



# Asymmetric Environmental Effects of Energy-Related Uncertainty: The Role of Renewable Energy

Trung Hai Le\*

Banking Faculty, Banking Academy of Vietnam, Hanoi, VIET NAM. \*Email: [trunglh@hvn.edu.vn](mailto:trunglh@hvn.edu.vn)

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## ABSTRACT

This study investigates the impacts of energy-related uncertainty (EUI) and environmental quality, measured by the per-capita CO<sub>2</sub> emissions, for 27 countries from 2000 to 2023. Employing a CS-ARDL framework, our analysis reveals that EUI exacerbates environmental degradation in the short run but contributes to the reduction of CO<sub>2</sub> emissions in the long run. Furthermore, we find that renewable energy penetration acts as a moderating factor, particularly in long term. In economies with a robust renewable sector, energy-related uncertainty prompts firms and households to shift toward stable and clean domestic energy sources. Causality analysis confirms this interpretation, revealing a unidirectional causal flow from EUI to CO<sub>2</sub> emissions, while finding no link between EUI and other macroeconomic variables. Ultimately, our findings suggest that building a robust, renewable-based energy system is important for creating resilience against the negative environmental impacts of energy-related uncertainty.

**Keywords:** Environmental Pollution, Energy-Related Uncertainty Index, Renewable Energy, CO<sub>2</sub> Emissions

**JEL Classifications:** Q43, Q54, C23, O44

## 1. INTRODUCTION

The persistent rise of carbon dioxide (CO<sub>2</sub>) emissions has posed global concerns due to its significant contribution to the increasing threats of climate change and its adverse effects on global health (Patz et al., 2007). The energy sector stands at the forefront of the CO<sub>2</sub> emissions, as total CO<sub>2</sub> emissions relating to the energy sectors continue to at the unprecedented level in 2024, far from the target as in the Paris Agreement (IEA, 2024). Energy-related activities, fueled by rapid industrialization and increasing globalization, are key contributors to these emissions (Hye, 2023; Rehman et al., 2023). These challenges are even more striking for developing countries, which have been contributing significantly to the global carbon emissions (Shahzad et al., 2021). These countries often adopt energy-intensive economic models powered by non-renewable, carbon-heavy energy sources. Moreover, their transitions to green economies remain slow because of underdeveloped financial markets and limited institutional capacity of the financial sectors (Barrero et al., 2017; Brunnschweiler,

2010). Energy-related uncertainty, stemming from volatile energy prices, geopolitical risks and regulatory changes, further complicates the energy-environment nexus and its effects on CO<sub>2</sub> emissions (Atsu and Adams, 2021; Kilian, 2008; Liu et al., 2021). Thus, understanding these uncertainties is essential for developing robust strategies to mitigate emissions and for formulating efficient energy policies to changing global dynamics.

This study examines the impacts of uncertainties relating to the energy market on the CO<sub>2</sub> emissions. Our contributions are threefold. First, fluctuations in energy prices create expectation shifts for both consumers and producers, causing changes in both aggregate supply and demand (Kilian, 2008). Volatile energy prices generate uncertainty about future fuel costs, prompting firms and consumers to delay investments and consumptions due to potential income declines and increased risk of unemployment (Bernanke, 1983; van de Ven and Fouquet, 2017). Ongoing political conflicts and trade disputes can also hinder energy transitions (Chang et al., 2023; Yasmeen and Shah, 2024) and exacerbate energy price

volatility (Liu et al., 2021). Furthermore, government interventions aimed at mitigating climate change can create an unpredictable policy environment, contributing to further instability in energy prices (Sarker et al., 2023), reducing firm-level productivity (Ren et al., 2022), and dampening corporate innovation and investments (Zhu et al., 2023). Such uncertainties can disrupt energy consumption patterns, households and firm behaviours, thus leading to changes in the CO<sub>2</sub> emissions levels overtime (Adams et al., 2020; Atsu and Adams, 2021).

We contribute to the literature in three areas. First, we employ the novel energy-related uncertainty index (EUI), recently proposed by Dang et al. (2023), on the CO<sub>2</sub> emissions in a wide range of countries. Rather than using energy price shocks, Dang et al. (2023) exploit the textual information from Economist Intelligence Unit reports to capture the uncertainty directly associated with the energy market in each country. Thus, the EUI is able to identify information across diverse energy domains and better reflect information about uncertainties in energy markets such as war risks, oil crises or energy price shocks (Li et al., 2024; Zhang and Guo, 2024). Dang et al. (2023) show that an increase in the EUI can negatively affect economic activity at both the national and industry levels. Recent studies showcase the usefulness of the EUI in forecasting volatility in the international stock market (Salisu et al., 2024) or oil price (Zhang and Guo, 2024) and jumps in cryptocurrency markets (Wang et al., 2024). The EUI also explains the G20 stock market shock transmission (Li et al., 2024), as well as amplifying inflation (Usman et al., 2024) and affecting firms' investment decisions and efficiency (Anh et al., 2024).

Second, uncertainties in the energy markets affect economic activities, investment decisions and consequently energy consumption in the short and long-run. Yin (2016) demonstrates that while macroeconomic uncertainty affects energy prices in the short-term, the long-term changes in the energy markets are mainly influenced by political ambiguity. In return, Yuan et al. (2010) show that the impacts of energy prices on the energy consumption changes over time. Barrero et al. (2017) argue that shocks in the energy prices are mainly linked to short-term changes in the economic output. Conversely, economic activities and investments are more associated with policy uncertainty in the long-term. Empirical evidence, however, remains inconclusive. While Adedoyin and Zakari (2020) show that uncertainty in the energy policy has significant impacts on the CO<sub>2</sub> emissions of UK in the short-run only, Adams et al. (2020) demonstrate a long-run cointegration between policy uncertainty and CO<sub>2</sub> emissions for 10 resources-rich countries. Interestingly, Syed and Bouri (2022) find that economic policy uncertainty exacerbates U.S. air pollution in the short run but significantly decreases CO<sub>2</sub> emissions in the long run. Building on this literature, we explore how energy-related uncertainty affects CO<sub>2</sub> emissions over time. As the EUI effectively covers uncertainties specific to the energy market and covers both energy price shocks and policy-related uncertainty, our investigation provide better understandings on the impact of energy-related uncertainty on CO<sub>2</sub> emissions in different time frames. We also explore the causality between the EUI and CO<sub>2</sub> emissions as understanding these temporal effects is crucial for policymakers in designing effective energy and environmental policies.

Third, the effects of the EUI on CO<sub>2</sub> emissions may varies between countries, depending on structural factors such as their energy mixes. Previous researches have exhibit the role of renewable energy sources in reducing the level of CO<sub>2</sub> emissions (Hagspiel et al., 2021; Inglesi-Lotz and Dogan, 2018; Usman et al., 2022), enhance energy security and environment sustainability (Shang et al., 2022), offer against uncertainties stemming from fossil fuel shocks (Yasmeen and Shah, 2024) and accelerate the low-carbon transition (Rechsteiner, 2021). Zhou et al. (2023) argue that firms and household would switch to more environment-friendly energy sources as uncertainty in the energy markets and climate policy heightened. However, several papers have demonstrated that uncertainty relating to the energy market may hinder the impacts in the renewable energy on the CO<sub>2</sub> emissions. Climate policy uncertainty relating to energy market could lower the renewable consumptions (Li et al., 2023; Shafiullah et al., 2021). This adverse effects persist in both short- and long-term horizons (Khan and Su, 2022). Ivanovski and Marinucci (2021) argue that volatile energy prices could adjust the consumers demand to environment-unfriendly energy portfolio and adversely affect the renewable energy usage. We further contribute to the literature investigate the role of energy mix in their moderations in the impacts of EUI on CO<sub>2</sub> emissions levels.

Our analysis is based on data from 27 developed and developing economies, for which Dang et al. (2023) have estimates of the EUI. Employing a cross-sectional dynamic autoregressive distributed lag (CS-ARDL) model, we find asymmetric impacts of EUI on the environmental quality. In particular, the EUI contribute to higher CO<sub>2</sub> emissions in the short-term horizon, while decreasing them in the long run. The negative impact of EUI on environmental quality may indicates that uncertainties relating to fluctuations in the energy prices or supply disruptions due to geopolitical risks, prompt firms and households to shift to cheaper, carbon-intensive fossil fuels in the short term (Ivanovski and Marinucci, 2021; Yuan et al., 2010). Moreover, climate policy uncertainty may also force firms to continue operating on less efficient and more polluting equipment and delay innovations in clean energy technologies (Wang et al., 2020; Cui et al., 2023).

The long-run sign reversal of EUI's effect on emissions can arise through two competing hypotheses. In the composition effect hypothesis, the positive impact of EUI could be the result of firms' strategic hedging against uncertainty by investing in energy efficiency, optimising operations, and diversifying energy sources (Tissaoui and Zaghdoudi, 2025). Prolonged uncertainty could also increase the public environmental concerns, thus motivating governments and firms to increase their environmental governance and spur innovations in long-term energy-efficient technologies (Gao et al., 2024). In contrast, this negative effect may stem from an economic stagnation in the scale mechanism. Heightened uncertainty in the energy market and policy might reduce overall business activities and eventually the energy consumption (Jiang et al., 2019; Ahmed et al., 2021), weakening consumer confidence and business performance, and lowering energy demand and CO<sub>2</sub> emissions (Cary, 2020; Ahmed et al., 2021).

We further highlight the moderating role of the energy mix on the relationship between the EUI and CO<sub>2</sub> emissions. We find that a

higher renewable energy consumption amplifies the mitigating effect of EUI on CO<sub>2</sub> emissions. This evidence supports the composition effect channel, in which uncertainty catalyzes a strategic shift toward stable, domestic clean energy, reducing emissions (Zhou et al., 2023). Particularly, countries already consuming significant amounts of renewable energy would have better renewable energy infrastructure and more effective environmental policies, resulting in smoother energy transitions and a lower marginal cost of expanding renewable capacity (Rechsteiner, 2021). The causality analysis using the Dumitrescu and Hurlin (2012) test further supports the composition mechanism rather than economic contraction as it confirms a unidirectional flow from EUI to CO<sub>2</sub>, while there is no causality between EUI and other macroeconomic variables.

The remainder of the paper is organized as follows. We outline the methodology, data and preliminary analysis in section 2. Section 3 discusses empirical results on the impacts of EUI on CO<sub>2</sub> emissions as well as the moderating role of energy mix and financial developments. Finally, section 4 concludes the paper with some remarks.

## 2. DATA AND EMPIRICAL METHODOLOGY

### 2.1. Data

This study examines the impacts of energy uncertainty on the environmental qualities of 27 countries from 2000 to 2023. We employ the total CO<sub>2</sub> emissions per capita as a proxy for the country's environmental degradation, sourced from the World Bank. Our core explanatory variable is the EUI from Dang et al. (2023) using a keyword-based text analysis of the frequency and context relating to the energy markets and policies from the monthly country reports of Economist Intelligence Unit (EIU). Following the text-mining methodology of Ahir et al. (2022) and Afkhami et al. (2017), this index quantifies the energy market uncertainties, including changes in the energy and environmental policies as well as volatility in the energy prices, in each country.<sup>1</sup> We further include three macroeconomic factors from the World Development Indicators (WDI) as control variables in the analysis, including real output (GDP), measured by the real GDP per capita in constant international dollars at 2021 prices, financial development (FD), measured by the percentage of GDP using total domestic credit to the private sector, and trade openness (TO), measured by the share of the total value from exports and imports to GDP.

The growth-emissions nexus has been widely documented in the literature. Researchers often find faster economic growth

<sup>1</sup> The EUI data is taken directly from the following website [https://www.policyuncertainty.com/energy\\_uncertainty.html](https://www.policyuncertainty.com/energy_uncertainty.html)

drives up the CO<sub>2</sub> emissions, largely due to higher energy usages accompanying with expanded industrial activities and increasing population and urbanization (Halsnæs, 1996; Chang et al., 2015; Salahuddin et al., 2016; Tissaoui and Zaghoudi, 2025). In contrast, the environmental impacts of financial development remain ambiguous. An efficient and developed financial system could accelerate capital for sustainable economic processes (Ahmed et al., 2022; Rehman et al., 2022), improve the advancement of renewable energy technologies (Kim and Park, 2016), increase renewable energy consumption (Yi et al., 2023), and therefore support the green transition to reduce the CO<sub>2</sub> emissions (Naqvi et al., 2023). Conversely, financial development can associate with higher CO<sub>2</sub> emissions via the channels of industrialization and economic growth (Ito, 2017; Gök, 2020; Omri et al., 2021) or indirectly by attracting foreign direct investment (FDI) (Kayani et al., 2020). Globalization, as proxied by the trade openness, is also an important determinant of environmental quality. An increase in the trade openness can affect the national environment via the scale, technology and comparative advantage channels (Shahzad et al., 2017). As a country increases its engagement in global trade activities, it could lead to higher pollution as a result of escalated energy consumption from shipping, aviation and industrial production (Peters et al., 2009; Dogan and Seker, 2016). Trade openness, on the other hand, can help reduce energy dependence, promoting energy security and cleaner energy sources (Bashir et al., 2020; Wang et al., 2024).

Table 1 provide the descriptive statistics of the variables. Except for the EUI, we take the natural logarithm of the CO<sub>2</sub>, GDP, FD and TO to address the difference in measurement unites and facilitate the comparative analysis between variables. The mean value of the CO<sub>2</sub> is 1.797, ranging from -0.724 to 3.051, suggesting significant heterogeneity in the air quality of the countries in the sample. The EUI averages at 1.186 with a high standard deviation (0.703), indicating large disparity in the energy-related uncertainty. The macroeconomic variables, GDP, FD and TO, also exhibit significant variation, with means of 10.358, 4.375 and 4.151, respectively. Skewness and kurtosis statistics suggest non-normality for all variables, particularly for the EUI its positive skewness and high kurtosis, suggesting a leptokurtic distribution with heavier tails. As shown in Table 2, the correlations between explanatory variables are always less than 0.8, suggesting that multicollinearity is unlikely to be a serious concern. GDP is positively associated with both FD and TO, whereas EUI exhibits negative correlations with all macroeconomic variables.

### 2.2. Empirical Methodology

#### 2.2.1. Cross-sectional dependency test

First, we detect possible interdependence among entities within the panel, in which the cross-sectional units are affected by common

**Table 1: Descriptive statistics**

Variables	Obs	Mean	Standard deviation	Min.	Max.	Skew.	Kurt.
CO <sub>2</sub>	756	1.797	0.829	-0.724	3.061	-1.003	3.326
EUI	756	1.186	0.703	0.225	5.164	2.237	9.861
GDP	756	10.358	0.844	7.894	11.794	-1.23	3.688
FD	756	4.375	0.665	2.38	5.395	-0.921	3.109
TO	756	4.151	0.633	2.75	6.081	0.684	3.499

This table provides descriptive statistics of the variables employed in the analysis

unobserved factors. We employ the cross-sectional dependence test of Pesaran (2015) that is built on the augmented Dickey-Fuller (ADF) regression estimated separately for each unit. The CD statistic is defined as:

$$CD = \frac{\sqrt{2T}}{N(N-1)} \left( \sum_{i=1}^{N-1} \sum_{j=i+1}^N \hat{\rho}_{ij} \right) \rightarrow N(0,1) \quad (1)$$

Where  $\hat{\rho}_{ij}$  be the sample pairwise correlation coefficients of the OLS residuals, T and N is the sample and panel sizes.

### 2.2.2. Panel unit root test

Second, we employ the second-generation unit-root test, the cross-sectionally augmented IPS (CIPS) test of Pesaran (2007) to address the non-stationarity issue of the panel data to ensure the robustness of the test in the presence of cross-sectional dependence. This test is conducted based on the cross-sectionally augmented ADF (CADF) regression with the averages of the lagged and first differences of cross-sections:

$$\Delta y_{it} = \alpha_i + \rho_i y_{it-1} + \beta_i \bar{y}_{t-1} + \sum_{j=0}^k Y_{ij} \Delta \bar{y}_{t-1} + \sum_{j=0}^k \delta_{ij} y_{it-1} + \varepsilon_{it} \quad (2)$$

the panel statistic is the simple average of the individual Augmented Dickey-Fuller (CADF) values:

$$CIPS = N^{-1} \sum_{i=1}^N CDF_i \quad (3)$$

### 2.2.3. Panel cointegration test

Third, we examine the long-run cointegration using the Westerlund and Edgerton (2007) error-correction-based panel test, which is robust to both heterogeneity and cross-sectional dependence (Jalil, 2014). The data generating process is assumed to be as follows:

$$\Delta Y_{it} = \delta_i' d_t + \alpha_i (Y_{it-1} - \beta_i' x_{it-1}) + \sum_{j=1}^{pi} \alpha_{ij} \Delta Y_{it-j} + \sum_{j=0}^{pi} \gamma_{ij} \Delta x_{it-j} + e_{it} \quad (4)$$

where  $i = 1, \dots, N$  and  $t = 1, \dots, T$ ;  $d_t = (1, t)'$  holds the time components and provide estimates of the adjusting speed. Westerlund and Edgerton (2007) constructs four statistics, two group-mean ( $G_r; G_a$ ) and two panel ( $P_r; P_a$ ) based on the least squares estimates of  $\hat{\alpha}_i$  and their standard errors to test on the cointegration in specific panel and throughout the whole panel, respectively. Rejection of the null for the group-mean ( $G_r; G_a$ ) implies that at least one cross-sectional unit exhibits cointegration.

**Table 2: Pairwise correlations**

Variables	CO <sub>2</sub>	EUI	GDP	FD	TO
CO <sub>2</sub>	1.000				
EUI	-0.142*	1.000			
GDP	0.830*	-0.227*	1.000		
FD	0.605*	-0.417*	0.581*	1.000	
TO	0.229*	-0.190*	0.425*	0.161*	1.000

This table provides the pairwise correlations between variables. \*\*\*, \*\* and \*Signifies significance level at 0.01, 0.05 and 0.1, respectively

### 2.2.4. CS-ARDL regression

Finally, the impacts of energy-related uncertainty on the CO<sub>2</sub> emissions is estimated as follows:

$$CO2_{it} = \alpha_i + \beta' X_{i,t} + \varepsilon_{it} \quad (5)$$

Where  $X_{i,t}$  is the vector of explanatory variables, including the annual average EUI from (Dang et al., 2023), the logarithm of the real GDP per capita (GD), and the logarithm of the domestic credit to the private sector (FD) and the sum of exports and imports of goods and services as percentages of GDP (TO).  $\beta'$  is the vector of estimated coefficients,  $\alpha_i$  is the country-specific fixed-effect and  $\varepsilon_{it}$  is the error term.

To analyze the relationship between the variables in both short and long-run, we employ the CS-ARDL regression method of Chudik and Pesaran (2015) that accounts for mixed stationary in the variables, cross-sectional dependence, slope heterogeneity and potential endogeneity issues in the panel data (Khan et al., 2020; Su et al., 2021; Tissaoui and Zaghdoudi, 2025). The method takes the cross-section average of the all variables to overcome the cross-sectional dependence issue using the dynamic CS-ARDL form as follows:

$$\bar{X}_t \quad (6)$$

Where  $\bar{CO2}_t$  and  $\bar{X}_t$  are the cross-sectional average of  $CO2_{i,t}$  and  $X_{i,t}$ ,  $\omega_t$  is the long-run coefficients, while  $\lambda_t$  is the rate of long-run adjustment.

## 3. EMPIRICAL RESULTS AND DISCUSSIONS

### 3.1. Preliminary Results

Table 3 presents the cross-sectional dependency test of Pesaran (2015). The null hypothesis of no cross-sectional dependence is rejected at 1% significance level in all variables, confirming the existence of cross-sectional dependence in the model. Consequently, we implement the CIPS unit-root test of Pesaran (2007) to evaluate the stationary of the variables. We find that all variables are stationary after first differencing, except only EUI being stationary at the level, whereas CO<sub>2</sub>, GDP, FD and TO become stationary after first differencing. Overall, the series exhibit a mixed order of the integration, comprising both I(0) and I(1). Collectively, the findings justify the use Westerlund (2007)

**Table 3: Cross-sectional dependence and Second-Generation Unit-root Test**

Variable	Cross-sectional dependence test	CIPS unit-root test		
		Level	First difference	Inference
CO <sub>2</sub>	11.890***	-0.609	-4.646***	I (1)
EUI	39.570***	-2.307**	-5.429***	I (0)
GDP	80.640***	-2.066	-3.408***	I (1)
FD	25.090***	-1.432	-3.753***	I (1)
TO	33.630***	-1.736	-4.083***	I (1)

CD refers to the Pesaran (2015) cross-sectional dependence statistic and CIPS refers to the (Pesaran, 2007) panel unit-root statistic. \*\*\*, \*\* and \* denote significance level at 0.01, 0.05 and 0.1, respectively. "Inference" indicates the integration order implied by CIPS

for panel cointegration test and the CS-ADRL regression method of (Chudik and Pesaran, 2015) in the main analysis.

Table 4 reports Westerlund and Edgerton (2007) test results for the long-run cointegration among the variables. The results of the group-mean  $G_t$  and the panel  $P_t$  signal the existence of cointegration in some panels, thus confirming the long-run association among the variables.

### 3.2. Empirical Results

Table 5 provides the estimation results from CS-ARDL regression method. The most prominent factor driving the environmental degradation is the economic growth as GDP consistently drives up the CO<sub>2</sub> emissions in both short-term and long-term associations. This finding aligns with the scale channel agreed upon in the literature, where increasing energy usages and expanding industrial production significantly reduce the environmental quality (Choudhury et al., 2023; Tissaoui and Zaghdoudi, 2025; Yilanci et al., 2025). We find that FD significantly contribute to the CO<sub>2</sub> emissions in the long-run but remains silent in short-run. Thus, financial systems in the countries in the sample are channeling capital towards carbon-intensive sectors rather than green investments (Ito, 2017; Omri et al., 2021). Another explanation is that financial development might stimulate citizens' purchasing power, enabling them to purchase goods like cars, houses, or air-conditioner that eventually pose threats to the ecosystem (Batool et al., 2022; Khan et al., 2024).

**Table 4: Panel co-integration test**

ECM panel cointegration test				
$H_0 = \text{No cointegration}$				
Statistics	$CO_2 = f(EUI, GDP, FD, TO)$			
	Group statistics		Panel statistics	
	$G_t$	$G_a$	$P_t$	$P_a$
Value	-3.114	-9.529	-14.954	-9.381
Z-value	-1.434	4.709	-1.302	2.721
Robust <i>P</i> value	0.030	0.460	0.070	0.270

$G_t$  and  $G_a$  are group-mean test;  $P_t$  and  $P_a$  are panel tests. Z-values are standardized test statistics. Robust *P* value reports the bootstrapped *P* values robust to cross-sectional dependence. \*\*\*, \*\* and \* denote significance level at 1%, 5% and 10%, respectively

**Table 5: The CS-ARDL Results**

Estimation results (CS-ARDL): $CO_2 = f(EUI, GDP, FD, TO)$		
Dependence variable: Per capita CO <sub>2</sub> emissions		
Variable	Coefficient	Standard errors
Panel A: Short-run coefficients		
Δ EUI	0.010*	0.006
Δ GDP	0.605***	0.153
Δ FD	0.051	0.099
Δ TO	0.040	0.037
Panel B: Long-run coefficients		
Error Correction Coef.	-1.644***	0.084
EUI	-0.017**	0.007
GDP	0.599***	0.127
FD	0.070**	0.035
TO	0.049	0.040

This table provide the estimation results using CS-ARDL method. Panel A presents the short-run coefficients, while the long-run coefficients are provided in Panel B. \*\*\*, \*\* and \* denote significance level at 0.01, 0.05 and 0.1, respectively

Interestingly, we find that the impacts of EUI on environmental quality shift over time. While an increase in EUI significantly raises the CO<sub>2</sub> emissions in the short-run, the relationship becomes negative and statistically significant in the long-run. Heightened uncertainty in the energy prices and regulatory frameworks creates a high-risk environment that might cause firms to flight to readily available, on-demand fossil fuels by the to manage unpredictability (Ivanovski and Marinucci, 2021; Yuan et al., 2010). Firms might also pause their energy-efficiency projects amidst policy unpredictability and continue to operate on less efficient and more polluting equipment, thereby increasing carbon intensity (Cary, 2020; Wang et al., 2020; Cui et al., 2023).

The switch in the sign of the EUI in the long-run can be explained by two potential pathways. One pathway is the composition channel where firms may strategically invest in energy efficiency, optimizing logistical operations, and diversifying energy sources to hedge against an unpredictable future (Tissaoui and Zaghdoudi, 2025). An alternative pathway is the scale mechanism, where firms would likely to wait-and-see" in their industrial investments, being more passive and less willing in making new investment, that would consequently defer industrial expansions and reduce the sources of future emissions growth (Jiang et al., 2019). Furthermore, heightened uncertainty in the energy market might dampen to the consumer confidence and business performance, which can reduce energy demand and, consequently, the CO<sub>2</sub> emissions (Cary, 2020; Ahmed et al., 2021).

To disentangle whether the negative relationship between EUI and CO<sub>2</sub> emissions in the long-run is driven by a proactive shift towards energy efficiency or an unintended consequence of economic stagnation, we extend our baseline model to include an interaction term between energy-related uncertainty and the share of renewable energy in Table 6. We find that the short-run coefficient of EUI remains positive and statistically significant. This adverse effect, however, is dampened in countries with a high share of renewable energy usage, as the coefficient of the interactive variable is negative and statistically significant. This finding suggests that

**Table 6: The role of renewable energy**

Estimation results (CS-ARDL): $CO_2 = f(EUI, EUI_{RENEW}, GDP, FD, TO)$		
Dependence variable: Per capita CO <sub>2</sub> emissions		
Variable	Coefficient	Standard errors
Panel A: Short-run coefficients		
Δ EUI	0.165**	0.073
Δ EUI_RENEW	-0.039**	0.018
Δ GDP	0.447***	0.132
Δ FD	-0.019	0.057
Δ TO	0.021	0.031
Panel B: Long-run coefficients		
Error Correction Coef.	-1.571***	0.072
EUI	0.069	0.061
EUI_RENEW	-0.027*	0.016
GDP	0.417***	0.079
FD	0.067***	0.020
TO	0.025	0.053

This table provide the estimation results using CS-ARDL method. Panel A presents the short-run coefficients, while the long-run coefficients are shown in Panel B. \*\*\*, \*\* and \* denote significance level at 1%, 5% and 10%, respectively

firms might prioritize operational continuity over environmental performance and revert to reliable but carbon-intensive fossil fuels when facing with a sudden shock in the energy uncertainty. However, a robust renewable energy sector can act as a structural buffer, making an economy less vulnerable to energy shocks by ensuring that cleaner alternatives are readily available.

The results for the long-run coefficients are particularly revealing. The direct coefficient of EUI now becomes positive but statistically insignificant. In contrast, we find that the interaction term has a negative and statistically significant coefficient. This observation means that impact of uncertainty on emissions is not uniform but is instead conditional on the level of renewable energy penetration. The argument that uncertainty reduces emissions simply by causing an economic drag is not fully supported, as that effect would likely persist regardless of the energy mix. Instead this finding indeed supports the pathway with which energy uncertainty triggers firms to adopt strategic changes in energy efficiency, accelerating process efficiency and fuel-mix substitution (Tissaoui and Zaghoudi, 2025). In an economy with a high share of renewables, firms and energy systems with access to a large, stable, and domestic renewable energy supply can strategically pivot towards it when facing with volatile fossil fuel markets. This result is align recent results of Zhou et al. (2023) and Khan et al. (2024). The former argue that climate policy uncertainty would lead to higher renewable energy consumption in the short term and long term, while the latter highlight that climate policy uncertainties, combined with increased renewable energy adoption, leads to lower CO<sub>2</sub> emissions.

### 3.3. Robustness Tests

#### 3.3.1. Panel causality results

We employ the panel Granger Causality test of Dumitrescu and Hurlin (2012) to examine the causality between variables, which is suitable for the panel data with the existence of cross-sectional dependence and panel heterogeneity. The test results is provided in Table 7.

The causality analysis yields several important insights that reinforce our main findings. We observe a unidirectional causality from EUI to CO<sub>2</sub> emissions. This aligns with our main analysis

**Table 7: The causality results**

Null hypothesis	Statistics		Inference
	Z <sub>N,T</sub>	Z̃ <sub>N,T</sub>	
CO <sub>2</sub> ≠EUI	5.1179	4.0893	
EUI≠CO <sub>2</sub>	4.0261**	3.1560**	
CO <sub>2</sub> ≠GDP	8.0779	6.6195	EUI⇒CO <sub>2</sub>
GDP≠CO <sub>2</sub>	17.8499***	14.9725***	
CO <sub>2</sub> ≠FD	26.1667***	22.0817***	CO <sub>2</sub> ⇔FD
FD≠CO <sub>2</sub>	8.3509**	6.8528**	
CO <sub>2</sub> ≠TO	13.6562**	11.3877**	TO⇔CO <sub>2</sub>
TO≠CO <sub>2</sub>	11.0561***	9.1652***	
EUI≠GDP	0.9881	0.5591	-
GDP≠EUI	3.5579	2.7558	
EUI≠FD	1.8939	1.3334	-
FD≠EUI	1.3670	0.8830	
EUI≠TO	0.0489	-0.2437	-
TO≠EUI	1.7034	1.1705	

Symbols (⇒) and (⇔) indicate unidirectional and bidirectional Granger Causality. \*\*\*, \*\* and \* denote significance level at 1%, 5% and 10%, respectively

results that EUI shocks move emissions in the short-run and act as an external shock to anchor the long-run adjustment. By contrast, there is no evidence that EUI Granger-causes GDP, FD, or TO, and vice versa, suggesting that the uncertainty–emissions nexus is driven by strategic firm-level changes in efficiency and composition rather than via a broad contraction in output, finance, or trade openness. Finally, we also find that economic growth (GDP) strongly cause the CO<sub>2</sub> emissions but not vice versa, reinforcing its role as a main driver of environmental quality. The bidirectional causality from/to CO<sub>2</sub> to/from FD and TO indicates feedbacks between emissions, financial development and globalization, as noted by Salahuddin et al. (2016).

#### 3.3.2. Alternative regression method

To ensure the robustness of our main findings, we re-estimate our model using an alternative econometric technique: The pooled mean group (PMG) estimator developed by Pesaran et al. (1999). PMG is well suited to our setting as it accommodates panels with mixed orders of integration as in our panel, as well as allowing for heterogeneous short-run dynamics across countries while imposing long-run coefficient homogeneity. Thus, it enables a direct comparison of with our CS-ARDL estimates.

Table 8 provides estimation results from the PMG method for the baseline regressions and its expanded version with interactive

**Table 8: Results from Pooled Mean Group (PMG) Method**

Panel A: Estimation results (PMG): CO <sub>2</sub> =f(EUI, GDP, FD, TO)		
Dependence variable: per capita CO <sub>2</sub> emissions		
Variable	Coefficient	Standard errors
Short-run coefficients		
Δ EUI	0.010**	0.004
Δ GDP	1.096***	0.114
Δ FD	0.117**	0.051
Δ TO	-0.013	0.036
Long-run coefficients		
Error correction coef.	-0.021***	0.003
EUI	-0.860***	0.189
GDP	0.401***	0.137
FD	0.343	0.211
TO	-1.090***	0.251
Panel B: Estimation results (PMG): CO <sub>2</sub> =f(EUI, EUI RENEW, GDP, FD, TO)		
Dependence variable: Per capita CO <sub>2</sub> emissions		
Variable	Coefficient	Standard errors
Short-run coefficients		
Δ EUI	0.316***	0.081
Δ EUI_RENEW	-0.088***	0.018
Δ GDP	0.862***	0.097
Δ FD	0.071*	0.043
Δ TO	0.037	0.198
Long-run coefficients		
Error Correction Coef.	-0.030***	0.006
EUI	0.246	0.165
EUI_RENEW	-0.218***	0.049
GDP	0.666***	0.087
FD	-0.318**	0.120
TO	-0.960***	0.137

This table provide the estimation results using Pooled Mean Group (PMG) method. Panel A presents the main regression results, while Panel B provide results with interactive term. \*\*\*, \*\* and \* denote significance level at 1%, 5% and 10%, respectively

variable. The results from the PMG model are found to be qualitatively consistent with our main CS-ARDL findings.

## 4. CONCLUSION AND POLICY IMPLICATION

This paper examines the impacts of energy-related uncertainty on environmental quality via the CO<sub>2</sub> emissions per capital. Using the CS-ARDL framework, our analysis provides several key insights. We show that EUI increases CO<sub>2</sub> emissions in the short-run, suggesting an immediate switch on carbon-intensive fossil fuels as firms and energy systems prioritize supply security during periods of uncertainty. This effect is significantly weaker where renewable penetration is higher, highlighting the buffering role of clean energy during volatile periods in the energy markets and uncertainty in the climate policy. In the long-run, however, EUI appears to reduce the environmental degradation, which could be attributed to proactive switch to cleaner energy or an unintended consequence of economic stagnation. By introducing the share of renewable energy as a moderating variable, we find evidence supporting the former pathway as the long-run environmental benefit of uncertainty is conditional on the maturity of a country's renewable energy sector. In an economy with sufficient sufficiently large renewable share, uncertainty catalyzes a strategic shift toward stable, domestic clean energy, reducing emissions. In contrast, without a significant renewable capacity, uncertainty does not lead to a meaningful reduction in emissions. The causality analysis further validates our interpretation, confirming a unidirectional causal flow from uncertainty to emissions, while there is no causality existing between EUI and other macroeconomic variables. This finding supports the mechanism in which EUI reduces the CO<sub>2</sub> emissions through efficiency and compositional changes rather than a broad economic contraction.

These findings yield several important policy recommendations. First, governments should focus on scaling up the renewable energy sources. Our results show that this strategy is not only promotes energy efficiency and accelerates the transition to a clean energy supply but also serves as a resilience strategy, enabling economies to hedge against the environmental and economic risks of energy market uncertainty. Second, in countries with low-renewable usage, uncertainty could lead to fossil fuel dependence and a buildup of emissions. Thus, policymakers should enforce renewable portfolio standards and provide targeted incentives for clean technology adoption, particularly during periods of market stress. Finally, given that both economic growth and financial development can drive emissions in the long-run, structural policies aimed at greening finance and decoupling growth from pollution remain essential.

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