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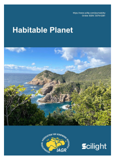

Article

Nexus between Energy Generation Sources and Environmental Deterioration Under Trade Policy Uncertainty in USA and China

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ABSTRACT

Considering pressures of trade war and geopolitical risk (GPR) on environmental deterioration by affecting countries' energy mix choices and environmental policies, this study investigates the nexus between energy generation sources and the environment while considering trade policy uncertainty (TPU) and GPR. In this vein, the research uses carbon dioxide (CO_2) emissions as an environmental indicator, considers main electricity generation (EG) types as explanatory variables, analyzes the USA and China, and performs the KRLS approach on daily data between 1st January 2019 and 31st July 2025. The study suggests that (i) fossil EG increases CO_2 emissions across all percentiles in the USA and China; (ii) renewable EG and GPR decreases CO_2 emissions across lower percentiles in the USA, renewable EG and GPR reduces CO_2 emissions across lower & middle percentiles in China; (iii) TPU reduces CO_2 emissions across lower percentiles in the USA and China, whereas there is an increasing impact across higher percentiles; (iv) the interaction between TPU and GPR has an increasing (insignificant) impact in the USA (China). Overall, the study concludes that fossil EG is harmful, renewable EG is partially beneficial, low-level TPU and GPR are advantageous, and the interaction between TPU and GPR is not effective on CO_2 emissions. So, considering that low levels of TPU and GPR make it easier to make good eco-friendly decisions on energy mix choices and high levels increase the tendency to make easy and short-term focused decisions, the countries need comprehensive environmental policies so that they can consider the aforementioned underlying mechanism.

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Research Highlights

- Trade policy and geopolitical risk are expected to have an impact on the environment.
- Both the USA and China are analyzed between 1st January 2019 and 31st July 2025.
- Trade policy uncertainty reduces CO_2 emissions across lower percentiles.
- Trade policy uncertainty increases CO_2 emissions across higher percentiles.
- Interaction between TPU and GPR has an increasing (insignificant) impact in the USA (China).

1. Introduction

The deterioration of climate change and the continuation of environmental degradation across the globe have increased the significance of energy transition issues and addressing environmental issues on a global scale. Despite the willingness of many countries for carbon mitigation, many challenges lie ahead for sustainability, hindered by geopolitical conflicts, trade frictions, and geopolitical instability [1, 2]. Recent adverse events, such as the intensifying trade disputes between the United States and China and other events such as the war between Russia and Ukraine, have created heightened uncertainty for policymakers, investors, and businesses [3, 4]. These developments not only shape international economic relations but also exert profound influence on countries' energy mix, energy transition, and their willingness and ability to sustain their commitments to carbon emission mitigation [5].

CO_2 emissions remain as the main driver of climate change, and EG stands as one of its largest sources [6, 7]. The nexus between energy generation and CO_2 emissions lies at the heart of environmental sustainability. Despite the promises of the nations to mitigate emissions and their willingness to increase the share of renewable energy in the energy mix, fossil EG has a dominant role, even with its well-documented contribution to rising emissions [8]. The increased fossil fuel use in EG has caused spikes in CO_2 emissions, which have been the major cause of the current climate crisis [9]. Fossil EG remains a major threat to sustainability; thus, renewable EG has an indispensable role in meeting net-zero carbon emissions targets and mitigating environmental deterioration [10]. Despite the significance of renewable EG, the transition from fossil to renewable energy sources is far from linear. The pace of this shift depends on various factors such as technological developments and investment flows, and also on the broader political and economic context in which energy policies are formulated [11, 12].

TPU and GPR are two elements of uncertainty and are critical factors in shaping the energy-environment nexus. TPU indicates the unpredictability in international trade rules, tariffs, and negotiations, which can hamper investments in energy infrastructure, delay cross-border cooperation, and limit the discussion of green technologies. Heightened TPU is associated with deteriorating impacts on long-term capital allocation, negatively affecting renewable energy projects that have enormous initial investment requirements [13]. Alternatively, moderate levels of TPU might suppress economic activity and energy demand and thus lower CO_2 emissions. Accordingly, the level of TPU might display mitigating and aggravating implications on environmental impacts.

Geopolitical risk arises from conflicts, wars, and political instability, which threaten energy supply chains and energy security. High GPR pressure countries to give priority to short-term energy security through increased fossil energy reliance, undermining environmental commitments. Recently, the Russia–Ukraine war triggered shifts back toward coal in various countries in Europe, highlighting the regressive potential of GPR shocks on decarbonization processes [14]. Similar dynamics affect major economies such as the USA and China, where geopolitical pressures shape domestic energy choices. The interaction between TPU and GPR further complicates this landscape, where the trade disputes are often intertwined with geopolitical tensions, strengthening uncertainty across multiple domains. The interaction of the two variables can be depicted as the introduction of trade barriers during periods of geopolitical tensions, which can diminish access to clean energy technologies and might reinforce the reliance on carbon-intensive energy generation.

The USA and China, being the world's two largest economies and leading energy consumers, have been central to recent energy generation transformations shaped by trade tensions, geopolitical realignments, and environmental challenges. Their strategic responses to these overlapping uncertainties not only define global economic stability but also determine the pace of the world's energy transition. Within the 2019–2025 period, both countries reveal significantly different trajectories in energy mix, environmental impacts, and policy coordination, yet share a common vulnerability to external shocks that influence carbon emissions and renewable integration. The USA's energy structure demonstrates gradual decarbonization through increased renewable generation and declining coal use [15]. However, periods of high TPU and GPR temporarily slowed renewable investment and increased reliance on domestic fossil resources, primarily natural gas [16]. Consequently, the USA's CO_2

emissions exhibit moderate cyclical fluctuations but no decisive downward trend, suggesting that policy uncertainty limits long-term environmental gains despite technological capacity for clean transition. China's energy system shows a consistent energy transition, where renewable energy generation has expanded rapidly, but fossil sources remain dominant to buffer against GPR and TPU risks. The country's CO_2 emissions remain structurally higher, displaying strong short-term sensitivity to both trade disruptions and geopolitical shocks.

Figures 1 and 2 illustrate daily CO_2 emission patterns in the USA and China from 1st January 2019 and 31st July 2025, respectively.

The USA shows moderate cyclical fluctuations with relative stability, whereas China records higher and more volatile emissions reflecting industrial intensity. The fluctuations are more visible, showing regular peaks and troughs that indicate strong sensitivity to production cycles, lockdown policies, and energy demand shifts. While emissions also oscillate around a relatively stable mean, short-term surges appear more intense in China, potentially due to rapid rebounds following restrictive policy phases or stimulus-driven industrial accelerations.

Figures 3 and 4 illustrate the daily FEG and REG in the USA and China from 1st January 2019 to 31st July 2025, measured in gigawatt-hours (GWh), respectively.

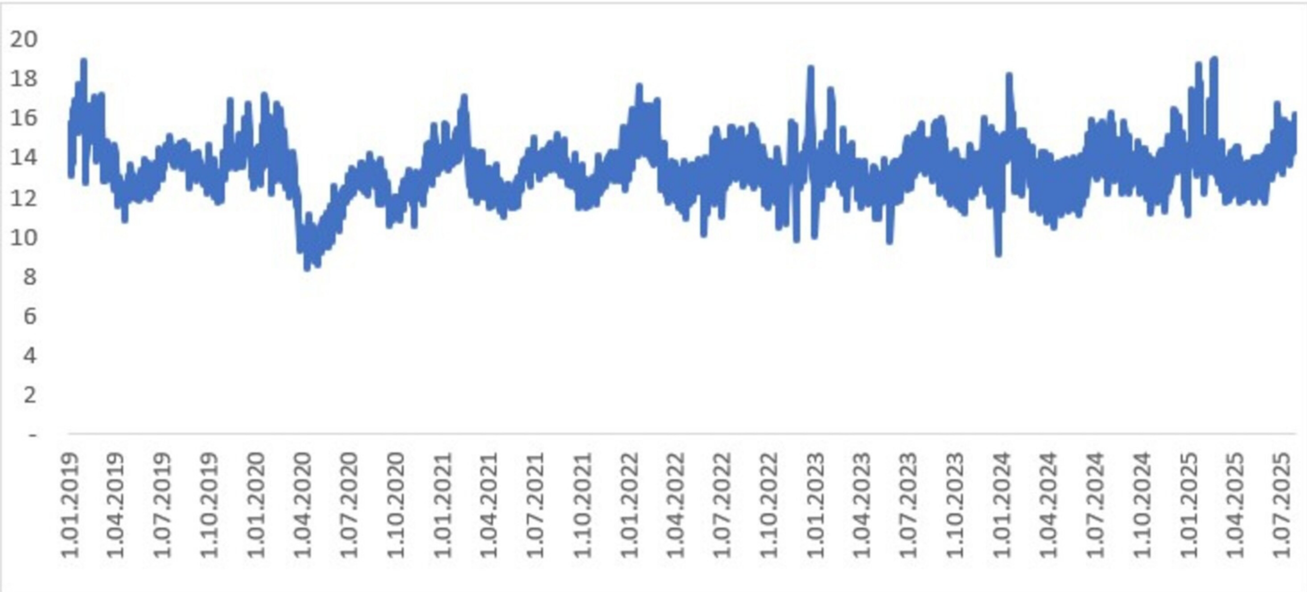

Figure 1. Progress Trend of CO_2 Emissions in the USA. **Source:** [17]. *Notes: The unit is MtCO$_2$/day.*

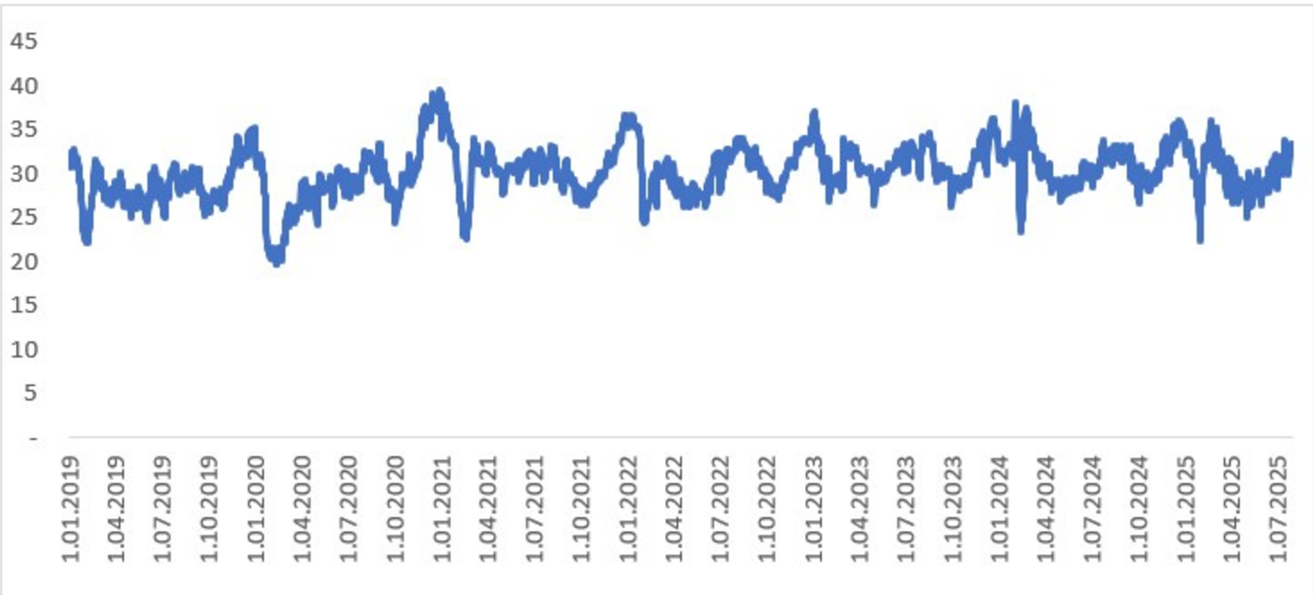

Figure 2. Progress Trend of CO_2 Emissions in China. **Source:** [17]. *Notes: The unit is MtCO$_2$/day.*

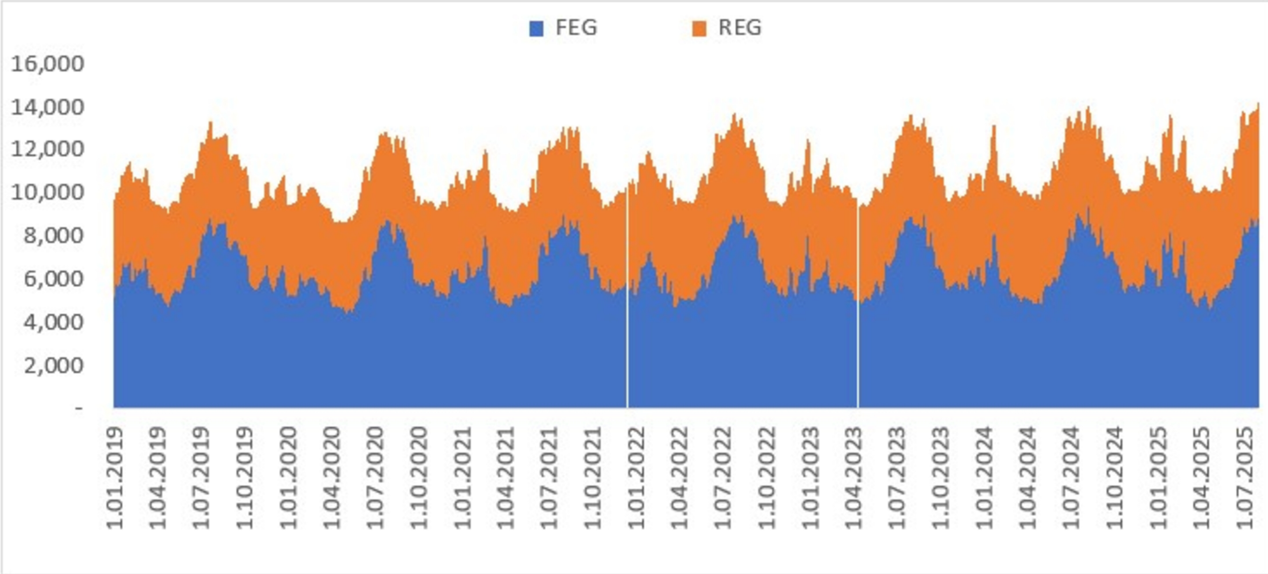

Figure 3. Progress Trend of EG in the USA. **Source:** [17]. *Notes: The unit is gigawatt-hour.*

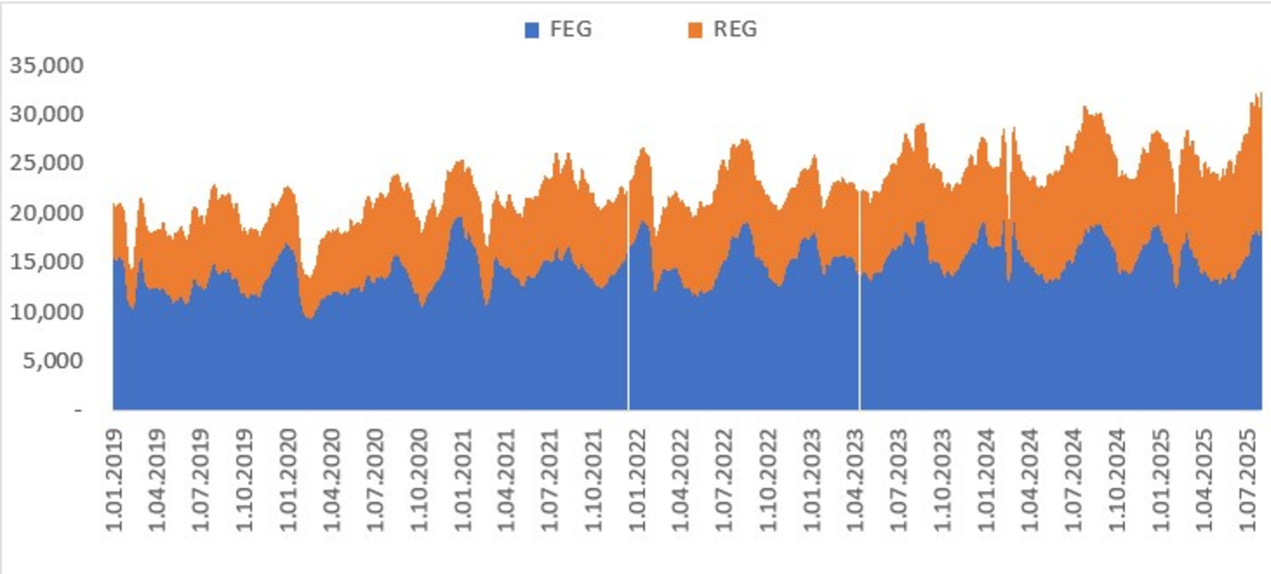

Figure 4. Progress Trend of EG in China. **Source:** [17]. *Notes: The unit is gigawatt-hour.*

The visual patterns highlight both countries' distinct energy mix structures and temporal variability, reflecting their industrial characteristics, energy transition policies, and responses to global shocks. In the USA, FEG dominates the overall electricity mix throughout the period, fluctuating between approximately 4,000 and 10,000 GWh/day, while REG varies between 2,000 and 6,000 GWh/day. The alternating peaks of fossil and renewable generation suggest seasonal substitution impacts, with renewables rising notably during periods of favorable solar and wind conditions. Despite fossil fuels maintaining a major share, the relative stability and gradual upward trend in REG indicate steady progress in clean energy integration. This balanced pattern implies that the USA's energy system is undergoing a moderate but consistent decarbonization trajectory, supported by diversification policies and technological improvements in renewable capacity. China's energy generation levels are substantially higher, ranging from 10,000 to 35,000 GWh/day, underscoring its larger industrial and population base. FEG constitutes the primary component, yet REG shows significant growth and a visible seasonal nature, demonstrating China's rapid renewable energy expansion, particularly after 2022. The sharper cyclical variations reflect industrial demand fluctuations, as well as climate and policy-driven shifts in EC and EG. Despite continuous reliance on fossil fuels, the expanding share of REG signals an active transition effort.

Figure 5 depicts the daily progress trends of the TPU index between 1st January 2019 and 31st July 2025.

Figure 5 illustrates a marked rise in TPU over time. Between 2019 and mid-2020, the TPU index exhibits intermittent spikes corresponding to USA–China trade tensions and early COVID-19 disruptions in global trade flows. Following a temporary moderation during 2021, the index begins a sharp upward trajectory from late 2022 onward, reaching its highest levels in 2024–2025. This escalation likely reflects the renewed trade friction, tariff adjustments, and supply-chain disruptions driven by post-pandemic protectionist measures and geopolitical realignments. The persistent elevation of TPU suggests that global trade policy uncertainty has become structural rather than episodic, directly influencing cross-border investment and energy-intensive production decisions.

Also, Figure 6 depicts the daily progress trends of the GPR index between 1st January 2019 and 31st July 2025.

Figure 6 displays the evolution of GPR, which also intensifies during the sample period, albeit with different timing and magnitude. Distinct peaks appear around early 2020 (COVID-19 onset), early 2022 (Russia–Ukraine war outbreak), and mid-2023 to 2024 (geopolitical spillovers and regional conflicts). These spikes reveal that geopolitical shocks are more event-driven but equally persistent in maintaining an increased risk environment.

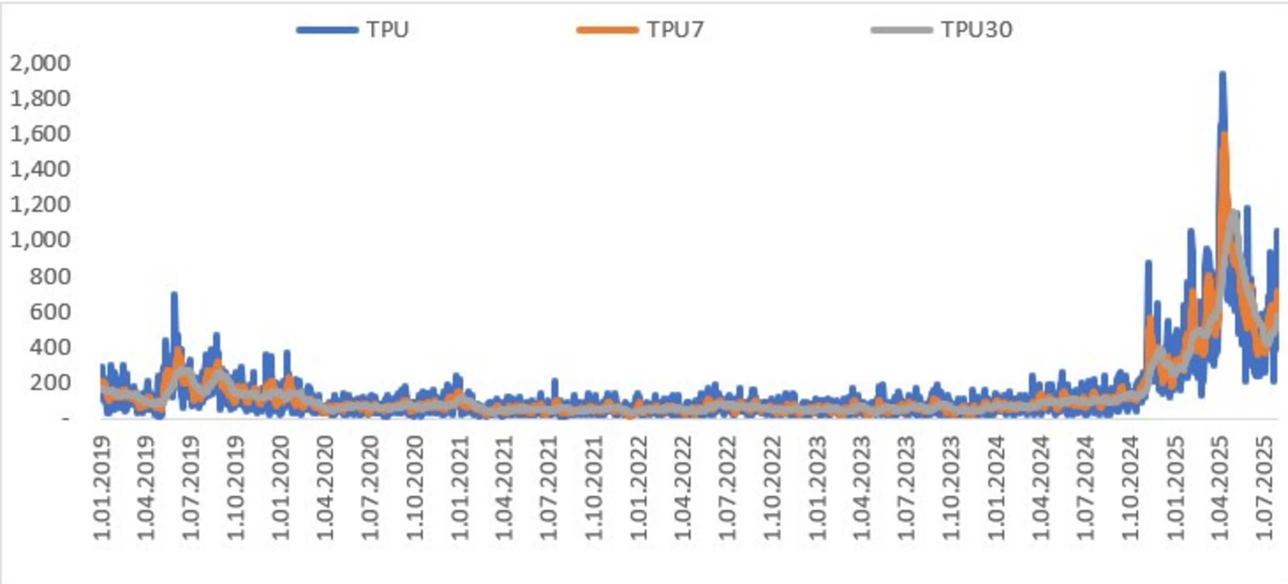

Figure 5. Progress Trend of TPU. **Source:** [18]. *Notes: The unit is the index.*

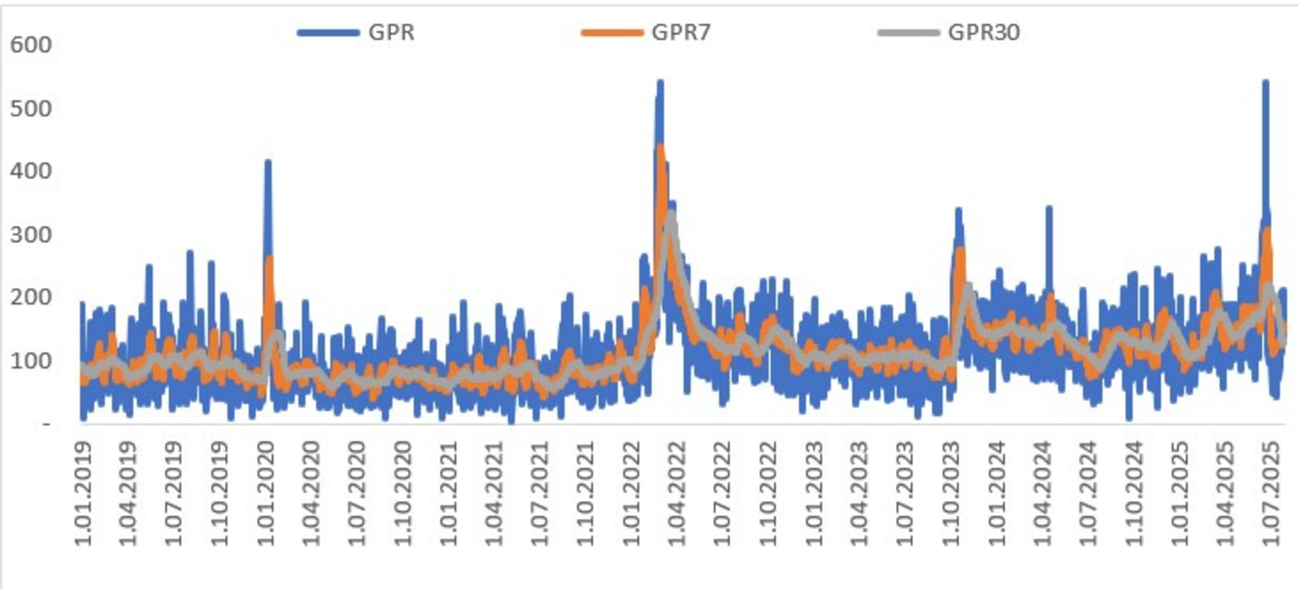

Figure 6. Progress Trend of GPR. **Source:** [19]. *Notes: The unit is the index.*

A change in both TPU and GPR may cause a change in the emissions level. That is why changes in trade and geopolitics-related environment have an impact on the choices of policymakers for the energy and environment-related policies under the moderating impact of both TPU and GPR. Specifically, low levels of TPU and GPR make it easier to make good eco-friendly decisions on energy mix choices, whereas high levels increase the tendency to make easy and short-term focused decisions. Moreover, high and overlapping levels of these risks stimulate emissions by disrupting energy transition efforts and policy coordination.

Consistent with the progressing significance of TPU and GPR, recent studies have begun to consider these factors empirically in investigating environmental deterioration. For example, [13, 20–26] are some studies that have focused on the impact of TPU on the environment for Chinese cities, the USA, China, global case, and Chinese companies. In addition to these, [27–29, 16, 30] have dealt with the impact of GPR on the environmental progress for the USA, E7 countries, BRICS, fragile countries, BRICS, and the globe, respectively. Despite extensive research on the determinants of CO_2 emissions, relatively few studies have integrated these variables into a unified framework. The literature also has a gap that the present studies have not focused on the leading developed (i.e., the USA) and developing (i.e., China) countries simultaneously, as well as they have not considered multiple poly-crisis (e.g., trade war represented by TPU and geopolitical conflicts and military war proxied by GPR). These points are important because the countries have a lighthouse role in their peer groups, and the aforementioned factors may be highly effective on the nexus between EG sub-types and CO_2 emissions through various mechanisms and channels. Moreover, because such studies have occasionally applied panel data approaches, they sometimes do not consider country-based differences. Furthermore, the impacts of the EG sub-types on CO_2 emissions may be marginal (i.e., incremental), where they may vary across different percentiles. This possibility necessitates applying a percentile-based analysis to consider both AMI and PMI across various levels.

Considering the aforementioned gaps in the literature, this research aims to investigate both the USA and China cases, considering the role of TPU and GPR, and applying a marginal impact analysis through the KRLS approach so that the impacts can be investigated across percentiles. These countries are not only the world's largest emitters, but also pivotal actors in trade disputes and geopolitical tensions. Using high-frequency daily data between 1st January 2019 and 31st July 2025, the analysis applies the KRLS approach, which allows for flexible, non-parametric estimation across the distribution of emissions. This methodological choice is particularly suited to capture nonlinear and heterogeneous impacts, offering a richer understanding of how fossil EG, renewable EG, TPU, GPR, and their interaction shape environmental impacts under varying conditions. Traditional environmental economics research has established the harmful role of fossil EC and the beneficial impacts of renewable energy, often at annual or quarterly frequencies. Yet, daily variations in energy generation, emissions, and policy uncertainty may provide additional insights into the short-term dynamics that shape long-run trajectories. Moreover, mean-based econometric approaches overlook the heterogeneous impacts across different levels of emissions. The environmental impact of renewables, for instance, may differ when emissions are already high compared to when they are low. Similarly, the impacts of TPU and GPR may vary across the distribution, reflecting thresholds or nonlinearities in their influence.

By explicitly integrating FEG, REG, TPU, and GPR into a unified analysis of CO_2 emissions, this study contributes to the literature on energy transition, climate policy, and environmental governance in different ways. First, this study examines the USA and China simultaneously and separately, which are significant counterparties of the recent trade war as well as leading developed and developing countries. Hence, considering the country-based differences. Second, the research uses high-frequency daily data, hence accounting for the daily variations. It provides high-frequency evidence on the heterogeneous impacts of energy sources and uncertainty across different emission levels. Third, the study performs the KRLS approach, which enables researchers to consider average and marginal impact across percentiles. Fourth, the study incorporates TPU and GPR into the nexus between EG subtypes and CO_2 emissions. This advance understanding of how geopolitical and trade-related uncertainties shape energy-environment dynamics, an area of growing importance in the context of global turbulence. Hence, the study offers policy-relevant insights for designing robust environmental strategies that insulate renewable deployment from political disruptions and mitigate the compounding risks of uncertainty. Thus, the study extends the current body of knowledge on the subject by providing the aforementioned contributions.

The results reveal several important findings: fossil EG consistently aggravates emissions in both economies, renewable EG reduces emissions only at lower percentiles but loses effectiveness at higher levels, TPU and GPR have asymmetric impacts depending on their intensity, and their interaction tends to exacerbate environmental degradation. These findings suggest that the impact of energy and policy variables is conditional, highlighting the need for adaptive and resilient environmental strategies.

The paper proceeds as follows: Section 2 summarizes the literature, Section 3 provides the methods, Section 4 presents the empirical results, and Section 5 concludes with a discussion, policy implications, and future research directions.

2. Literature Review

Climate change is a global problem driven by rising pollution, primarily in the form of rising CO_2 emissions and the environmental footprint of human activities. This work specifically probes the role of energy production sources, including fossil and alternative power sources, on environmental quality in the USA. This research also attempts to explore this nexus in the framework of various uncertainties (i.e., TPU & GPR). In the following, this study presents the recent studies that explored the energy generation sources-environmental deterioration nexus explicitly. Along with this, this study examines the recent studies that explore how uncertainties play a role in identifying EG sources and the link between environmental deterioration.

2.1. Energy Generation Sources-Environmental Deterioration Nexus

Ref. [31], using the multivariate adaptive regression splines approach for the period of 1965–2019 for the top five carbon-emitting nations, reveals that EC, coal consumption, nuclear EC, and renewable EC influence CO_2 emission in some of these nations, but not in some others. Also, the study determines that coal, oil, and natural gas consumption are the most influential drivers for CO_2 emissions. Ref. [32], through a dynamic autoregressive distributed lag (ARDL) simulation approach from 1980 to 2018 in China, find that fossil fuel EC significantly stimulates CO_2 emissions in both the short and long run. In addition, GDP increases CO_2 emissions in the long run but has a strong negative impact on China's environment in the short run. However, REC has a short-run negative impact on CO_2 emissions. Ref. [33], employing quantile-on-quantile and quantile regression analysis from 1985 to 2018 for China, conclude that hydro EC decreases CO_2 emissions. Ref. [34], employing ARDL from 1990 to 2019 for China, conclude that green energy decreases CO_2 emissions.

Moreover, [35], employing a cross-sectional ARDL approach between 1990 and 2019 in OECD countries, illustrate that both fossil fuel consumption and GDP growth increase CO_2 emissions in the short and long run. Nevertheless, REC decreases CO_2 emissions. Ref. [36], with dynamic ARDL simulation and KRLS approaches from 1980 to 2018 for the USA, indicate that renewable energy serves to decrease CO_2 emissions. Nevertheless, the fossil fuel energy shock increases CO_2 emissions in the long run. Ref. [37], employing ARDL and cointegration regression approaches between 1972 and 2021 in South Korea, reveal that rising GDP and population result in higher CO_2 emissions, and a plan shifting to renewable energy can reduce CO_2 emissions. Ref. [38], using the Fourier approach between 2000 and 2019 in the United Kingdom, highlight that primary EC and trade increase CO_2 emissions, whereas GDP and environmental tax decrease CO_2 emissions.

Furthermore, [39], using the Fourier approach between 1995 and 2020 in France, find that green electricity and environmental tax improve environmental quality. Ref. [40], employing symmetric ARDL and GMM from 1990 to 2022 for Romania, report that REC and trade negatively affect CO_2 emissions, whereas fossil fuel electricity production, financial development, and urbanization have a positive impact on CO_2 emissions. Ref. [41], employing dynamic ARDL and spectral causality test between 1990 and 2018 for South Africa, determine that fossil fuel EC and economic development are causes of a decline in environmental quality, but an increase in renewable EC improves ecological sustainability. Further, the spectral causality test shows that fossil fuel and renewable EC, as well as economic growth, can estimate the ecological quality in the long run. Ref. [42], employing the ARDL approach, whose robustness is confirmed by DOLS, with the support of the Granger causality test between 1965 and 2022 for Indonesia, stress that fossil fuel EC, natural disasters, and economic development are the drivers of higher CO_2 emissions in the long run, with renewable energy decreasing them. In the short run, fossil fuel EC increases CO_2 emissions, whereas renewable EC decreases. Ref. [43], using the ARDL bound test and Granger causality test from 1970 to 2022 for India, establish two-way causality between CO_2 emission, economic development, and urbanization. Also, the authors highlight that investments in renewable power capacity are necessary to replace non-renewable ones.

In sum, the literature shows that energy utilization is an important driver of CO_2 emissions, fossil fuel-based energy generally stimulates the emissions, and the impact of renewable energy sub-types varies (i.e., beneficial or inefficient) across countries based on time interval, method selection, and consideration of the other variables in the estimation models.

2.2. The Impacts of TPU and GPR on Environmental Deterioration

Some studies have specifically probed to determine the impact of uncertainties, such as TPU and GPR, on environmental quality. For instance, [44], using the ARDL approach for the USA from 198/5Q1 to 2014/Q4, finds that TPU puts a downward pressure on ecological footprint. Ref. [45], using AMG and cointegration regression approaches from 1995 to 2015 for five emerging nations (namely, Brazil, Mexico, Russia, Colombia, & China), state that GPR lowers ecological footprint.

Besides, [20] illustrate that the decrease in TPU can considerably improve ecological quality between 1998 and 2007 in China. Also, the authors highlight that TPU can significantly improve ecological quality through industrial structure and technological impacts. Ref. [46], employing panel quantile regression from 1990 to 2015 in BRICST economies, find that GPR increases CO_2 emissions in lower quantiles, but decreases CO_2 emissions in middle and higher quantiles. Similarly, [47], using data from 1985 to 2019 and applying a quantile-on-quantile regression approach for India, highlight that GPR increases ecological degradation in middle quantiles but decreases ecological degradation in lower and upper quantiles.

Moreover, [21], employing augmented ARDL and nonlinear ARDL between 1985 and 2022 for the USA, find that TPU exerts a negative influence on CO_2 emissions in the residential sector, whereas negative changes in TPU exert a positive influence on CO_2 emissions in the commercial sector in the short and long run. Ref. [48] determines that there is a long-run link between economic complexity, economic policy uncertainty (EPU), GPR, EC, and ecological quality for the period of 1995–2018 in E7 economies. Ref. [49], employing AMG and cointegration regression approaches from 2000 to 2021, proves that EPU, GPR, and economic growth are the causes of increasing CO_2 emissions.

Furthermore, [50], employing wavelet methodology from 1997 to 2022 for the USA, concludes that GPR decreases CO_2 emissions in residential, commercial, industrial, and electricity sectors, but increases CO_2 emissions in the transport sector. The authors also prove that the reduction in CO_2 emissions provided by EPU is higher in comparison to GPR. Ref. [23] reveal that fossil EC reduced by TPU would be 3.95% greater than non-fossil EC on average, making its contribution towards environmental sustainability in China. Ref. [51], employing cross-sectional ARDL, AMG, and cointegration regression approaches between 1992 and 2021 for BRICS nations, determine that GPR and EPU are correlated with a rise in environmental degradation. The result of a work by [52] uncovers that GPR and renewable energy reduce environmental footprint, but EPU and non-renewable EC have an opposite impact in BRICS countries from 2000 to 2021.

To sum up, the literature suggests that TPU and GPR have a significant impact on the environment, where both TPU and GPR have either an increasing or a decreasing impact on the environmental quality across countries and economic sectors.

2.3. Literature Gap

Considering the aforementioned contemporary literature reviewed, energy sources have a significant impact on the environment. In addition, the studies underscore that environmental quality can be affected by policy uncertainties and geopolitical risk. However, based on the best understanding, there is scarce research in the literature that empirically scrutinizes the nexus of FEG and REG with CO_2 emissions under the moderating impact of TPU and GPR to assess environmental quality concerns. Hence, this study fills in the gap by focusing on the USA and China cases, which are leading developed and developing countries, as well as they are significant counterparties of the recent trade-war, through the use of high-frequency daily data between 1st January 2019 and 31st July 2025 and performing the KRLS approach.

3. Methods

3.1. Data and Variables

This study explores the nexus between EG sources and the environment by incorporating the impacts of TPU and GPR. In doing so, it employs CO_2 emissions as a proxy for environmental deterioration and fossil and renewable EG as proxies for energy sources. The analysis focuses on the USA and China, representing advanced and emerging economies as well as the key actors in recent trade conflicts—applying the KRLS approach to measure daily dynamics and using high-frequency daily data between 1st January 2019 and 31st July 2025. The data starts from the 1st January 2019 because of the fact that daily data for CO_2 emissions is available from this date in the source of [17].

The dependent variable is CO_2 emissions, measured in tons and obtained from [17]. To investigate the role of energy structure, two additional energy-related variables are included: FEG and REG, both measured in exajoules and sourced from [17]. The independent variables focus on policy-related and geopolitical uncertainties as well. TPU is measured using the [18] index, with alternative specifications: the 7-day average and 30-day average, which serve as robustness checks. Similarly, GPR is derived from [19] index, with the 7-day average and 30-day average included as alternative measures. To capture the combined impact of trade policy and geopolitical conditions, an interaction term TPU*GPR is included.

Table 1 summarizes the key details of the variables used in the study.

Table 1. Description of the Variables.

Symbol	Definition	Unit	Data Source
CO_2	Carbon Dioxide*	Tons	[17]
FEG	Fossil EG	Exajoules	[17]
REG	Renewable EG		
TPU	Trade Policy Uncertainty	Index	[18]
TPU7	Trade Policy Uncertainty for 7-day average**		
TPU30	Trade Policy Uncertainty for 30-day average***		
GPR	Geopolitical Risk	Index	[19]
GPR7	Geopolitical Risk for 7-day average**		
GPR30	Geopolitical Risk for 30-day average***		
TPU*GPR	Interaction between TPU and GPR	—	Calculated by authors

*Notes: * denotes the dependent variable. ** and *** denote the alternative variables for TPU and GPR to validate their impact on CO_2 within the scope of robustness.*

Following the data collection from the data sources, the study applies logarithmic (Ln) differences so that the impact of a 1% change in the explanatory variables on 1% change in CO_2 emissions can be considered and examined.

3.2. Estimation Models

The empirical framework of this study relies on a set of main and robustness models that collectively aim to investigate the nexus between CO_2 emissions, energy generation sources, and uncertainty measures. All models take the natural logarithm of CO_2 emissions ($LnCO_2$) as the dependent variable. The specifications can be grouped into two categories: main models and robustness models.

In the main models (Models 1–4), $LnCO_2$ is explained by LnFEG and LnREG, taking into account the uncertainty factors.

$$\text{Model 1: } LnCO_2 = f(LnFEG, LnREG) \quad (1)$$

$$\text{Model 2: } LnCO_2 = f(LnFEG, LnREG, LnTPU) \quad (2)$$

$$\text{Model 3: } LnCO_2 = f(LnFEG, LnREG, LnGPR) \quad (3)$$

$$\text{Model 4: } LnCO_2 = f(LnFEG, LnREG, LnTPU*LnGPR) \quad (4)$$

Model 1 establishes the baseline by linking $LnCO_2$ emissions solely to LnFEG and LnREG. This model captures the direct energy & environment nexus without considering uncertainty factors. Model 2 extends the baseline by including LnTPU, thereby allowing an assessment of how fluctuations in trade policies influence the energy–environment nexus. Model 3 includes LnGPR in Model 1 to examine the role of political instability and global tensions in shaping environmental impacts. Finally, Model 4 incorporates both sources of uncertainty simultaneously by including an interaction term (LnTPU*LnGPR), which enables the analysis of their combined and potentially reinforcing impacts on emissions.

The robustness models (Models 5–8) validate the findings by employing alternative measures of TPU and GPR, specifically their 7-day and 30-day averages (TPU7, TPU30, GPR7, GPR30).

$$\text{Model 5: } LnCO_2 = f(LnFEG, LnREG, LnTPU7) \quad (5)$$

$$\text{Model 6: } LnCO_2 = f(LnFEG, LnREG, LnTPU30) \quad (6)$$

$$\text{Model 7: } LnCO_2 = f(LnFEG, LnREG, LnGPR7) \quad (7)$$

$$\text{Model 8: } LnCO_2 = f(LnFEG, LnREG, LnGPR30) \quad (8)$$

Model 5 replaces TPU with its 7-day average, capturing short-term fluctuations in trade policy uncertainty. Model 6 uses the 30-day average of TPU, focusing instead on more persistent uncertainty trends. Model 7 uses the 7-day average of GPR, reflecting short-term geopolitical risks. Also, Model 8 employs the 30-day average of GPR, which captures longer-term geopolitical instability.

In this study, STATA software is used to perform the KRLS approach. Also, the study applies specific codes to obtain empirical results for the prediction of CO_2 emissions, which are provided in Supplementary Explanations 1 and 2, in order.

3.3. Methodological Flow

A 6-step methodological framework is applied to measure the nexus between energy generation sources and the environment by including the impacts of TPU and GPR. The methodological framework is given in detail in Figure 7.

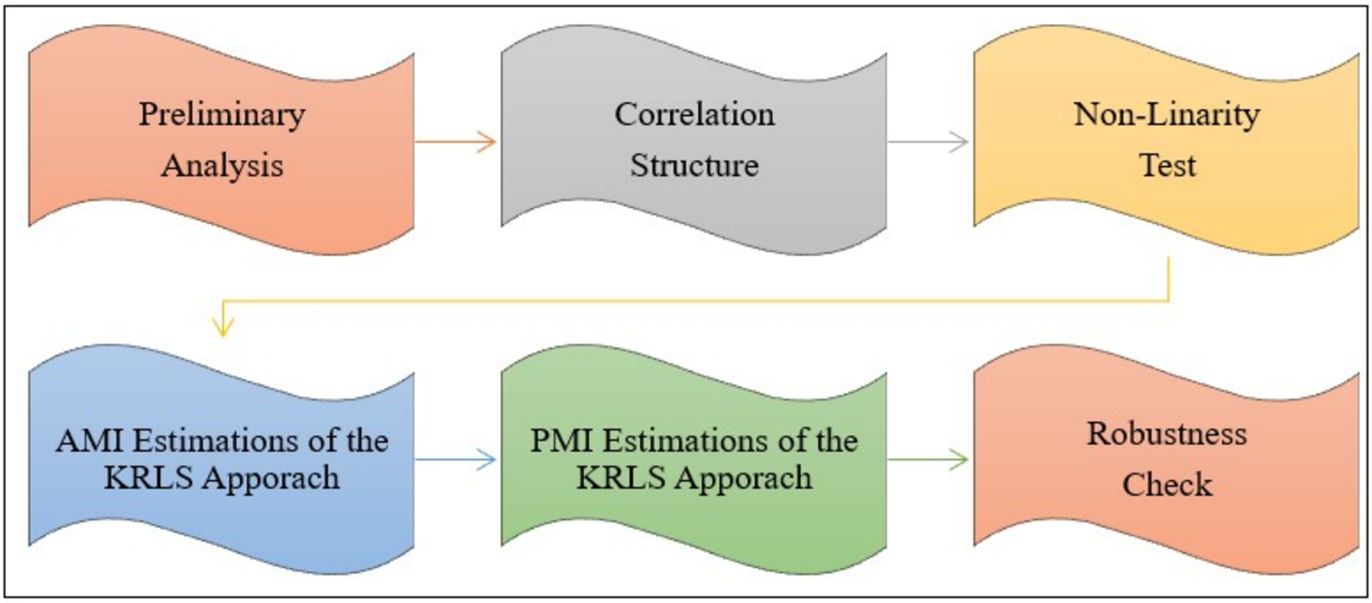

Figure 7. Methodological Framework.

In the first step, preliminary analysis is performed to summarize the main characteristics of the data, including averages and distributional properties, to gain an initial understanding of the variables. The second step applies correlation analysis to examine the strength and direction of pairwise associations among the key variables. Moving further, the third step focuses on the BDS non-linearity test results, whether the impacts of explanatory variables on CO_2 emissions follow non-linear patterns rather than simple linear associations [53]. In the fourth step, the KRLS approach is used to derive AMIs. In contrast to standard OLS or panel approaches, the KRLS approach enables the identification of nonlinear marginal impacts across percentiles. Given the advanced estimative performance of the KRLS approach, its capacity to capture hidden data features, and its frequent use in recent studies [54], the present research adopts this approach. These estimations provide an overall measure of how changes in energy sources, trade policy uncertainty, and geopolitical risk influence CO_2 emissions on average across the entire sample [54]. The fifth step extends the analysis by calculating PMIs from the KRLS approach. Unlike AMIs, PMI estimations allow for the identification of heterogeneous impacts by showing how the marginal impact of explanatory variables may vary at different points of their distributions. Finally, in the sixth step, a robustness check is applied by re-estimating the models with alternative measures of TPU7, TPU30, GPR7, and GPR30. This final step ensures that the findings are not sensitive to short-term fluctuations or different measurement horizons, thereby reinforcing the credibility and stability of the results.

Taking data characteristics of the variables into consideration, which is highly critical issue in the selection of appropriate econometric approach as highlighted by [55–57], this research applies the KRLS approach [54] for predictions because it is superior to conventional econometric approaches due to the providing better prediction results through benefitting from machine learning and derivative calculation. Moreover, the KRLS approach does not have any preconditions and enables researchers to uncover AMI and PMI across percentiles [58].

4. Empirical Results

4.1. Preliminary Statistics

Preliminary statistics for all variables used in the analysis for both the USA and China are given in Supplementary Table 1 in detail. The results provide initial insights into the central tendencies, variability, and distributional properties of the data over the examined period, which is the first step of the methodology.

The average level of $LnCO_2$ is lower in the USA (2.60) than in China (3.40), which may reflect differences in data scaling and the composition of energy use rather than total emission volumes. The relatively small SD across both countries implies low volatility in daily CO_2 emissions. For both countries, the mean values of LnFEG are higher than those of LnREG, indicating that fossil-based energy relatively dominates total EG. However, the relatively close mean values between LnFEG and LnREG. Regarding the uncertainty measures, both LnTPU and LnGPR display substantial variation, as indicated by their relatively higher standard deviations (0.94 and 0.56, respectively). This highlights the dynamic nature of policy and geopolitical developments during the sample period (2019–2025). The interaction term LnTPU*LnGPR shows the highest variability (SD = 1.18), suggesting that combined uncertainty impacts fluctuate more intensely than individual components. The skewness and kurtosis values indicate asymmetries and deviations from normality in almost all variables, which is confirmed by the JB normality test results, all of which are statistically significant at the 1% level.

The correlation analysis, which is given in Supplementary Table 2, shows that $LnCO_2$ is positively related to LnFEG in both countries, more strongly in China, confirming the dominant role of fossil sources in emission levels. LnREG exhibits a weaker but positive association with $LnCO_2$, indicating its complementary rather than substitutive role. The correlations between uncertainty indicators (TPU & GPR) are strong internally but relatively low with energy variables, suggesting they capture distinct dynamics. Overall, no severe multicollinearity is detected, confirming the suitability of the variables for KRLS estimation. Moreover, the results of the nonlinearity tests (DM2–DM6) confirm that all variables for both the USA and China exhibit a nonlinear nexus (p-value = 0.0000). This finding suggests that the associations among energy generation, uncertainty indicators, and CO_2 emissions cannot be adequately captured through linear models. Thereby, all these preliminary results show that the use of the KRLS approach in subsequent estimations [16, 30].

4.2. AMI Results by KRLS Approach

At the fourth step of the methodology, the models based on the KRLS approach are estimated for each country, and the obtained AMI statistics are used to explore how the independent variables relate to CO_2 emissions. The full outputs for the USA are shown in Supplementary Table 4, and their summary is given in Table 2.

The results in Table 2 reveal several consistent patterns across models. Starting with LnFEG, its impact on $LnCO_2$ remains positive and statistically significant throughout all models, underscoring the strong dependency of the USA energy system on fossil sources. This finding is also in line with the literature (e.g., [36, 59]). However, the coefficient gradually declines from 0.3748 in Model 1 to 0.3347 in Model 4, suggesting that with an increase in uncertainty, fossil energy continues to contribute to emissions but with a slightly reduced marginal impact. But still, the results are consistent. The impact of LnREG is positive in all models, suggesting that the growth of renewable energy does not bring environmental benefits in the long run. The main reason for the inefficiency of REG in reducing CO_2 emissions is due to the fact that the share of total renewable energy in the energy mix has been decreasing over time. Specifically, REG has a 34% share on 7th July 2025, whereas it had a 46% share on 1st January 2019 [17]. Because its share in the total energy mix decreases, REG does not ensure a reduction in CO_2 emissions. Moreover, the coefficient in the baseline model is significantly higher than in other models but still positive. In other words, when uncertainty variables are included in the baseline model, the explanatory power of renewables becomes weaker.

LnTPU has a positive and statistically significant impact in Model 2. This suggests that when trade-related uncertainty increases, emissions also rise—likely because production patterns are disrupted or shift toward less efficient energy use. This result is also consistent with the studies in literature (e.g., [60, 61]). The inclusion of LnGPR in Model 3 reveals a clear positive and significant nexus with $LnCO_2$, emphasizing that political instability and global tensions tend to increase environmental degradation-possibly through disruptions in trade, energy markets, or policy coordination. Also, in the studies of [28] and [62], it is underlined that the GPR has a significant impact on environmental stress as well. When both uncertainties' interaction term is included in Model 4, its impact also emerges as positive and significant, suggesting that simultaneous increases in trade and geopolitical uncertainty amplify their individual adverse impacts on emissions.

To sum up, these findings show that while fossil energy remains the primary driver of emissions, the influence of energy variables relatively weakens once policy and geopolitical uncertainties are considered. The positive and significant impacts of TPU and GPR, as well as the interaction term (LnTPU*LnGPR), indicate that uncertainty acts as an independent and reinforcing factor on CO_2 emissions in the USA. Also, the combined rise in TPU and GPR exerts an amplified adverse impact on environmental degradation, carrying important implications for energy security and emission-reduction policies.

Details of the outputs for China are given in Supplementary Table 5, and a summary is provided in Table 3.

Table 2. AMI Results for USA.

Variable	Detail	Models			
		1	2	3	4
LnFEG	Coef.	0.3748	0.3407	0.3527	0.3347
	p-value	0.0000	0.0000	0.0000	0.0000
LnREG	Coef.	0.2610	0.2264	0.1797	0.1844
	p-value	0.0000	0.0000	0.0000	0.0000
LnTPU	Coef.		0.0149		
	p-value		0.0000		
LnGPR	Coef.			0.0397	
	p-value			0.0000	
LnTPU*LnGPR	Coef.				0.0186
	p-value				0.0000
R^2		38.85	41.77	42.74	42.63

Table 3. AMI Results for China.

Variable	Detail	Models			
		1	2	3	4
LnFEG	Coef.	0.5006	0.5061	0.4943	0.5026
	p-value	0.0000	0.0000	0.0000	0.0000
LnREG	Coef.	−0.0298	−0.0282	−0.0257	−0.0317
	p-value	0.0000	0.0000	0.0000	0.0000
LnTPU	Coef.		0.0016		
	p-value		0.1950		
LnGPR	Coef.			0.0001	
	p-value			0.9700	
LnTPU*LnGPR	Coef.				−0.0010
	p-value				0.3030
R^2		79.99	80.68	81.03	81.16

The results for China reveal a significantly different dynamic compared to the results obtained from the USA in Table 2. According to the current literature, while LnFEG remains the dominant and highly significant driver of $LnCO_2$ in both countries, its magnitude in China (approximately 0.50) is considerably higher than in the USA (approximately 0.35) [32, 63, 64]. Also, its impacts are statistically significant and positive in all models, showing that the results are consistent. The stability of the LnFEG coefficient across all models in China suggests that uncertainty factors show little mediating impact on the energy–emission nexus, in contrast to the USA. On the other hand, LnREG shows consistently negative and significant coefficients in China, in contrast to the positive ones observed for the USA, suggesting that the growth of renewable energy provides environmental benefits in the long run, which is also emphasized in the previous studies in the literature (e.g., [65, 66]). The main reason for the curbing impact of REG on reducing CO_2 emissions is due to the fact that the share of total renewable energy in the energy mix has been increasing over time. Specifically, REG has a 42% share on 7th July 2025, whereas it had a 26% share on 1st January 2019 [17]. Because its share in the total energy mix increases, REG makes a reducing impact on CO_2 emissions. The magnitude of the impact, although small ($\sim$0.03), is stable across all specifications, meaning that the impact of LnREG is consistent in explaining the variation of $LnCO_2$.

Uncertainty measures, both LnTPU and LnGPR, are statistically insignificant in China, while in the USA, they had positive and significant impacts on emissions. Similarly, the interaction term (LnTPU*LnGPR) is not significant and even turns slightly negative (consider that its impact is positive at higher percentiles), suggesting that simultaneous increases in both types of uncertainty do not increase CO_2 emissions. Hence, differentiating from the USA, the combined rise in TPU and GPR does not exert an amplified adverse impact on environmental degradation, implying that China does not suffer too much from the interaction of TPU with GPR because of its exporter position in international trade and having rich sources that preserve China from geopolitical tension's adverse impacts. These findings stand in contrast to the existing literature, which suggests that rising TPU and GPR lead to higher carbon emissions (e.g., [24, 67, 68]). The overall explanatory power of models in China ($R^2 \sim$ 80–81%) is significantly higher than that of the USA models ($R^2 \sim$ 39–43%), confirming that China's emissions are more systematically determined by its energy generation mix.

4.3. PMI Results by KRLS Approach

In the fifth step of the analysis, PMI is employed separately for each country to capture how the marginal impact of the independent variables changes across different points of the dependent variable's distribution. The corresponding PMI results are displayed in Supplementary Tables 4 and 5.

PMI results show a clear and consistent pattern for the USA. LnFEG is the dominant driver of CO_2: its average impact is large and significant in each model, and its marginal impact increases from lower to higher quartiles in all models. Similarly, LnREG is also positive and significant on average, but at the lower quartile, the impact is near zero or even slightly negative. On the other hand, it turns positive at the median, and the magnitude is increasing at the upper quartile. Adding uncertainty variables changes levels of impact but not signs. LnTPU is small, positive, and significant on average (0.015), with PMIs shifting from slightly negative at P25 (-0.006) to positive by the median and upper tail. LnGPR shows a larger positive average impact (0.040) and the same upward trend across quartiles. Finally, the interaction term (LnTPU*LnGPR) is positive and significant on average (0.019) and strengthens from lower to higher quartiles, indicating a reinforcing impact when trade and geopolitical uncertainties rise together.

Supplementary Table 5 for China shows a very consistent output. LnFEG is the main factor of $LnCO_2$ in China as well. Its average impact is large and highly significant in every model, and its marginal impact rises from lower to higher quartiles, showing that LnFEG leads emissions most especially in a high-emission level. LnREG, by contrast, is reducing on average $LnCO_2$ and is clearly negative at the lower and median quartiles. At the upper quartile, the impact is reducing and close to zero. However, LnTPU and LnGPR are statistically insignificant on average, and their PMIs are close to zero across quartiles. The interaction term (LnTPU*LnGPR) is also insignificant. Importantly, adding these variables to the model barely moves the energy coefficients, emphasizing the stability of the energy and emissions nexus in China.

4.4. Robustness Check

To verify the robustness of the baseline estimates, the KRLS approach is used to re-estimate with different independent variables. The corresponding AMI and PMI results are reported in Supplementary Table 6 in detail. The summary of AMI results for the USA is given in Table 4.

The results from the robustness analysis largely confirm the main findings, with only a few notable differences in the impact of uncertainty variables. The impact of LnFEG remains stable and strongly positive, with coefficients ranging between 0.32 and 0.36, very close to those in the baseline models. This consistency shows the central role of fossil energy as the key driver of emissions. The impact of LnREG also stays positive and significant, and its magnitude is even slightly larger in the TPU-based robustness models compared to the main estimates. For uncertainty variables, TPU7 shows a similar positive and significant impact as in the original results, indicating that short-lived uncertainty tends to increase emissions. By contrast, the TPU30 turns negative and significant, suggesting that this type of uncertainty is linked to lower emissions. Geopolitical risk remains positive and significant for 7-day and 30-day averages.

Overall, the robustness checks confirm the stability of the core energy impacts and highlight that the direction and magnitude of uncertainty impacts depend on their duration.

Details of the outputs for the USA are presented in Supplementary Table 7, and a summary is presented in Table 5.

For China, the robustness checks leave the core energy results mostly unchanged. LnFEG remains strongly positive and highly significant in all models, mirroring the main models and confirming its role as the dominant driver of $LnCO_2$. LnREG continues to apply a mitigating impact, negative and significant in Models 5, 6, and 7. The robustness analysis provides a clearer view of how uncertainty influences emissions in China. LnTPU7 has a small but positive and statistically significant impact, pointing to a slight increase in emissions during temporary trade shocks. In contrast, LnTPU30 remains insignificant, which is in line with the baseline results and suggests that uncertainty does not have a direct impact on emissions. Geopolitical risk shows the opposite pattern: both LnGPR7 and LnGPR30 are negative and significant, indicating that rising geopolitical tensions are associated with lower emissions. Model fit remains strong in all models.

Table 4. AMI Results for USA.

Variable	Detail	Models			
		5	6	7	8
LnFEG	Coef.	0.3226	0.3351	0.3547	0.3488
	p-value	0.0000	0.0000	0.0000	0.0000
LnREG	Coef.	0.2617	0.3009	0.2304	0.2359
	p-value	0.0000	0.0000	0.0000	0.0000
LnTPU7	Coef.	0.0148			
	p-value	0.0000			
LnTPU30	Coef.		−0.0167		
	p-value		0.0010		
LnGPR7	Coef.			0.0233	
	p-value			0.0010	
LnGPR30	Coef.				0.0566
	p-value				0.0000
R^2		43.80	46.20	41.41	41.37

Table 5. AMI Results for China.

Variable	Detail	Models			
		5	6	7	8
LnFEG	Coef.	0.5079	0.5093	0.4893	0.5059
	p-value	0.0000	0.0000	0.0000	0.0000
LnREG	Coef.	−0.0184	−0.0215	−0.0127	−0.0058
	p-value	0.0030	0.0020	0.0190	0.3220
LnTPU7	Coef.	0.0053			
	p-value	0.0110			
LnTPU30	Coef.		0.0012		
	p-value		0.6940		
LnGPR7	Coef.			−0.0103	
	p-value			0.0020	
LnGPR30	Coef.				−0.0183
	p-value				0.0000
R^2		81.31	81.38	82.85	83.41

The robustness results are broadly in line with the main model and further strengthen the findings. The impacts of fossil energy remain strong, positive, and stable across all models, showing that fossil generation is consistently the key driver of emissions. Renewable energy also continues to have a positive and significant impact, and its magnitude even grows slightly in some robustness models, confirming that the energy results are not sensitive to the choice of uncertainty indicators. The uncertainty variables provide additional information. LnTPU7 again shows a small but positive impact, while LnTPU30 turns negative and significant. Geopolitical risk remains positive, with a stronger impact in LnGPR30, indicating that sustained geopolitical tensions contribute more to emissions than short-lived shocks.

Overall, the direction and magnitude of the impacts remain largely unchanged, confirming the robustness and stability of the baseline estimates.

4.5. Empirical Summary

Table 6 summarizes AMI and PMI outputs for $LnCO_2$ and other independent variables.

Table 6 summarizes the direction and significance of the AMI and PMI obtained from the KRLS approach for both countries. The results reveal distinct cross-country dynamics in how energy generation and uncertainty variables shape CO_2 emissions.

For the USA, both LnFEG and LnREG show positive and significant impact across all AMI and PMI estimations, indicating that increases in both types of energy output tend to increase emissions. The impact of LnTPU is mostly positive under the AMI results but fluctuates under the PMI, negative at lower quantiles (0.25) and positive at higher ones (0.50 and 0.75). This pattern suggests that the impact of trade uncertainty on emissions is asymmetric. Similar asymmetries are visible in LnGPR's lagged variants: geopolitical risk generally strengthens emissions across all quantiles, especially at the upper end of the distribution. The interaction term (LnTPU*LnGPR) remains positive at all quantile levels. Combined rise in TPU and GPR exerts an amplified adverse impact on environmental degradation, carrying important implications for energy security and emission-reduction policies.

In contrast, the Chinese results show a more stable and partially balanced structure. LnFEG has a consistent positive and significant impact on emissions, but LnREG exerts a negative influence across all models, confirming that renewables in China play a genuinely substitutive role in reducing emissions. The impacts of TPU and GPR are weaker and often statistically insignificant. Also, the interaction term (LnTPU*LnGPR) shows a mostly insignificant result. Combined rise in TPU and GPR does not exert an amplified adverse impact on environmental degradation, implying that China has not suffered too much from the interaction of TPU with GPR because of its exporter position in international trade and having rich sources that protect China from geopolitical tension's adverse impacts. Furthermore, LnGPR's lagged variants also have a negative impact on $LnCO_2$.

Table 6. Summary of the Results.

Country	Variable	AMI	PMI		
			0.25	0.50	0.75
USA	LnFEG	+	+	+	+
	LnREG	+	−	+	+
	LnTPU	+	−	+	+
	LnTPU7	+	−	+	+
	LnTPU30	−	−	−	+
	LnGPR	+	+	+	+
	LnGPR7	+	−	+	+
	LnGPR30	+	−	+	+
	LnTPU*LnGPR	+	+	+	+
China	LnFEG	+	+	+	+
	LnREG	−	−	−	+
	LnTPU	+(*)	−(*)	+(*)	+(*)
	LnTPU7	+	−	+	+
	LnTPU30	+(*)	−(*)	+(*)	+(*)
	LnGPR	+(*)	−(*)	+(*)	+(*)
	LnGPR7	−	−	−	+
	LnGPR30	−	−	−	+
	LnTPU*LnGPR	−(*)	−(*)	−(*)	+(*)

*Notes: +, −, and * denote increasing, decreasing, and insignificant impact, in order.*

Overall, these results show a clear difference between the two countries. In the USA, emissions react more strongly to uncertainty, especially when risks are high. In China, however, emissions are mainly driven by the energy structure, where renewable energy helps reduce emissions, and uncertainty has only a minor impact.

5. Conclusion, Policy Implications, and Future Research

5.1. Conclusion and Discussion

The study aims to capture the impacts of sources of main EG sub-types (namely, FEG & REG) on the environment (proxied by CO_2 emissions) under the moderating role of TPU and GPR. In this vein, the study considers the USA and China by using AMI and PMI approximations of the KRLS approach. The results identify that enhanced EG through fossil fuels positively contributed to CO_2 emissions in the USA and China. Yet, renewable EG has both mixed but mostly positive (negative) impact in the USA (China). Renewable EG decreases CO_2 emissions at low and middle levels but has a limited potential because of problems associated with shortages of infrastructure, costliness, and non-stable policies. As indicated in the results, TPU and GPR impose asymmetric impacts on CO_2 emissions; low levels of the two variables decrease CO_2 emissions, whereas high levels cause an increase. This is an indicator that the less geopolitics and trade stabilize, the less people want to depart from fossil fuels.

By considering that changes in TPU and GPR make it easier to make good eco-friendly decisions on energy mix choices, and high levels increase the tendency to make easy and short-term focused decisions, the countries need comprehensive environmental policies so that they can consider the underlying mechanism between energy structure, uncertainty factors, and environmental degradation. In short, the increases in TPU and GPR direct policymakers to focus on much more short-term, focused decisions instead of long-term ones. Hence, the countries are able to benefit from the uncertainty factors by converting them into a leverage in rearranging the EG structure and preventing the adverse impacts of uncertainty factors on the EG structure and environmental degradation in turn.

Both AMI and PMI estimates confirm that the results are robust, as well as highly reliable and predictable. They both highlight that broader political and economic conditions, which bear upon national decisions and environmental quality, as well as the manner in which energy is generated. Both nations will gain from cleaner energy usage and less CO_2 emissions if their geopolitical relations continue to improve and their relations grow less tense. Briefly, this study contributes to the literature further by demonstrating the combined environmental impact of geopolitical uncertainty and EG choices by using high-frequency daily data and a sophisticated estimation method. Thus, to ensure a positive global nexus and lower policy uncertainty, the USA and China must advance renewable energy more effectively. Long-term economic progress, environmental conservation, and a greener future will all be facilitated in this way.

5.2. Policy Implications

Based on the findings of the empirical research, the USA and China should follow coordinated, flexible, and harmonized environmental and energy policies that efficiently reduce the negative impacts of fossil fuel production and volatility caused by uncertainty of trade and geopolitics. Governments must speed up their shift to renewable power through higher fiscal incentives, greater investment in renewable infrastructure, and technology transfer and innovation, as EG from fossil fuels continues to be the major source of CO_2 emissions for both economies. To provide energy security even in times of geopolitical or trade-related tensions, policymakers should assign priority to the incorporation of renewable energy into the grids of nations by using smart-grid networks and energy storage devices. Environmental stabilization impacts can also be attained with the assistance of dynamic carbon price mechanisms that adjust in accordance with temporary variations in TPU and GPR. This will stimulate industries to transform their patterns of EG in response to signals from the market and sustainability goals.

Moreover, as the study points out, the interconnection between TPU and GPR tends to compromise environmental advancement, especially in the case of greater uncertainty, which requires more intensified global coordination. To temper tensions and stabilize commerce between nations, both the USA and China should embrace trade and diplomacy through dialogue. This may provide an environment for the emergence of sustainable energy. To restrict uncertainty regarding CO_2 emissions, the USA and China may also set up mutual green investment funds or climate cooperation platforms that deal with low-carbon technologies. Promoting eco-friendly business conduct and consumption patterns, public awareness campaigns, and green financing instruments can also improve domestic resilience. The USA and China policymakers should work on mitigating such dual uncertainties through policy coordination, international cooperation, or energy mix diversification. In this vein, they can rely on efforts to decrease trade policy uncertainty and geopolitical risk between the two countries through further collaboration between both countries, enhancing the removal of trade barriers between the two countries, and reducing the geopolitical tension about various issues through working together by diplomatic talks and meetings instead of pushing for sanctions and limitations against each other.

For country-specific cases, both the USA and China should consider that FEG is completely harmful for environmental sustainability, implying that they should work to decrease the share of FEG in the total energy mix by supporting the renewable energy transition much more. In this way, they should provide many more incentives to support further renewable energy investments.

Also, because REG is beneficial at lower levels in both the USA and China, it is critical to consider that the countries cannot benefit from REG at higher levels. This implies that there can be a potential displacement between energy sources and REG sub-types, as highlighted in the studies of [69, 70], which prevents the further progress of renewable energy in the total energy mix to ensure a substitution impact.

Moreover, since it is defined that TPU and GPR have a much stronger impact on CO_2 emissions in the USA than in China, it is critical for USA policymakers to consider this fact. Accordingly, trying to ensure a collaboration with China is highly critical for USA policymakers so that a change in TPU and GPR cannot cause an adverse impact on the CO_2 emissions of the USA. The same thing is valid for the interaction of TPU and GPR with each other. On the other hand, although a change in TPU and GPR cannot cause an adverse impact on CO_2 emissions of China, China needs to cooperate with the USA and other countries so that China can contribute to preserving the global environment, not only China's.

In sum, to meet sustainability goals even in uncertain times, there must be policies that support both the expansion of the use of renewable energy and the protection of environmental ventures from trade and geopolitical turmoil.

5.3. Limitations and Future Research Directions

Despite the study's aims to include a broad scope, it has some limitations as well.

Firstly, while employing data daily indicates short-run shifts, it is bound to overlook long-run shifts in environmental performance and energy policy. So, it is suggested that new studies consider using both high and low-frequency data simultaneously.

Secondly, it may be difficult to generalize the findings to other countries, given that the study focuses on the USA and China. Accordingly, new studies can consider including many more developed and developing countries simultaneously so that the findings can be validated to generalize to other countries.

Thirdly, while the KRLS approach can effectively model nonlinearities, it fails to capture interdependencies among the variables. Therefore, new studies can consider applying other novel econometric techniques (e.g., Wavelet & Fourier-based ones as well as dynamic causal models with machine learning) so that different econometric perspectives can be included in new empirical analysis.

Fourthly, more understanding of the complex interplay among trade, geopolitical uncertainty, and environmental sustainability can be achieved by the incorporation of such other determinants as financial instability, technological innovation, and policy response.

By considering the aforementioned limitations, future studies can proceed with the analysis of other countries and consider other econometric models.

Author Contributions

M.T.K.: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project Administration; Resources; Software; Supervision; Validation; Visualization; Writing – original draft; Writing – review & editing. D.K.: Writing – original draft; Writing – review & editing. D.T.: Writing – original draft; Writing – review & editing. S.K.D.: Writing – original draft; Writing – review & editing. S.A.A.: Writing – original draft; Writing – review & editing. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Use of AI and AI-Assisted Technologies

During the preparation of this work, the authors have not used AI/AI-assisted technologies.

Supplementary Material

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Acronyms	
AMI	Average Marginal Impact
BDS	Broock, Scheinkman, Dechert, and LeBaron
CO_2	Carbon Dioxide
EC	Electricity Consumption
EG	Electricity Generation
GPR	Geopolitical Risk
KRLS	Kernel Regularized Least Squares
OLS	Ordinary Least Squares
PMI	Pointwise Marginal Impact
FEG	Fossil EG
REG	Renewable EG
TPU	Trade Policy Uncertainty

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