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GREEN RULES & GREY MARKETS: DO ENVIRONMENTAL POLICIES INFLUENCE THE INFORMAL ECONOMY?

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ABSTRACT. The relationship between environmental policy stringency and the shadow economy is a critical issue, as stringent regulations can either formalise economic activities or push businesses into informality. This study aims to analyse how different types of environmental policies influenced the size of the shadow economy across 24 countries from 2003 to 2020. This study uses panel data regression techniques, including Fixed Effects and Random Effects models, to evaluate the impact of market-based policies, command-and-control regulations, and environmental taxation on informal economic activities. The results indicate that overall environmental policy stringency is negatively correlated with the shadow economy, with a one-unit increase in policy stringency reducing the informal economy by approximately 2.18 percentage points. Market-based environmental policies, such as carbon trading schemes and financial incentives, are more effective in reducing informality than command-and-control regulations. However, high environmental taxation, particularly sulphur oxide taxes, is associated with an increase in the shadow economy, suggesting that excessive regulatory costs may incentivise tax evasion and informal operations. The study highlights the importance of balancing environmental regulations with economic incentives and governance reforms to ensure both sustainability and economic de-shadowing.

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Introduction

Stringent environmental regulations, while aiming to reduce pollution, can sometimes push firms to operate informally to evade compliance costs. This shift to the shadow economy allows businesses to bypass environmental standards, potentially leading to higher pollution levels. The leather tanning industry in India is known for its significant environmental impact, especially concerning water pollution. When the government imposed strict environmental regulations on tanneries, including mandatory wastewater treatment, many small and medium-sized enterprises found compliance costs too high. Instead of upgrading their facilities, many shifted to informal operations, setting up illegal tanneries in rural areas or less regulated regions. These unregulated businesses often discharge toxic chemicals, such as chromium, directly into rivers, worsening pollution levels (MacCarthy, 2017).

In Pakistan, the government introduced strict environmental policies targeting the brick kiln industry to reduce air pollution, particularly smog. The policy required kilns to adopt "zigzag technology," a cleaner but expensive alternative. However, many kiln owners, unable or unwilling to bear the costs, started operating informally, avoiding taxes and regulations. A systematic review by Climate and Clean Air Coalition (2021) highlights that brick kilns are significant sources of air pollution in Pakistan, with many operating without regulation. The lack of formal oversight allows these kilns to evade environmental standards, exacerbating pollution levels.

The presence of a substantial shadow economy can adversely affect environmental quality. Research focusing on developing countries found that a sizable shadow economy significantly elevates levels of air pollutants like CO_2 and N_2O emissions. However, robust governance frameworks – characterised by enhanced corruption control, a stronger rule of law, and superior regulatory quality – can mitigate these harmful effects. This underscores the importance of strengthening governance mechanisms to reduce the shadow economy's size and its harmful environmental impact.

In the Amazon rainforest, illegal logging – a significant component of the shadow economy – has led to extensive deforestation. This deforestation contributes to increased CO_2 emissions, as trees that absorb carbon dioxide are removed. Illegal logging operations often operate without oversight, leading to environmental degradation and loss of biodiversity. The lack of enforcement and regulatory oversight allows these activities to flourish, exacerbating environmental harm (Edwards, n.d.).

In Nigeria, numerous small-scale industries operate informally to avoid regulatory scrutiny and compliance costs. These unregulated operations often bypass environmental standards, leading to significant air pollution. In Lagos, Nigeria, fewer than 10% of industries have installed proper treatment facilities. For example, metallic smelting companies contribute 9% of all emissions in the city, leading to significant air pollution and increased CO_2 and N_2O emissions (Clean Air Fund, n.d.).

Corruption within environmental regulation and the presence of a shadow economy are intricately linked, collectively undermining environmental sustainability. India’s solar energy sector has faced significant challenges due to corruption and regulatory weaknesses. A notable case involves allegations against Indian billionaire Gautam Adani and his associates, who were indicted in the United States for orchestrating a $265 million bribery scheme to secure solar energy contracts. This scheme aimed to obtain favourable energy supply agreements with the Solar Energy Corporation of India, a government-owned entity responsible for implementing renewable energy projects.

The indictment alleges that between 2020 and 2024, Adani and his co-defendants conspired to bribe Indian officials to secure these contracts, which were projected to yield

significant profits over two decades (Newslaundry, 2024). This case highlights vulnerabilities within India's renewable energy sector, where corrupt practices can undermine the integrity of environmental initiatives, leading to financial inefficiencies and project delays.

The interplay between environmental policies and the shadow economy presents challenges for policymakers. While strict environmental regulations are essential for sustainability, they may drive businesses underground, increasing pollution.

1. Literature review

The interaction between environmental policies and the shadow economy has gained increasing attention in economic and policy discourse. As governments impose environmental regulations to mitigate ecological degradation, unintended consequences such as expanding informal economic activities emerge. Environmental regulations often aim to curb industrial pollution and promote sustainability.

However, stringent policies may lead to increased costs for businesses, which, in turn, may drive some firms into the informal sector to evade compliance costs. Kudełko (2023) explores the impact of environmental regulations on the national energy sector, emphasising how regulatory stringency can influence market behaviour. Similarly, Surma and Leśniak (2023) highlight how EU environmental regulations affect energy sector efficiency, indirectly shaping shadow economic activities. A study by Biswas et al. (2011) highlighted that production in the shadow economy enables firms to avoid environmental regulations, suggesting that a large informal sector may be associated with increased pollution. An article by Chandan (2012) on environmental compliance in India's leather industry discusses how stringent environmental standards have impacted the sector. It highlights that while some firms have adapted, others, particularly small-scale operations, have struggled with compliance costs, leading to informal practices.

Environmental initiatives, particularly those related to renewable energy adoption, are frequently linked to opportunities for formalisation and development. For instance, Balcerzak et al. (2024), Bușu et al. (2024), and Kędzierski and Bielecki (2023) emphasise that effective energy mix strategies and prosumer models can support decentralised, sustainable practices that encourage participation in formal markets. Kuzior et al. (2021) further highlight how public demand for green energy in Ukraine influences shifts toward formal energy systems, creating a disincentive for informal energy consumption.

However, environmental policy impacts are mediated by structural governance factors. Kaya (2023) points to how corruption, poor licensing enforcement, and crisis-related state failures can diminish the credibility and enforcement of environmental laws – conditions under which informal economies often thrive. This is echoed by Tran (2023), who finds that in Southeast Asia, political instability and inflation can interact with shadow economy dynamics, reducing the effectiveness of formal economic and environmental governance. The circular economy model presents a promising framework for aligning environmental goals with economic formalisation (Amin et al., 2024). Kuzior et al. (2022a) argue that strategic enterprise development under circularity principles encourages regulatory compliance. Meanwhile, Kuzior et al. (2022b) extend this to digital governance, noting that transparency and cybersecurity improve institutional trust – which is key to shrinking informality. Sidii (2024) also explores these digital transitions and discusses how healthcare sustainability and digital resilience frameworks offer blueprints for broader sectors grappling with informal practices.

Business ethics also plays a critical role in shaping enterprise behaviour regarding environmental compliance. Martins and Casais (2024) delve into the ethical tensions between audit independence and customer-centric strategies, suggesting that unclear boundaries may

enable informal practices to persist under the guise of flexibility. The relevance of ethics and transparency is further emphasised by Alsayed (2024) and Kobiyh et al. (2024), who argue that responsible leadership and ethical governance create institutional environments less conducive to informality.

Fiscal policies play a crucial role in shaping the informal economy. Giedraitis et al. (2024) examine the role of taxation in mitigating the shadow economy, suggesting that overly complex tax structures may push firms into informality. Similarly, Mazurenko et al. (2023a, 2023b) and Dobrovolska et al. (2024) indicate that governance quality, tax burdens, and court efficiency directly shape the shadow economy's response to policy changes, including green initiatives.

Consumer behaviour and awareness are significant indirect influencers of informality in environmental sectors. Studies such as Elbaar and Masliani (2024), Phuong et al. (2024), Lu et al. (2023) and Nguyen et al. (2024) explore how environmental knowledge, social media, and informal costs shape purchasing decisions and business strategies in sectors with high informal participation, such as agriculture and retail. These findings align with Tran (2024), who notes that military spending and state priorities often shift the balance between public spending and regulatory control over informal markets. Bank and Badyda (2024) stress the role of financial instruments and market price changes in shaping business behaviour, with implications for informal actors who may either be pushed out by cost increases or pulled in by new green opportunities. In parallel, Badreddine and Larbi Cherif (2024) and Wołowiec et al. (2022) link public health-driven environmental reforms to broader societal transformations, including potential declines in informal activities due to better governance and energy security. However, several studies caution against oversimplifying this dynamic. For instance, Balas and Kaya (2024) show that global crises, such as the 2008 recession, can push firms toward informality, especially under competitive pressures or weak enforcement. Kaya and Engkuchik (2024) further explore how crises distort legal perceptions, potentially weakening compliance with environmental rules.

Financial development plays a dual role in influencing the informal economy. On the one hand, well-developed financial institutions provide businesses access to credit and investment opportunities, reducing the need for informal financial activities. On the other hand, restrictive financial regulations and limited access to formal banking services can push economic actors into informal markets, exacerbating shadow economic activities. Khayati and Terzi (2023) investigate how the informal economy affects financial development and economic growth. Their findings suggest that informal activities often thrive in economies with weak financial regulation and limited access to formal credit. This is echoed by Lyeonov et al. (2024), who explore the role of artificial intelligence and machine learning in combating illegal financial operations, underscoring the need for digital enforcement mechanisms to regulate informal financial activities. Michalkova et al. (2024) examine earnings manipulations in corporate life cycles, revealing how financial irregularities can contribute to informality. Masrick Hasan et al. (2024) explore macroeconomic shifts and their effects on financial stability, emphasising the impact on mutual funds and informal financial behaviours.

Green finance has been proposed to mitigate the unintended consequences of environmental policies. Minh Sang (2024) maps the evolution of green finance, demonstrating its role in supporting formal economic structures. Wang and Lu (2024) analyse collateral-based monetary policies in China, showing how financial instruments can incentivise sustainable investments while reducing informality. Kamarudin et al. (2024) further discuss regulatory efficiency and market openness, arguing that a well-structured regulatory environment can improve economic productivity while minimising shadow economic activities. Triantafyllidou et al. (2024) provide a systematic literature review on renewable and non-renewable energy consumption in Greece, highlighting the economic implications of environmental policies.

The informal economy plays a complex role in achieving Sustainable Development Goals. Dell Anno et al. (2024) analyse the informal economy's contribution to the SDGs in Europe, highlighting both the positive and negative impacts of informal labour markets. Maphumulo et al. (2023) focus on administrative practices for environmental compliance in South Africa's small and medium-sized enterprises, suggesting that informal firms often evade environmental compliance, leading to regulatory inefficiencies. Nosková et al. (2024) systematically review the circular economy's impact on business performance, suggesting that sustainability practices influence formal and informal economic structures.

Industrial transitions often create opportunities for informal entrepreneurship as businesses and workers adapt to evolving market conditions, sometimes bypassing regulatory frameworks to sustain economic activities. Avlogiaris et al. (2023) discuss the transition to green economies in post-lignite regions, highlighting the challenges businesses face shifting from carbon-intensive operations to sustainable models. Their findings suggest that firms may resort to informal economic activities without proper support mechanisms. Mehedintu and Soava (2024) examine renewable energy consumption's impact on economic growth, emphasising sectoral differences across EU countries. Maza-Avila et al. (2023) explore how Venezuelan migration has influenced informal trading in Cartagena de Indias, demonstrating how economic transitions can drive informal entrepreneurship. Tutar et al. (2024) analyse migration patterns to Turkey through macroeconomic indicators, linking demographic changes to shadow economic activities.

Governance is critical in regulating both environmental policies and shadow economic activities. Krudycz et al. (2023) explore decision-support models in public budget management, indicating that better fiscal governance can reduce informal economic transactions. Sarker et al. (2023) analyse the relationship between political will and public management reforms, highlighting how governance improvements can enhance regulatory compliance. Tkacova et al. (2024) examine the effects of EU climate targets on environmental efficiency, illustrating how well-structured environmental policies can foster formal economic growth. Dias et al. (2023) and Tran (2024) underline how external shocks – like pandemics or military spending – can inadvertently expand informal activities despite environmental ambitions. Alishli et al. (2024) discuss labour market regulations under Keynesian and Friedman economic theories, providing insights into policy mechanisms that may indirectly influence shadow economic activities.

Additionally, studies such as those by Masrick Hasan et al. (2024) suggest that macroeconomic shifts can influence shadow economic behaviours, which should be further investigated in future research. Moreover, the works of Triantafyllidou et al. (2024) and Tutar et al. (2024) highlight the intersection of migration, energy policy, and shadow economies, providing further avenues for policy interventions. Yarovenko et al. (2024) emphasise the importance of understanding illicit financial practices in developed economies to inform policy measures against shadow economic growth.

Lastly, the interaction of digitalisation, innovation, and green financing has emerged as a critical domain. Krause et al. (2024), Užík et al. (2024), and Runiewicz-Wardyn and Winogradska (2023) demonstrate that trust, reputation, and access to green finance tools can improve firm formalisation, while Takyi et al. (2024) and Oe et al. (2023) show how green policy leadership and enterprise innovation contribute to aligning sustainability with regulatory legitimacy.

The existing literature suggests a complex interplay between environmental policies and the shadow economy. While stringent environmental regulations promote sustainability, they may inadvertently push businesses into informality due to increased compliance costs. Effective governance, tax reforms, and green financial instruments are crucial in balancing environmental objectives with economic formalisation. Future research should focus on designing policies

integrating environmental goals with economic inclusivity, ensuring that sustainability efforts do not inadvertently expand the shadow economy. This study aims to analyse the relationship between environmental policy stringency and the size of the shadow economy across 24 countries over the period 2003–2020. Specifically, the research seeks to determine whether stricter environmental regulations and market-based policies influence the prevalence of informal economic activities. The study tests the following main hypotheses:

H1 – stricter environmental policy stringency (EPS) reduces the size of the shadow economy. This hypothesis assumes that countries with more stringent environmental regulations experience lower levels of informal economic activity due to improved regulatory enforcement and compliance.

H2 – market-based environmental policies (e.g., CO_2 trading schemes, carbon taxes) have a more substantial impact on reducing the shadow economy than command-and-control policies. Market-based mechanisms provide economic incentives for compliance, potentially reducing the incentives to operate informally.

H3 – high environmental taxation (e.g., diesel tax, CO_2 tax, SOx tax) may unintentionally increase the shadow economy. This hypothesis suggests that excessive environmental taxes could push businesses and individuals to evade formal regulations by shifting their activities into the informal sector.

H4 – the relationship between environmental policy stringency and the shadow economy varies across countries due to institutional and economic differences. Different economic structures, levels of governance, and enforcement capacities may result in heterogeneous effects of environmental policies on the shadow economy.

2. Methodological approach

Data and variables

This study utilises a panel dataset comprising 432 observations from 24 countries over 18 years (2003–2020). The dependent variable (y) represents the size of the shadow economy as a percentage of official GDP. The primary independent variables (x1 to x8) represent various Environmental Policy Stringency (EPS) indices, capturing overall policy stringency, market-based instruments, CO_2 trading schemes, renewable energy trading schemes, carbon dioxide taxes, nitrogen oxides taxes, sulphur oxides taxes, and diesel taxes.

Variables and their data sources are presented in Table 1.

Table 1. Variables and Their Sources

Variable	Description	Source
y	Size of the shadow economy (in % of off. GDP)	Schneider, 2022
x1	Environmental Policy Stringency Index (All environmental policies)	OECD, n.d.
x2	Environmental Policy Stringency Index (Market-based policies)	OECD, n.d.
x3	Environmental Policy Stringency Index (CO2 trading scheme)	OECD, n.d.
x4	Environmental Policy Stringency Index (Renewable energy trading scheme)	OECD, n.d.
x5	Environmental Policy Stringency Index (Carbon dioxides (CO2) tax)	OECD, n.d.
x6	Environmental Policy Stringency Index (Nitrogen oxides (NOx) tax)	OECD, n.d.
x7	Environmental Policy Stringency Index (Sulphur oxides (SOx) tax)	OECD, n.d.
x8	Environmental Policy Stringency Index (Diesel tax)	OECD, n.d.

Source*: authors' compilation*

The list of the countries in panel data includes Austria, Belgium, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Luxembourg,

Netherlands, Poland, Portugal, Slovenia, Spain, Slovakia, Sweden, United Kingdom, Norway, Switzerland, Turkey.

However, the study is limited by the OECD database, which only provides data up to 2020, and by the selection of 24 countries, which may not fully represent the diversity of global economic and regulatory environments.

Econometric model specification

Panel data regression techniques are applied to analyse the relationship between environmental policy stringency and the shadow economy. The baseline model is in Formula 1:

$$y_{it} = \beta_0 + \beta_1 x_{it} + \alpha_i + \varepsilon_{it}, \quad (1)$$

where, y_{it} represents the shadow economy size in the country at the time; x_{it} is the vector of explanatory variables representing environmental policy stringency indices; α_i represents country-specific fixed effects; ε_{it} is the idiosyncratic error term.

Both Fixed Effects (FE) and Random Effects (RE) models are estimated to determine the most appropriate specification. The Hausman test is applied to choose between the two.

Estimation approach

1. The FE model accounts for unobserved heterogeneity across countries by controlling time-invariant country-specific factors. This model is estimated to use the within estimator where and are the within-group averages for each country.

2. The RE model assumes that individual country effects are uncorrelated with the explanatory variables. It is estimated that using Generalized Least Squares (GLS) transformation will account for both within and between variations where the random effect captures country-specific heterogeneity.

3. The Hausman test determines whether the FE or RE model is more suitable. A significant test result ($p < 0.05$) indicates that the FE model is preferred due to the correlation between individual effects and explanatory variables.

Robustness checks

1. To account for heteroskedasticity and serial correlation in panel data, heteroskedasticity-robust and cluster-robust standard errors are used in the FE model. The Breusch-Pagan test is applied to detect heteroskedasticity.

2. A time-fixed effects model is estimated to account for unobserved macroeconomic trends affecting all countries over time. Year dummies are included in the regression specification, which represents year-fixed effects.

3. Model selection is based on Adjusted R-squared, Akaike Information Criterion (AIC), and Bayesian Information Criterion (BIC). The Full and Reduced models are compared to determine the most parsimonious specification.

Software and computation

All statistical analyses are performed using R Studio, employing packages such as “plm” for panel data estimation, “lmtest” for hypothesis testing, and “sandwich” for robust standard error estimation. The correlation matrix and regression outputs are validated through multiple robustness checks to ensure consistency and reliability.

3. Conducting research and results

The summary statistics in Table 2 presented key descriptive measures for the variables in the dataset, including the shadow economy (y) and various environmental policy stringency indices (x1 to x8).

Table 2. Summary statistics

Variable	Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
y	5.40	11.18	15.40	16.56	21.90	32.50
x1	0.5278	2.5278	2.9444	2.9610	3.4722	4.8889
x2	0.3333	1.0000	1.3333	1.5868	2.0000	4.1667
x3	0.000	1.000	1.000	1.664	3.000	5.000
x4	0.0000	0.0000	0.0000	0.6713	0.0000	6.0000
x5	0.000	0.000	0.000	1.373	2.000	6.000
x6	0.000	0.000	0.000	1.238	1.000	6.000
x7	0.0000	0.0000	0.0000	0.6736	1.0000	6.0000
x8	0.0	3.0	4.0	3.9	4.0	6.0

Note: y=size of the shadow economy; x1, x2, x3, x4, x5, x6, x7, x8=environmental policy stringency indices; 1st Qu.=first quartile; 3rd Qu.=third quartile.

Source*: authors' calculations in R Studio.*

As shown in Table 2, for y, representing the size of the shadow economy as a percentage of GDP, the minimum recorded value is 5.40%, while the maximum reaches 32.50%. The mean value of 16.56% suggests that, on average, the shadow economy constitutes a significant portion of GDP, with a median of 15.40% indicating a slightly right-skewed distribution.

Table 3. Summary Statistics for the Shadow Economy (y) and Various Environmental Policy Stringency Indices (x1 to x8)

	y	**x1**	**x2**	**x3**	**x4**	**x5**	**x6**	**x7**	**x8**
Number of observations	432	432	432	432	432	432	432	432	432
Mean	16.56	2.96	1.59	1.66	0.67	1.37	1.24	0.67	3.90
Standard deviation (spread of data)	6.45	0.68	0.87	1.25	1.61	2.06	2.07	1.42	0.89
Median	15.40	2.94	1.33	1.00	0.00	0.00	0.00	0.00	4.00
Mean after removing extreme values (robust mean)	16.21	2.98	1.46	1.58	0.21	0.97	0.80	0.32	3.87
Median absolute deviation (a robust measure of spread)	7.41	0.68	0.74	1.48	0.00	0.00	0.00	0.00	1.48
Minimum	5.40	0.53	0.33	0.00	0.00	0.00	0.00	0.00	0.00
Maximum	32.50	4.89	4.17	5.00	6.00	6.00	6.00	6.00	6.00
Difference between max and min	27.10	4.36	3.83	5.00	6.00	6.00	6.00	6.00	6.00
Skew	0.40	-0.30	1.14	0.43	2.36	1.36	1.51	2.67	-0.31
Kurtosis	-0.84	0.63	0.50	-0.82	4.28	0.42	0.70	6.80	2.31
Standard error (uncertainty in mean estimate)	0.31	0.03	0.04	0.06	0.08	0.10	0.10	0.07	0.04

Note: y=size of the shadow economy; x1, x2, x3, x4, x5, x6, x7, x8=environmental policy stringency indices.

Source*: authors' calculations in R Studio.*

Among the environmental policy stringency indices, x1, which represents overall environmental policy stringency, has a mean of 2.9610 and a median of 2.9444, with values ranging from 0.5278 to 4.8889. This suggests that most countries have moderate levels of environmental policy enforcement. x2, representing market-based policies, has a mean of 1.5868 and a median of 1.3333. This indicates that many countries have relatively low levels of market-based environmental policies, with some exceptions where policies are more stringent.

The x3 variable, which measures the stringency of CO_2 trading schemes, has a mean of 1.664 and a median of 1.000, with a maximum value of 5.000. This suggests that while some countries have highly developed CO_2 trading schemes, many have minimal or moderate levels of implementation. x4, representing renewable energy trading schemes, shows a mean of 0.6713 with

a median and first quartile of 0.0000. This indicates that most countries do not have strong policies in this area, but a few have highly stringent regulations.

The carbon dioxide tax (x5), nitrogen oxides tax (x6), and sulphur oxides tax (x7) all show similar patterns, with medians and first quartiles at 0.000, meaning many countries do not impose these taxes. In contrast, others enforce them at higher levels, as seen in the maximum values 6.000. The diesel tax (x8) presents a higher median of 4.000 and a mean of 3.900, indicating that diesel taxation is more commonly enforced than other environmental taxes. Table 3. presents summary statistics for the shadow economy (y) and various environmental policy stringency indices (x1 to x8).

The key insights from the data reveal important patterns in the relationship between the shadow economy and environmental policy stringency (Table 4). The size of the shadow economy, represented by y, has a mean value of 16.56% of GDP, with a median of 15.40%, indicating a slight right skew with a skewness of 0.40. The standard deviation is 6.45, reflecting significant variability across observations. A kurtosis value of -0.84 suggests lighter tails than a normal distribution, meaning extreme values are less frequent.

In Table 4, environmental policy stringency, represented by variables x1 to x8, varies significantly across different categories. The overall stringency index (x1) has a mean of 2.96 and a relatively small range of 4.36, with a slight left skew of -0.30. Market-based policies (x2) have a mean of 1.59, showing a strong right skew of 1.14, indicating that most countries have low values, but a few exhibit very high levels of policy stringency. The CO_2 trading scheme (x3) follows a similar pattern, with a mean of 1.66 and a moderate right skew of 0.43.

Table 4. Correlation Matrix

	y	x1	x2	x3	x4	x5	x6	x7	x8
y	1.000								
x1	-0.423 (0.000)	1.000							
x2	-0.158 (0.0001)	0.566 (0.000)	1.000						
x3	-0.162 (<0.0001)	0.293 (<0.0001)	0.304 (<0.0001)	1.000					
x4	-0.053 (0.272)	-0.001 (0.981)	0.207 (<0.001)	0.122 (0.011)	1.000				
x5	-0.240 (<0.0001)	0.430 (0.000)	0.712 (0.0e+00)	0.065 (0.177)	-0.082 (0.089)	1.000			
x6	0.052 (0.272)	0.434 (0.00)	0.804 (0.000)	0.043 (0.376)	0.032 (0.508)	0.451 (0.000)	1.000		
x7	0.066 (0.168)	0.311 (<0.0001)	0.474 (0.000)	0.040 (0.403)	0.018 (0.709)	0.087 (0.071)	0.485 (0.000)	1.000	
x8	-0.235 (<0.0001)	0.067 (0.162)	0.138 (0.004)	-0.157 (<0.0001)	0.035 (0.464)	0.084 (0.080)	-0.079 (0.103)	-0.068 (0.159)	1.000

Note: () is p-values; y=size of the shadow economy; x1, x2, x3, x4, x5, x6, x7, x8=environmental policy stringency indices.

Source*: authors' calculations in R Studio.*

The renewable energy trading scheme (x4) stands out with a highly skewed distribution, where the mean is only 0.67, but with an extreme right skewness of 2.36 and a kurtosis of 4.28. This suggests that while many countries have very low levels of policy implementation, a few have exceptionally high values. Carbon dioxide tax (x5), nitrogen oxides tax (x6), and sulphur oxides tax (x7) all exhibit large variability, with means ranging from 1.24 to 1.37. Among these,

the sulphur oxides tax (x7) shows the most extreme distribution, with a skewness of 2.67 and a kurtosis of 6.80, implying a concentration of very low values but in some extreme cases where taxation is high.

The diesel tax (x8), with a mean of 3.90, is more generally distributed than the others, exhibiting only slight left skewness (-0.31) and moderate kurtosis (2.31). This suggests that diesel taxation policies are more evenly spread across countries than other environmental taxes.

The correlation matrix and p-values (Table 4) provide insights into the relationships between the shadow economy (y) and various Environmental Policy Stringency Index (EPS) variables (x1 to x8).

The correlation analysis reveals important insights into the relationship between the shadow economy and various environmental policy stringency indices. The size of the shadow economy, represented by y, exhibits a moderate negative correlation of -0.423 with x1, representing overall environmental policy stringency. This suggests that stricter environmental regulations are generally associated with a reduction in the shadow economy, and the relationship is statistically significant with a p-value of less than 0.0001.

A weaker negative correlation of -0.157 is observed between the shadow economy and x2, representing market-based policies. This indicates that these policies have a limited but significant effect in reducing informal economic activity. The correlation between y and x3, representing the CO_2 trading scheme, is also negative at -0.162, suggesting a slight reduction in the shadow economy due to stricter emissions trading policies. The p-values for x2 and x3 (0.0010 and 0.0007, respectively) confirm that these relationships are statistically significant.

In contrast, the correlation between the shadow economy and x4, representing the renewable energy trading scheme, is nearly zero at -0.052. This indicates that stricter renewable energy policies do not significantly impact the shadow economy, which is supported by the high p-value of 0.2720, showing no statistical significance. A moderate negative correlation of -0.240 is observed between y and x5, representing the CO_2 tax, indicating that higher carbon taxes are associated with reducing the shadow economy. This relationship is also statistically significant with a p-value of less than 0.0001.

For x6, which represents the nitrogen oxides (NOx) tax, the correlation with the shadow economy is slightly positive at 0.052, suggesting that higher NOx taxation might be linked to a slight increase in informal economic activities. However, this relationship is not statistically significant, as indicated by the p-value of 0.2720. Similarly, x7, which represents the sulphur oxides (SOx) tax, has a weak positive correlation of 0.066 with y, suggesting that higher SOx taxation may slightly contribute to an increase in the shadow economy. However, this effect is minimal and not statistically significant, with a p-value of 0.1685.

Lastly, x8, representing the diesel tax, exhibits a moderate negative correlation of -0.235 with the shadow economy, suggesting that stricter diesel taxation is associated with reducing informal economic activities. This relationship is statistically significant, as indicated by the p-value of less than 0.0001.

The results come from panel data regression analysis using the FE (Within) and the RE models in Table 5.

As shown in Table 5, the FE model results indicate that the coefficient for x1 is -2.17909, meaning that a one-unit increase in environmental policy stringency (x1) is associated with a 2.18 percentage point decrease in the shadow economy (y). The t-value of -15.473 and a p-value of less than 0.0001 confirm that this effect is highly statistically significant. The R-squared value of 0.37037 suggests that the model explains 37.04% of the variation in y, indicating a moderate fit.

Table 5. The Outputs from the Fixed Effects (Within) and the Random Effects models of Interrelations Between the Size of the Shadow Economy (y) and Environmental Policy Stringency Index (x1)

	Oneway (individual) effect within the model	Oneway (individual) effect Random Effect Model (Swamy-Arora's transformation)
Estimate	-2.17909	-2.19148
Std. Error	0.14083	0.14092
t-value	-15.473	
z-value		-15.551
Pr(>|t|)	< 0.0001 ***	< 0.0001 ***
R-Squared	0.37037	0.35995
Adj. R-Squared	0.33324	0.35846
F-statistic	239.407	
Chisq		241.824
p-value	< 0.0001	< 0.0001
Hausman Test		
Chisq	5.98	
p-value	0.01447	

Note: Std. Error=standard error of the estimate; t-value/z-value=test statistic; p-value=probability value; Pr(>|t|)=p-value for hypothesis test; Chisq=Chi-squared test.

Source*: authors' calculations in R Studio.*

Additionally, the F-statistic of 239.407 with a p-value below 0.0001 validates the overall significance of the model. These findings suggest that stricter environmental policies are associated with a reduction in the shadow economy, and this effect persists even after accounting for individual country characteristics.

The RE model assumes that the individual effects (α_i) are randomly distributed and uncorrelated with the explanatory variables. The Swamy-Arora transformation allows variation across individuals while incorporating within-group and between-group differences.

The coefficient for x1 is -2.19148, which is nearly identical to the estimate from the FE model, indicating a similar magnitude of impact. The p-value of less than 0.0001 confirms this effect is highly statistically significant. The intercept, estimated at 23.04715, suggests that in the absence of environmental policy stringency considerations, the average size of the shadow economy is approximately 23.05% of GDP. The R-squared value of 0.35995, though slightly lower than that of the FE model, still indicates a moderate fit.

The Chi-Square statistic of 241.824, with a p-value below 0.0001, confirms the overall significance of the model. Variance decomposition reveals that 93.4% of the total variance is attributed to individual-specific effects. In comparison, 6.6% is due to idiosyncratic errors, indicating that most of the variation in the shadow economy is driven by country-specific differences.

The Hausman test helps determine whether the FE or RE model is more appropriate. The null hypothesis states that RE is preferred (individual effects are uncorrelated with x1), while the alternative hypothesis suggests that FE is preferred (individual effects are correlated with x1). Since the p-value (0.01447) < 0.05, the null hypothesis should be rejected. This means the FE model is the better choice because it accounts for unobserved heterogeneity correlated with environmental policy stringency. Since the FE model is preferred, it implies that country-specific characteristics significantly influence the relationship between environmental policies and informal economic activities.

Table 6 presents the results of the FE (Within) model estimated using panel least squares regression with time-fixed effects (year dummies). This model aims to analyse the impact of environmental policy stringency (x1) on the shadow economy (y) while controlling for year-specific effects.

Table 6. The Results of a Fixed Effects (Within) model estimated using panel least squares regression with time-fixed effects (year dummies)

Oneway (individual) effect Within Model
Call:
plm(formula = y ~ x1 + factor(year), data = df, model = "within")
Balanced Panel: n = 24, T = 18, N = 432

Residuals:

Min.	1st Qu.	Median	3rd Qu.	Max.
-9.1892521	-0.4032957	-0.0077216	0.3688724	4.8408584

Coefficients:

	Estimate	Std. Error	t-value	Pr(>|t|)
x1	0.284704	0.157503	1.8076	0.07144.
factor(year)2004	0.051678	0.283097	0.1825	0.85525
factor(year)2005	-0.546050	0.290423	-1.8802	0.06083.
factor(year)2006	-1.409413	0.299149	-4.7114	< 0.0001***
factor(year)2007	-2.113654	0.295519	-7.1523	< 0.0001***
factor(year)2008	-2.875295	0.310245	-9.2678	< 0.0001***
factor(year)2009	-2.355559	0.326472	-7.2152	< 0.0001***
factor(year)2010	-2.663394	0.334741	-7.9566	< 0.0001***
factor(year)2011	-3.057857	0.344587	-8.8740	< 0.0001***
factor(year)2012	-3.314053	0.334937	-9.8946	< 0.0001***
factor(year)2013	-3.801479	0.341269	-11.1393	< 0.0001***
factor(year)2014	-3.938671	0.345111	-11.4128	< 0.0001***
factor(year)2015	-4.177160	0.345427	-12.0928	< 0.0001***
factor(year)2016	-4.462566	0.343439	-12.9938	< 0.0001***
factor(year)2017	-4.867391	0.343647	-14.1639	< 0.0001***
factor(year)2018	-5.288576	0.347757	-15.2077	< 0.0001***
factor(year)2019	-5.878404	0.352619	-16.6707	< 0.0001***
factor(year)2020	-4.471550	0.363048	-12.3167	< 0.0001***

*Notes: Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1; Total Sum of Squares: 1478.5; Residual Sum of Squares: 372.28; R-Squared: 0.7482; Adj. R-Squared: 0.72173; F-statistic: 64.3821 on 18 and 390 DF, p-value <0.0001; Std. Error=standard error; 1st Qu.=first quartile; 3rd Qu.=third quartile; t-value=test statistic; p-value=probability value; Pr(>|t|)=p-value for hypothesis test.*

Source*: authors' calculations in R Studio.*

In Table 6, the coefficient for x1 (Environmental Policy Stringency) is 0.2847, meaning that a one-unit increase in policy stringency is associated with a 0.285 percentage point increase in the shadow economy. However, the t-value (1.8076) and p-value (0.07144) indicate that this effect is not statistically significant at the 5% level but is marginally significant at the 10% level. This suggests that stricter environmental policies may lead to a slight expansion of the shadow economy, but the evidence is not strong enough to be conclusive.

The year dummy variables (factor(year)) capture time-fixed effects, indicating how the size of the shadow economy varies over time relative to the baseline year (which is omitted, like 2003). The coefficients for the year dummies are all negative and significant, showing a clear downward trend in the shadow economy over time. For instance, in 2019, the shadow economy is estimated to be 5.878 percentage points smaller than in the baseline year, with a

highly significant t-value of -16.6707 (p-value < 0.0001). This suggests that the shadow economy has generally declined over the years, possibly due to improvements in governance, enforcement, or economic formalisation.

The difference in the coefficient for x1 between the two FE models arises from including time-fixed effects (year dummies) in the second model. Below is a breakdown of why this occurs and what it implies. The change in the coefficient for x1 from -2.17909 to 0.2847 is primarily due to the inclusion of time-fixed effects, which corrects for omitted variable bias in the first model. In the initial fixed effects model, time-specific factors such as economic cycles, global financial crises, or technological advancements were not explicitly accounted for. If x1 is correlated with these unobserved time factors, the estimate in the first model may have absorbed some of their influence, leading to a more significant negative effect.

When time-fixed effects are introduced in the second model, these year-specific trends are controlled, meaning the downward trend in the shadow economy that could be due to broader economic developments is now accounted for separately. As a result, the impact of x1 appears much weaker and shifts from a strong negative relationship to a marginally positive one. Additionally, the shadow economy may have declined over time due to structural reforms, improved governance, or other macroeconomic factors independent of x1. In the first model, the negative correlation could have been overstated if x1 had increased over time while the shadow economy had naturally decreased. By including time-fixed effects, the second model isolates these time-related influences, resulting in a smaller and less significant coefficient for x1.

Multicollinearity between x1 and the year dummies may also contribute to this change. Since environmental policies tend to evolve, x1 may strongly correlate with the year effects, reducing the independent variability in x1. When both x1 and the time dummies are included in the model, much of the variation in x1 that previously drove the negative coefficient is now explained by the time dummies, leading to a weaker and less significant estimated effect.

Overall, the change in the coefficient reflects the role of omitted variable bias in the first model and the importance of controlling for time trends. The second model provides a more refined estimate by separating the effect of x1 from general trends in the shadow economy, showing that the direct impact of environmental policy stringency is much weaker than initially estimated.

Applying heteroskedasticity-robust standard errors to the FE model helps correct for potential violations of homoskedasticity and serial correlation in panel data. The estimated coefficient for x1 remains at -2.17909, indicating that a one-unit increase in environmental policy stringency (x1) is associated with a 2.18 percentage point decrease in the shadow economy (y). The robust standard error is 0.24397, slightly larger than the standard error in the original FE model, meaning that the model initially underestimated the estimate's uncertainty. The t-value is -8.9316, which remains large, indicating that x1 still has a substantial and statistically significant effect on y. The p-value (< 0.0001) confirms that the effect is highly significant, even after adjusting for potential heteroskedasticity or clustering effects.

Table 7 presents FE and RE models estimated using panel regression analysis to study the impact of environmental policy stringency subindices (x2 to x8) on the shadow economy (y). The Hausman test is used to determine which model provides more reliable estimates.

Since the p-value (0.6957) is more significant than 0.05, the null hypothesis fails to be rejected, meaning that the RE model is preferred over the FE model (Table 7). This suggests that individual (country-specific) effects are not significantly correlated with the explanatory variables, making RE a more efficient estimator. The RE model assumes that individual-specific effects are uncorrelated with the explanatory variables, allowing it to estimate the impact of x2 to x8 while considering both within-group and between-group variations.

Table 7. The Outputs from the Fixed Effects (Within) and the Random Effects (Swamy-Arora's Transformation) models of Interrelations Between the Size of the Shadow Economy (y) and Environmental Policy Stringency Indices (x2 to x8)

	Oneway (individual) effect within model	Oneway (individual) effect Random Effect model (Swamy-Arora's transformation)
Estimate		
(Intercept)		18.465926 (<0.0001)***
x2	-2.946960 (0.0386786)*	-2.620896 (0.058186) .
x3	0.238482 (0.3363294)	0.179526 (0.457891)
x4	-0.163278 (0.4912024)	-0.209549 (0.363336)
x5	0.100150 (0.6960711)	0.044372 (0.860365)
x6	-0.089591 (0.7263209)	-0.125275 (0.618659)
x7	1.002250 (0.0008456)***	0.936291 (0.001191)**
x8	0.467815 (0.0874911) .	0.399041 (0.136076)
R-Squared	0.2747	0.25841
Adj. R-Squared	0.22044	0.24617
F-statistic	21.6961	
Chisq		147.746
p-value	< 0.0001	< 0.0001
Hausman Test		
Chisq	4.7068	
p-value	0.6957	

Note: y=size of the shadow economy; x1, x2, x3, x4, x5, x6, x7, x8=environmental policy stringency indices; Chisq=Chi-squared test; p-value=probability value.

Source*: authors' calculations in R Studio.*

Regarding significant variables, x7 (SOx Tax) remains statistically significant, with a coefficient of 0.9363 and a p-value of 0.0012, reinforcing the idea that higher sulphur oxide taxation is associated with a larger shadow economy. Among the marginally significant variables, x2 (Market-Based Policies) has a coefficient of -2.6209 and a p-value of 0.0582, close to statistical significance at the 10% level. This suggests a possible negative relationship between market-based policies and the shadow economy, though the effect is not definitive.

For non-significant variables, x3, x4, x5, x6, and x8 remain statistically insignificant, indicating that these specific environmental policies do not strongly influence the shadow economy within the RE model framework. Regarding model fit, the R^2 value of 0.2584 suggests that the model explains 25.84% of the variation in y, slightly lower than the FE model. The Chi-Square statistic of 147.746 with a p-value < 0.0001 confirms that the overall model is highly statistically significant.

Variance decomposition analysis shows that 93.02% of the variation in the shadow economy is due to individual (country-specific) effects, while only 6.98% is attributed to idiosyncratic (random) error. This suggests that most of the variation in the shadow economy is driven by country-specific differences rather than random fluctuations.

The following step simplifies the model by removing non-significant variables (x3, x4, x5, x6, x8). Reducing unnecessary variables can increase degrees of freedom, potentially leading to a better-fitting and more interpretable model. Table 8 presents a regression output summary from a RE panel model, re-estimated using only variables that were previously significant or near-significant: x2 and x7.

Table 8. The Outputs of Re-estimating the Model with only Significant and Near-significant Variables (x2 and x7)

Oneway (individual) effect Random Effect Model (Swamy-Arora's transformation)
Call:
plm(formula = y ~ x2 + x7, data = df, model = "random")
Balanced Panel: n = 24, T = 18, N = 432

Effects			
	Var	Std. dev	Share
Idiosyncratic	2.810	1. 676	0.063
Individual	41.777	6.464	0. 937
Theta	0.939		

Residuals				
Min.	1st Qu.	Median	3rd Qu.	Max.
-8.01300	-1.20941	-0.16006	1.20306	4.50238

Coefficients				
	Estimate	Std. Error	z-value	Pr(>|z|)
(intercept)	19.83999	1.35254	14.669	< 0.0001
x2	-2.38871	0.22442	-10.644	< 0.0001
x7	0.75494	0.17945	4. 207	<0.0001

*Notes: Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1; Total Sum of Squares = 1539.8; Residual Sum of Squares = 1200.5; R-Squared = 0.22034; Adj. R-Squared = 0.21671; Chisq = 121.24 on 2 DF; p-value = < 0.0001; Std. dev. = standard deviation; Std. Error = standard deviation; z-value=test statistic; p-value=probability value; Pr(>|z|)=p-value for hypothesis test; Var = Variance; 1st Qu.=first quartile; 3rd Qu.=third quartile*

Source*: authors' calculations in R Studio.*

The intercept value of 19.84 indicates that when both x2 and x7 are zero, the expected value of the dependent variable y is 19.84. The coefficient for x2 is -2.39, meaning that, assuming x7 remains constant, a one-unit increase in x2 is associated with a decrease of approximately 2.39 units in y. This effect is highly statistically significant. Similarly, the coefficient for x7 is 0.76, which suggests that holding x2 constant, a one-unit increase in x7 leads to an increase of about 0.76 units in y, and this relationship is also statistically significant.

Breusch-Pagan test result (BP = 36.776, df = 2, p-value <0.0001) for the reduced model allows us to conclude the presence of heteroskedasticity since the p-value is very small and the rejection of the null hypothesis of homoskedasticity. This means the variance of residuals is not constant, which can lead to biased standard errors and incorrect inference in your model.

The next step is addressing heteroskedasticity using robust standard errors (preferred solution). If heteroskedasticity varies across individuals (panels), it tries to make clustered standard errors (Table 9).

After applying heteroskedasticity-robust standard errors, as demonstrated in Table 9, the updated t-tests indicate that x2 is highly significant with a p-value less than 0.0001. The coefficient of x2 is -2.39, suggesting that an increase in x2 significantly reduces y. x7 is also significant, with a p-value of 0.01852. The coefficient for x7 is 0.75, indicating a positive relationship with y. The intercept is highly significant as well.

Table 9. The output of a robust standard error correction applied to a RE model using the coeftest() function with heteroskedasticity-consistent (HC0) standard errors – both with and without clustering by the group.

coeftest(re_model_reduced, vcovHC(re_model_reduced, type = "HC0"))				
t-test of coefficients:				
	Estimate	Std. Error	z-value	Pr(>|z|)
(intercept)	19.83999	1.51112	13.1293	<0.0001***
x2	-2.38871	0.27916	-8.5568	<0.0001***
x7	0.75494	0.31935	2.3640	0.01852*
Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1				
coeftest(re_model_reduced, vcovHC(re_model_reduced, type = "HC0", cluster = "group"))				
t-test of coefficients:				
	Estimate	Std. Error	z-value	Pr(>|z|)
(intercept)	19.83999	1.51112	13.1293	<0.0001
x2	-2.38871	0.27916	-8.5568	<0.0001
x7	0.75494	0.31935	2.3640	0.01852

*Note: Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1; Std. Error=standard error; z-value=test statistic; p-value=probability value; Pr(>|z|)=p-value for hypothesis test*

Source*: authors' calculations in R Studio.*

When applying clustered standard errors (cluster = "group"), the results remain identical to those with robust standard errors (HC0). This suggests that clustering by group does not notably alter the standard errors, meaning that while heteroskedasticity is present, it is not firmly related to the grouping structure in the data.

The Variance Inflation Factor (VIF) results show that both x2 and x7 have a VIF of 1.29. This suggests that there is no significant multicollinearity between these variables. The correlation between x2 and x7 is relatively weak, and removing or adjusting these variables for multicollinearity is unnecessary. The AIC results show that the whole model has a value of 441.19, while the reduced model has a value of 447.54. Since the AIC for the whole model is lower, it suggests that the entire model provides a better fit to the data, balancing goodness of fit and model complexity more effectively.

For the BIC, the full model has a value of 473.74, and the reduced model has a value of 459.75. The reduced model's lower BIC indicates that it is more parsimonious, offering a better balance of complexity and fit, given the penalty for additional parameters.

Therefore, the choice between the two models depends on prioritisation complexity versus fit: if minimising fit error is most important, the whole model might be the better choice. The reduced model may be more appropriate if prioritisation is simple and balanced.

Table 10 shows the individual-specific random effects for each country in panel data. These values represent the country-specific deviations from the overall mean effect in the RE model.

In Table 10, Turkey (10.87) and Estonia (10.20) exhibit significant positive random effects, suggesting that unobserved factors contribute to an increase in the size of the shadow economy beyond what is explained by environmental policy stringency measures. In contrast, Austria (-9.02) and Luxembourg (-9.18) display significant negative random effects, indicating that unobserved characteristics in these countries reduce the shadow economy size beyond what is accounted for by environmental policy stringency.

Poland (8.68) and Slovenia (7.08) also show relatively high positive deviations, suggesting that certain unmeasured factors are associated with a larger shadow economy despite the level of environmental policy stringency. On the other hand, Germany (-4.84) and France

(-4.42) have negative random effects, implying that factors not included in the model contribute to a reduction in the shadow economy.

Table 10. The Individual-Specific Random Effects for Each Country

Country	Individual-specific random effects	Country	Individual-specific random effects
Austria	-9.0234290	Luxembourg	-9.1761141
Belgium	0.7752914	Netherlands	-7.8436676
Czech Republic	-1.4963510	Norway	1.2954051
Denmark	-3.8945779	Poland	8.6837095
Estonia	10.1975311	Portugal	1.4868799
Finland	-2.1511841	Slovakia	-2.2004989
France	-4.4213041	Slovenia	7.0808668
Germany	-4.8441826	Spain	1.3882937
Greece	6.0560672	Sweden	3.4661464
Hungary	6.0788083	Switzerland	-8.4490374
Ireland	-5.1294817	Turkey	10.8715117
Italy	5.5803939	United Kingdom	-4.3310766

Source*: authors' calculations in R Studio.*

Since these random effects capture unobserved heterogeneity, they highlight variations in how different countries' structural, institutional, or economic conditions interact with environmental policy stringency to influence the shadow economy.

Figure 1 illustrates the distribution of the estimated random effects from the RE model. These effects represent individual-specific deviations from the overall population mean in your panel data model.

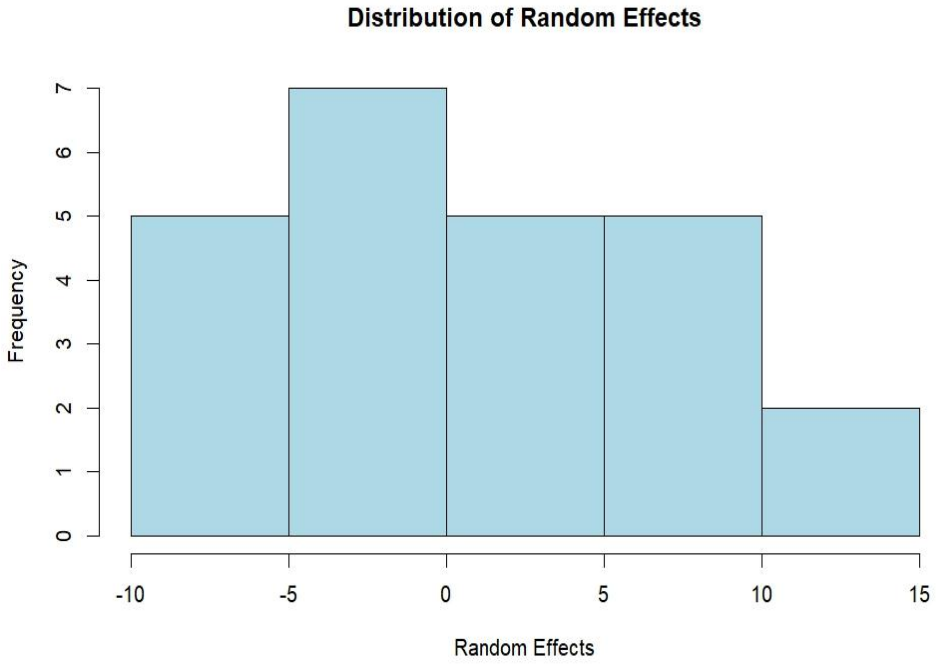

Figure 1. The Distribution of the Estimated Random Effects from the RE model
Source*: authors' calculations in R Studio.*

The random effects distribution appears to be roughly centred around zero, with values ranging from approximately -10 to 15 (Figure 1). The shape of the histogram suggests that the distribution is somewhat symmetric. However, a slight right skew may indicate that some entities exhibit relatively more significant positive random effects. Most observations fall between -5 and 5, implying that most entities have relatively minor deviations from the population mean.

However, a few entities have more significant positive or negative random effects, suggesting that certain groups behave significantly differently from the overall average.

The Normal Q-Q Plot (Figure 2) assesses whether the random effects from the model follow a normal distribution. The plot compares the sample quantiles (observed random effects) to the theoretical quantiles of a normal distribution.

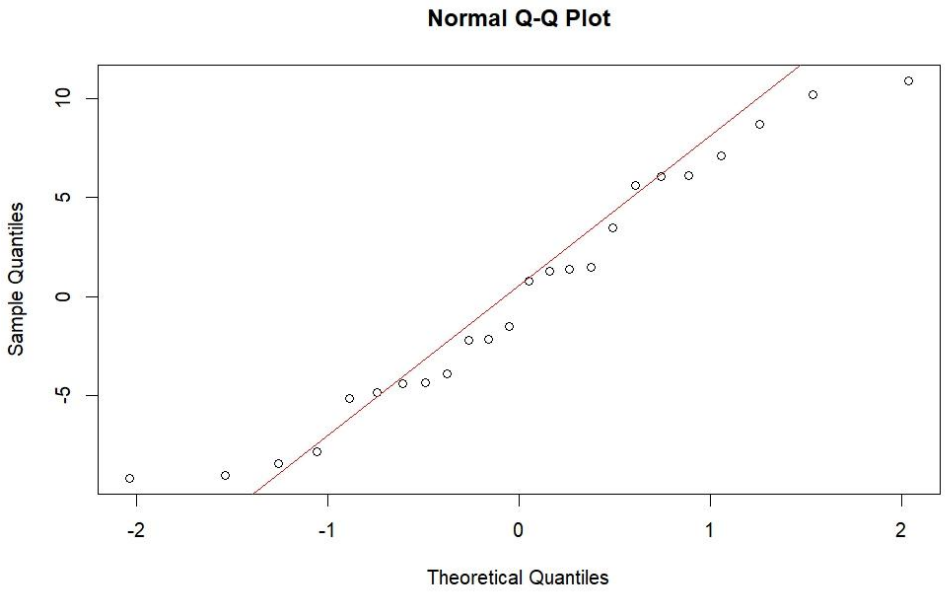

Figure 2. The Normal Q-Q Plot
Source*: authors' calculations in R Studio.*

If the random effects were perfectly normally distributed, all points would lie precisely along the 45-degree reference line (red line).

The middle section of the distribution aligns pretty well with the reference line, indicating that most random effects follow an approximately normal distribution. However, deviations from normality appear at the distribution's tails, with lower and upper extremes diverging from the line (Figure 2). Higher positive and negative values suggest potential heavy tails or outliers, indicating that some entities have more significant deviations than expected under normality.

4. Limitations

Despite the robustness of the analysis, this study has several limitations that should be acknowledged.

- This research relies on a panel dataset comprising 432 observations from 24 countries over 18 years (2003–2020). While this dataset provides valuable insights, it may not fully capture all country-specific factors that influence the shadow economy. Furthermore, some variables, mainly those measuring environmental policy stringency,

are derived from OECD sources, which may not comprehensively reflect the enforcement and effectiveness of environmental regulations in each country.

- While FE and RE models are employed and robustness checks, omitted variable bias is still possible. Factors such as labour market regulations, tax enforcement mechanisms, corruption levels, and informal sector characteristics are not explicitly included in our models but may significantly influence the shadow economy. Future research could incorporate additional control variables to mitigate this limitation.
- This econometric approach assumes that the relationship between environmental policy stringency and the shadow economy remains stable across countries and time periods. However, structural economic differences, institutional frameworks, and political stability can alter the impact of environmental regulations on informal economic activities. The Hausman test results indicate that the FE model is preferred, but this does not entirely eliminate concerns regarding unobserved heterogeneity.
- Although panel data techniques mitigate endogeneity concerns, the possibility of reverse causality remains. It is plausible that a larger shadow economy influences environmental policy stringency rather than vice versa. Future research could employ instrumental variable approaches or dynamic panel data models to address potential endogeneity better.
- This study is limited to 24 countries, most developed or emerging economies. The findings may not directly apply to developing countries with weaker institutional frameworks and different economic structures. Additionally, this study period ends in 2020, and recent policy changes or economic disruptions, such as those induced by the COVID-19 pandemic, are not reflected in the analysis.

While this study provides valuable insights into the relationship between environmental policy stringency and the shadow economy, the above limitations highlight areas for future research.

5. Discussion

The results of this study provide strong empirical evidence that environmental policy stringency (EPS) significantly impacts the size of the shadow economy. The findings reveal a negative correlation between overall EPS (x1) and the shadow economy (y), indicating that stricter environmental regulations generally reduce informal economic activities. This aligns with prior research, such as Kudełko (2023) and Surma and Leśniak (2023), who found that stringent environmental policies influence market behaviour and push firms towards formalisation.

The results also confirm the complexity of this relationship. The fixed effects (FE) model suggests that a one-unit increase in EPS is associated with a 2.18 percentage point decrease in the shadow economy. However, when controlling for time-fixed effects, the coefficient becomes weaker and statistically insignificant. This suggests that while environmental regulations contribute to reducing informality, broader economic and governance factors also play a crucial role, as emphasised by Mazurenko et al. (2023a, 2023b) and Lyeonov et al. (2023), who highlighted the interplay between taxation, governance quality, and informality.

A key contribution of this study is the distinction between market-based environmental policies (x2) and command-and-control regulations. The results indicate that market-based policies, such as CO_2 trading schemes and carbon taxes, negatively impact the shadow economy more than command-based approaches. The coefficient for x2 is -2.39, suggesting that countries implementing market-based solutions experience a more significant reduction in informal economic activity. This finding is consistent with Biswas et al. (2011) and Minh Sang (2024),

who argued that market-based mechanisms provide financial incentives for compliance, making it more attractive for firms to remain in the formal economy. Furthermore, Wang and Lu (2024) demonstrated that green finance initiatives can reinforce these effects by improving access to sustainable investments, thus reducing incentives for informal operations.

An important nuance in the results is the impact of specific environmental taxes on the shadow economy. While the overall EPS index reduces informality, high environmental taxes, particularly on sulphur oxides (SOx) (x7), positively correlate with the shadow economy. The coefficient for x7 is 0.75, indicating that excessive taxation can push firms into informality, a concern Yarovenko et al. (2024) raised regarding illicit financial practices and regulatory avoidance. This aligns with prior findings from Clean Air Fund (n.d.), which reported that industries in Nigeria, particularly metallic smelting and small-scale manufacturing, often evade compliance costs by shifting to the informal sector. Similarly, Chandan (2012) noted that stringent environmental standards in India's leather industry led to the proliferation of illegal tanneries that operate without regulatory oversight, worsening pollution levels.

The study also confirms that governance quality plays a significant role in determining the effectiveness of environmental regulations. The country-specific random effects in the RE model indicate that countries with strong governance structures (e.g., Austria, Luxembourg, Germany) experience a lower prevalence of informal economic activities despite stringent regulations. In contrast, weaker governance frameworks (e.g., Turkey, Estonia, Poland) are associated with higher levels of informality. This supports Dell Anno et al. (2024) findings, which emphasised that governance mechanisms such as corruption control and enforcement capacity influence the extent to which environmental regulations are adhered to. Similarly, Sarker et al. (2023) noted that political will and institutional reforms are critical in reducing regulatory evasion in environmental policymaking.

The heterogeneous effects of environmental policies across different countries suggest that economic structure and industrial composition matter. The study's findings are in line with Avlogiaris et al. (2023) and Mehedintu and Soava (2024), who found that countries undergoing industrial transitions – such as post-lignite regions in Europe – experience a shift of businesses into the informal sector as they struggle to adapt to new regulatory standards. Furthermore, Maza-Avila et al. (2023) and Tutar et al. (2024) demonstrated how economic transitions and migration patterns can drive informal entrepreneurship. The results of this study provide empirical support for this argument, showing that informal activities remain persistent in countries with weaker economic diversification and higher transition costs.

The findings of this study provide several policy insights. First, policymakers should focus on implementing market-based environmental policies rather than relying solely on command-and-control mechanisms. Market-based approaches encourage compliance and reduce the unintended shift towards informal activities.

Second, while environmental taxation is necessary, excessive taxes can have counterproductive effects, pushing firms into informality. Policymakers should consider tax rebates, subsidies, or phased tax implementation to minimise this risk. Third, strengthening governance structures ensures environmental policies achieve their goals. Enhancing regulatory enforcement, reducing corruption, and improving institutional quality can significantly mitigate the adverse effects of environmental regulations on the shadow economy.

Lastly, future research should explore financial inclusion's role in mitigating environmental policies' impact on informal activities. Studies such as those by Lyeonov et al. (2024) suggest that improved financial access can reduce the reliance on informal networks, potentially complementing environmental regulations in reducing informality.

Conclusion

This study aimed to analyse the relationship between environmental policy stringency and the size of the shadow economy across 24 countries over the period 2003-2020. Specifically, it sought to determine whether stricter environmental regulations reduce the prevalence of informal economic activities and assess whether market-based policies are more effective in curbing informality than command-and-control regulations. Additionally, the study explored the potential unintended consequences of environmental taxation on the shadow economy.

To achieve these objectives, the study utilised a panel dataset comprising 432 observations from 24 countries over 18 years. The econometric analysis employed Fixed Effects and Random Effects models to estimate the impact of different environmental policy stringency indices on the shadow economy. The Hausman test was used to determine the appropriate model specification. At the same time, robustness checks, including heteroskedasticity-robust standard errors and time-fixed effects, were conducted to ensure the reliability of the results.

The empirical analysis revealed several key findings:

- There is a significant negative correlation between overall environmental policy stringency and the shadow economy. The FE model estimates that a one-unit increase in EPS is associated with a 2.18 percentage point decrease in the size of the shadow economy.
- Market-based policies (e.g., CO_2 trading schemes, carbon taxes) have a more substantial adverse effect on informal economic activity than command-and-control regulations. The coefficient for market-based policies (x2) was -2.39, indicating their effectiveness in reducing informality.
- High environmental taxes, mainly sulphur oxides (SOx) taxation (x7), positively correlate with the shadow economy. Excessive environmental taxation may incentivise firms to evade compliance by shifting to informal operations.
- The impact of environmental policies on informality varies across countries, with governance quality playing a crucial role. Stronger institutional frameworks in countries such as Austria, Germany, and Luxembourg are associated with lower levels of informality. At the same time, weaker governance structures in Turkey and Estonia correspond to higher informal economic activities.

Based on these findings, the study proposes the following policy recommendations:

- Policymakers should prioritise market-based solutions, such as carbon trading schemes and financial incentives for compliance, over rigid command-and-control approaches. These policies provide economic benefits that encourage firms to remain within the formal sector.
- While environmental taxes are necessary, excessive taxation can have counterproductive effects by increasing informal activities. Governments should consider phased tax implementation, exemptions for small businesses or tax credits to ease compliance costs.
- Effective environmental policies require strong institutional frameworks. Enhancing regulatory oversight, corruption control, and streamlined compliance processes can improve enforcement and prevent businesses from operating informally.
- Access to green financing and low-interest loans for environmental compliance can help businesses transition smoothly into regulatory frameworks without resorting to informality.

- Since the effects of environmental policies on the shadow economy vary by country, policymakers should tailor strategies to national economic contexts, ensuring that regulatory measures do not disproportionately burden vulnerable sectors.

This study highlights the delicate balance between environmental policy enforcement and economic formalisation. Well-designed market-based policies and governance reforms can enhance environmental sustainability while minimising the unintended expansion of the shadow economy.

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