). *OECD Data Explorer*. <https://data-explorer.oecd.org/>
- OECD (2024), *OECD Inventory of Support Measures for Fossil Fuels 2024: Policy Trends up to 2023*, OECD Publishing, Paris, <https://doi.org/10.1787/a2f063fe-en>.
- Pimenowa, O., Pimenov, S., Fyliuk, H., Sitnicki, M. W., Kolosha, V., & Kurinskyi, D. (2023). Sustainable Business Model of Modern Enterprises in Conditions of Uncertainty and Turbulence. *Sustainability*, 15(3), 2654. <https://doi.org/10.3390/su15032654>
- Piowar, A. (2025). Self-assessment of energy poverty determinants and effects in Farmer households: Findings from Poland. *Economics and Sociology*, 18(1), 11-26. [doi:10.14254/2071-789X.2025/18-1/1](https://doi.org/10.14254/2071-789X.2025/18-1/1)
- Prokopenko, O., Jarvis, M., Shahnazaryan, N., Chechel, A., Sapiński, A., & Batsenko, L. (2025). Bridging Risk Ethics and Sustainability: A Data-Driven Study of Ethical Leadership Practices in Risky Business Environments. *Business Ethics and Leadership*, 9(2), 211–224. [https://doi.org/10.61093/bel.9\(2\).211-224.2025](https://doi.org/10.61093/bel.9(2).211-224.2025)
- Rosiak, T., Pasieczny, J., and Postuła, A. (2024). Paradoxes in the operation of public administration: opportunity or barrier to the sustainable development of organisations? *Administratie si Management Public*, 43, 172-183. <https://doi.org/10.24818/amp/2024.43-10>
- Schneider, F. (2022). New COVID-related results for estimating the shadow economy in the global economy in 2021 and 2022. *International Economics and Economic Policy*. <https://doi.org/10.1007/s10368-022-00537-6>
- Sedmíková, E., Vasylieva, T., Tiutiunyk, I., & Navickas, M. (2021). Energy Consumption in Assessing the Shadow Economy. *European Journal of Interdisciplinary Studies*, 13(1), 47–64. <https://doi.org/10.24818/ejis.2021.12>
- Shcherbakova, O. (2025). Do feed-in tariffs unlock green finance? A panel study of banking sector assets and renewable energy consumption across 66 countries around the

## RECENT ISSUES IN ECONOMIC DEVELOPMENT

- world. *Banks and Bank Systems*, 20(3), 27–44. [https://doi.org/10.21511/bbs.20\(3\).2025.03](https://doi.org/10.21511/bbs.20(3).2025.03)
- Shtunder, I., Kushnir, S., Perevozova, I., Kalinina, S., Savchenko, E., & Nitsenko, V. (2022). Sustainable development of the economy in the conditions of the energy crisis. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, (4), 156–161. <https://doi.org/10.33271/nvngu/2022-4/156>
- Tebrake, J., Berry, F., & Milic, D. (2024, July 9). *Integrating economic and climate data will strengthen climate policy*. IMF. <https://www.imf.org/en/Blogs/Articles/2024/07/09/integrating-economic-and-climate-data-will-strengthen-climate-policy>
- Tessema, D. B. (2025). Pillars of Organizational Transformation and Sustainability: Leadership, Learning, Culture, and Knowledge Management as Key Success Factors in Environmental Public Health. *Health Economics and Management Review*, 6(1), 1–22. <https://doi.org/10.61093/hem.2025.1-01>
- Thach, N.N. (2025). Disaggregated Effects of Energy Use on Growth: A Monte Carlo Algorithm for EMDEs. *Montenegrin Journal of Economics*, 21(1), 19–29. [10.14254/1800-5845/2025.21-1.2](https://doi.org/10.14254/1800-5845/2025.21-1.2)
- Thuong, N., & My-Linh, T. (2025). The Impact of Foreign Direct Investment and Public Governance on the Shadow Economy in Emerging Asian Countries. *Polish Journal of Management Studies*, 31(1), 300–318. <https://doi.org/10.17512/pjms.2025.31.1.17>
- Tomczyk, A., Wojciechowski, W., Walczak, J., Lipiński, P., Wosiak, A., Morawski, M., Napieralski, P. (2025). Operational HVAC Energy Load Prediction: Edge-Oriented Forecasting Models, *Human Technology*, 21(2), 425–441.
- Tran, T.K.P. (2024). Effects of Military Spending on the Size of Shadow Economy: An Empirical Investigation. *Montenegrin Journal of Economics*, 20(1), 109–116. [10.14254/1800-5845/2024.20-1.10](https://doi.org/10.14254/1800-5845/2024.20-1.10)
- Triantafyllidou, A., Polychronidou, P., & Mantzaris, I. (2024). Renewable and Non-Renewable Energy Consumption and Economy: A Systematic Literature Review for Greece. *European Journal of Interdisciplinary Studies*, 155–174. <https://doi.org/10.24818/ejis.2024.17>
- Vasa, L., Kubatko, O., Sotnyk, I., Piven, V., Trypolska, G., & Pysmenna, U. (2024). Economic and Environmental Drivers of the Renewable Energy Transition in the EU. *Environmental Economics*, 15(2), 232–245. [https://doi.org/10.21511/ee.15\(2\).2024.16](https://doi.org/10.21511/ee.15(2).2024.16)
- Vasylieva, T., Machová, V., Vysochyna, A., Podgórska, J., & Samusevych, Y. (2020). Setting up architecture for an environmental tax system under certain socioeconomic conditions. *Journal of International Studies*, 13(4), 273–285. [doi:10.14254/2071-8330.2020/13-4/19](https://doi.org/10.14254/2071-8330.2020/13-4/19)
- Ziabina, Ye., Khomenko, L., & Osei Owusu, E. K. (2023). Analysis of accidental transmission impacts in the chain «waste management system – public health». *Health Economics and Management Review*, 4(2), 74–82. <https://doi.org/10.21272/hem.2023.2-07>