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Charting a Sustainable Future: The Impact of Economic Policy, Environmental Tax, Innovation, and Natural Resources on Clean Energy Consumption

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Abstract: Energy availability, especially derived from renewable sources, has sustainable effects on economic progress and environmental rectifications. However, using clean energy in the energy mix has been influenced by several macro fundamentals. The motivation of this study is to gauge the impact of uncertainties, environmental restrictions, and innovation on clean energy consumption for the period 1997–2021 by employing the new econometrical estimation techniques commonly known as CUP-FM and CUP-BC. Referring to the preliminary assessment with the slope of homogeneity, cross-sectional dependency, and the panel cointegration test, it is unveiled that research variables have exposed heterogeneity prosperities, cross-sectional dependence, and long-run association in the empirical equation. According to the empirical model output with CUP-FM and CUP-BC, EPU has a native statistically significant connection to clean energy consumption. At the same time, environmental tax and technological innovation have found beneficial effects on clean energy development. Additionally, the nonlinear estimation disclosed an asymmetric linkage between explanatory and explained variables in the long and short-run. Directional causality revealed a feedback hypothesis explaining the relationship between EPU, TI, and clean energy consumption. This study has offered policy suggestions based on the findings for future development.

Keywords: economic policy uncertainty; technological innovation; environmental tax; clean energy; CUP-FM; CUP-BC; NARDL; DH-causality

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1. Introduction

The global economy is presently experiencing transformative events that bear significant implications for climate change and introduce diverse political and economic uncertainties. In light of the current challenges, diligent researchers thoroughly analyze these issues to enhance and fortify the global economy. Energy has recently garnered significant focus as a crucial component in fulfilling fundamental human necessities and propelling economic development. However, although the existing body of literature on the relationship between energy and economic performance is growing, there is still a dearth of research specifically focused on the intersection of energy and economic policies, particularly in relation to economic policy uncertainty (EPU, hereafter) and its impact on energy consumption. Economic policy uncertainty pertains to an atmosphere of uncertainty engendered by governmental determinations regarding regulatory, monetary, and fiscal policies, exerting subsequent influence on economic outcomes and interactions. When confronted with elevated levels of policy uncertainty, economic agents, such as firms, are inclined to reassess their economic decisions. For example, companies may choose to defer their investment plans. At the same time, consumers may opt to postpone their consumption, saving, and investment decisions. In an uncertain economic environment, policies about the public and financial sectors can weaken, resulting in the postponement of environmental initiatives to alleviate consumption pressure. Moreover, companies tend to utilize conventional and cost-effective energy sources in their production processes due to heightened policy uncertainty, offsetting reduced turnovers. On the contrary, firms increasingly embrace cleaner energy sources as net income rises, enhancing environmental quality.

The present study has considered EPU, environmental tat (ET, hereafter), Technological Innovation (TI, hereafter), and Natural resources (NR, hereafter) in the equation of clean energy consumption. The existing literature on the correlation between policy uncertainty and the environment indicates favorable and unfavorable consequences within an open economy. Several studies have posited that policy uncertainty harms energy investment and consumption, reducing emissions and enhancing environmental quality (commonly called the consumption effect). However, these studies also suggest that policy uncertainty may impede investment in green projects and renewable energy sources, leading to a potential rise in emissions (referred to as the investment or substitution effect). Therefore, it remains an empirical question to determine which effect predominates in an economy. In a recent study by Pirgaip and Dinçergök [1], an investigation was carried out to explore the dynamic associations among EPU uncertainty, energy consumption, and CO_2 emissions for G7 economies spanning 1998 to 2018. The researchers employed panel Granger causality analysis as their methodology. The research findings unveiled a unidirectional causality relationship between Economic Policy Uncertainty (EPU) and energy consumption in Japan, the United States of America, Germany, and Canada. However, it is worth noting that Italy has exhibited a bidirectional causality pattern in this regard. Based on the findings presented, the authors strongly recommend that G7 economies carefully consider the detrimental effects of EPU on energy conservation and take proactive measures to transition towards cleaner energy sources. The advancement and promotion of renewable energy sources are intricately tied to the progress and investment in financial development. Investments have demonstrated a noteworthy correlation with technology transfer from innovating nations to their host countries [2,3]. In contrast to conventional energy sources, producing renewable energy necessitates more significant capital incentives [4–7].

The complex relationship between environmental taxation and the utilization of clean energy is a crucial determinant in shaping the course of sustainable development. Implementing an environmental tax, regarded as an economic instrument, internalizes the external costs associated with pollution and resource depletion [8]. Additionally, environmental taxation incentivizes companies and individuals to adopt more sustainable energy sources by implementing fees on carbon emissions and other harmful pollutants [8–10]. The transition towards cleaner energy sources is paralleled by an increase in the utilization of clean energy, thereby facilitating the transition away from carbon-intensive fossil fuels [8–13]. Moreover, the implementation of effective environmental tax legislation not only promotes the adoption of well-established clean energy technologies, but also fosters a conducive environment for the advancement of innovative green energy solutions. The potential allocation of proceeds from environmental taxes towards research and development endeavors related to renewable energy technology can provide crucial financial support to foster innovation and improve efficiency [8–16]. Furthermore, the correlation between environmental taxation and the utilization of clean energy facilitates a mutually beneficial process of promoting sustainability. The increase in the utilization of clean energy is correlated with a reduction in levels of pollution and emissions of greenhouse gases, leading to improved air quality and overall environmental welfare. Therefore, this phenomenon significantly contributes to the improvement of the general well-being of individuals, resulting in various health benefits and reducing healthcare costs associated with environmental pollution [7,17,18]. Environmental tax policies are pivotal in the economy as they incentivize firms and individuals to shift towards more sustainable energy alternatives. This, in turn, fosters the development of innovative technologies. The subsequent increase in the utilization of clean energy contributes to mitigating climate change impacts, improving environmental conditions, and advancing a sustainable and resilient future for future generations. Society can expedite the transition towards a more environmentally sustainable energy landscape by actively embracing and strategically improving this intricate and interdependent connection. Considering the variables in the equation, this study has intended to evaluate the following hypothesis.

H1. *Economic policy has a detrimental effect on clean energy inclusion;*

H2. *Environmental tax fosters the development of clean energy in the energy mix;*

H3. *Technological innovation has a contributory effect on clean energy inclusion.*

The imperative to transition towards a sustainable future, marked by adopting clean energy sources, has grown urgently due to the escalating challenges of global climate change and environmental degradation. Understanding the complex interplay among various factors that influence clean energy consumption is of utmost importance for policymakers, corporations, and academics as they strive to devise effective solutions to tackle these challenges. The research is motivated by the necessity to understand the interplay between economic policy uncertainty, environmental tax, technical innovation, and natural resources in their impact on adopting clean energy. By comprehensively analyzing the interrelated factors, this research aims to offer innovative insights into the determinants of clean energy adoption. Moreover, it seeks to significantly contribute to developing targeted policies and interventions that promote the sustainable utilization of energy resources.

The present research significantly contributes to the existing literature on clean energy consumption and sustainable development through various means: First, the research employs a comprehensive methodology to understand the complexities of clean energy consumption. This is achieved by incorporating various factors, including economic policy uncertainty, environmental tax, technical innovation, and natural resources. The comprehensive analysis presented in this research enhances the understanding of the intricate interconnections and synergistic impacts among different factors, thereby bolstering the scholarly contribution of the study. Second, the present study employs state-of-the-art estimation techniques: the Continuously Updated Fully Modified (CUP-FM) and Continuously Updated Bias-Corrected (CUP-BC) panel estimation approaches. The utilization of advanced econometric methodologies effectively addresses various issues about panel data, encompassing cross-sectional dependency, endogeneity, and serial correlation. Consequently, these methodologies yield more robust and reliable estimations regarding the relationships among the variables under investigation. Third, this study's comprehensive understanding of the various factors that influence REC holds substantial policy implications for policymakers and stakeholders within the energy sector. The findings of this study possess the potential to offer valuable insights for the formulation of impactful strategies aimed at promoting the utilization of renewable energy sources and advancing sustainable practices in energy consumption.

The motivation of this study is to gauge the effects of EPU, TI, ET, and natural resources on clean energy consumption through the execution of advanced panel data estimation commonly known as CUE-HM and CUP-BC. According to the study findings, technological innovation and environmental taxes are positively tied to clean energy, while EPU and natural resources established an adverse linkage with clean energy. Moreover, the causality revealed a feedback association between TI and clean energy, whereas there was unidirectional causality for the rest of the assessment.

2. Literature Review and Hypothesis Development

2.1. Economic Policy Uncertainty and Renewable Energy Consumption

The clean energy sector has emerged as a pivotal industry that drives economic development and has become an integral part of the rapidly changing and complex economic landscape. The momentum of REC holds considerable importance in facilitating economic growth. The decisions made by enterprises concerning clean investments are intricately linked to changes in economic policies, thereby impacting the consumption patterns of both conventional and renewable energy sources. The literature elucidates the intricate relationship between economic policy uncertainty, conventional energy consumption, and adopting renewable energy sources [1]. Significantly, studies such as Gong Gong [19] have examined the potential impact of changes in monetary policy on the level of investments in clean energy. A loose monetary policy can potentially stimulate investment in clean energy enterprises. In contrast, a tight monetary policy could impede such economic investments. Similarly, the work of Ju, et al. [20] provides insight into the impact of fiscal and monetary policy adjustments on clean energy investments. Their research underscores the significance of maintaining economic policy stability in shaping enterprises' investment behavior and risk perceptions [21]. Johnson and Kwak [14] emphasize the significant impact that the timing, direction, and content of economic policy changes can have on the decision-making behavior of consumers and enterprises. These changes can foster a sense of caution among individuals and businesses, particularly during periods of uncertainty. Therefore, it can be inferred that economic policy uncertainty significantly influences the operations of renewable energy enterprises, affecting both the supply and demand aspects of the renewable energy market [22]. Economic policy uncertainty, which refers to the condition marked by the unpredictability surrounding potential modifications to existing economic policies by government authorities, plays a crucial role in influencing the clean energy sector. The presence of uncertainty regarding economic policies has a significant impact on the strategic decisions made by enterprises that operate within the renewable energy sector. Consequently, this uncertainty has a ripple effect on renewable energy's supply and demand dynamics [23,24].

Khan and Su [25] focus on the implications of economic policy uncertainty (EPU) on renewable energy (RE) in G7 nations from January 2000 to December 2020. The results show that EPU disrupts macroeconomics and lowers RE across all quantiles. This effect is more substantial in upper quantiles, suggesting that increased EPU quickly affects RE. As the relationship lengthens, EPU's impact decreases in Germany, but increases in Italy, Japan, the UK, and the US. Economic stability is achieved by transparent policymaking and stakeholder involvement in planning, implementing, and modifying economic policies for sustainable RE development. Similar findings are available in the study of Refs. [26–28]. Zhang, et al. [29] review the mediating function of foreign direct investment (FDI) and financial development (FD) in BRIC nations from 1997q1 to 2018q4 to shed light on the relationship between economic policy uncertainty (EPU) and REC. The data were analyzed using unit root, cointegration, and non-granger causality tests. Results show that EPU hurts REC both long-term and short-term. In contrast, FDI and FD positively affect REC, demonstrating that financial sector expansion and foreign investment can improve renewable energy integration. The study also shows long-term asymmetry between EPU, FDI, and FD on REC. The findings suggest that FDI and financial development promote clean energy adoption by advancing renewable energy technology and capital investments. The same vein of evidence is available in the findings of Zhang and Razzaq [9]. Nakhli, et al. [30] evaluate US economic policy uncertainty, renewable/non-renewable electricity use, and CO_2 emissions. Using monthly data from 1985 to 2020 and the Bootstrap Rolling method, they found a one-way causal link between energy consumption and economic policy uncertainty and a bidirectional causation between CO_2 emissions and uncertainty. Parameter estimations are unstable in three models. The research promotes US SDGs 7, 10, and 13 by promoting climate-aware policies for carbon neutrality, energy security, clean energy, and sustainable production. Policymakers should consider uncertainty while creating environmental legislation. This 1990–2021 study by Rong and Qamruzzaman [31] examined how economic policy uncertainty, oil prices, and technological progress affected REC in the top five oil-importing nations. The linkages and variable effects were examined using linear and nonlinear frameworks. Technology and oil price volatility boosted renewable energy use, whereas economic policy uncertainty hurt it, especially over time. Technology, economic policy uncertainty, and renewable energy demand were asymmetrically linked. The study also revealed feedback linkages between oil prices, economic policy uncertainty, technology innovation, and REC. The results show that energy policy must include oil pricing and economic stability to promote energy transition Zeng and Yue [32]. This research by Shafiullah, Miah, Alam, and Atif [11] presents a nonparametric econometric analysis of economic policy uncertainty and US renewable energy usage. The study finds nonlinearity and structural changes in models using monthly data from 1986 to 2019. Nonparametric unit root tests show nonlinear cointegration and variable nonstationarity. Robust Granger causality analysis shows a bidirectional nonlinear causation between policy uncertainty and renewable energy variables, except geothermal energy. In the long run, nonparametric regressions show that economic policy uncertainty decreases REC and vice versa. The results of this analysis suggest consistent US economic policy to promote renewable energy usage, which is supported by Lu, et al. [33]. The study of Amin and Dogan [34] investigates EPU's position in China's energy-environment interaction from 1980 to 2016. Real income and energy intensity increase pollute the environment, but renewable energy growth reduces emissions, according to unique bounds testing with dynamic simulations. Increased EPU increases carbon emissions. Elevated EPU may distract from environmental efforts. To effectively reduce pollution, economic and environmental policies must be aligned for environmental sustainability (Zakari, et al.) [35]. Some studies contradict the above findings, conveying a positive association between EPU and REC. Refs. [36–39] explore economic policy uncertainty's impact on energy-growth-emissions in 32 Sub-Saharan African nations from 1996 to 2014. Using a one-step system-GMM, real GDP and non-renewable energy contribute to CO_2 emissions. Interestingly, economic policy uncertainty increases emissions and moderates energy generation, reducing emissions. This emphasizes the region's need for strong macroeconomic and energy policies to maintain energy stability, environmental protection, and sustainable growth.

2.2. Environmental Tax and Clean Energy Consumption

Environmental taxes motivate individuals and corporations to adopt renewable energy sources [40]. Governments have the potential to effectively steer society towards sustainable habits through the implementation of tariffs on activities that are ecologically detrimental, as well as by providing incentives for clean energy alternatives [41]. Research has demonstrated that implementing environmental tax policies yields positive results regarding carbon emissions mitigation and promoting renewable energy utilization [7,42–44]. Using renewable energy sources plays a key role in effectively tackling environmental issues, including but not limited to climate change and air pollution. Environmental taxes have become prominent instruments of policy that aim to address the issue of external costs associated with pollution and encourage the use of greener energy options. This literature review delves into the correlation between environmental tax policies and the usage of renewable energy. It examines the empirical data and theoretical viewpoints presented in a range of research. A plethora of scholarly investigations have been conducted to examine the impact of environmental levies on the usage of renewable energy [3,7,40,40,44–46]. For instance, Wang and Zhang [47] analyzed the effects of carbon taxes on adopting renewable energy in China. Their findings indicate a positive relationship between carbon prices and REC. In a similar vein, the impact of environmental tax changes in South Korea was examined by Oke, Ibrahim, and Bokana [12], who saw a notable rise in the use of renewable energy after the enactment of the tax reform. The impact of diverse environmental tax schemes on the usage of renewable energy might vary.

Several research projects have examined the correlation between environmental levies and additional incentives for renewable energy. In a study conducted by Wang, et al. [48], the authors examined the synergistic impact of feed-in tariffs and environmental levies on using renewable energy resources inside China. The researchers discovered that the two regulations had a synergistic effect, resulting in a more substantial augmentation in the use of renewable energy compared to the impact of each policy in isolation. Raihan, et al. [49] conducted a study examining the transportation sector. The researchers discovered that implementing environmental taxes proved to be a successful strategy in encouraging the uptake of electric cars and other environmentally friendly modes of transportation. Comparative analyses conducted across many nations have provided insights into the efficacy of several environmental taxation strategies in promoting renewable energy sources. In their study, Liu, et al. [50] performed comparative research across many countries to ascertain the optimal strategies in environmental tax policy that resulted in increased adoption of renewable energy sources in various geographical areas.

Several studies have investigated the relationships between different factors and their influence on the consumption of clean energy and the sustainability of the environment. In their study, Sharif, et al. [51] investigate the impact of green energy investment, environmental tax, and economic growth on green technology innovation in the ASEAN-6 countries. The study's findings demonstrate that green energy and investment positively impact the advancement of green technology innovation. Additionally, it is observed that economic development and the implementation of environmental taxes also contribute to promoting such innovation. In their study, Refs. [3,52,53] delve into the multifaceted realm of energy efficiency, green technology, environmental taxes, and natural resources within the OECD countries. The study demonstrates that the implementation of environmental taxes and the adoption of green technology have a positive influence on both energy efficiency and intensity. Moreover, Behera and Sethi [54] delve into the relationship between China's clean energy development and economic growth. The findings of their study reveal that the production of clean energy plays a significant role in stimulating economic growth, particularly in well-developed regions. Furthermore, their research highlights the positive impact of market-based environmental regulation on improving clean energy initiatives.

In their study, Fang and Qamruzzaman [55] examine the relationship between environmental tax and the utilization of renewable energy in countries along the Belt and Road. The study uncovers a reciprocal correlation between environmental tax and the utilization of renewable energy. They propose policy recommendations to enhance environmental quality and formulate sustainable energy policies, considering the non-linear impact of environmental taxes on REC. In their comprehensive analysis, Meng, et al. [56] examine the effects of green growth on various key factors, including CO_2 emissions, human capital, environmental technology development, and environmental levies, within the G7 countries. The study's findings support the theory that green growth is conducive to maintaining environmental quality. Moreover, these findings offer valuable insights that can inform policymakers actively advocating for the promotion of green growth. A similar vein of findings is available in the Refs. [57–59].

2.3. Technological Innovation and REC

The relations between technical innovation and the utilization of clean energy are a crucial factor in the endeavor toward sustainable development and climate change mitigation. There exists a significant amount of research within the academic literature that provides strong evidence supporting the positive correlation between these two variables. An example can be found in a recent study Johnstone, et al. [60], which emphasizes the importance of technological innovation in enabling the transition to renewable energy sources. The authors emphasized the significance of continuous research and development in enhancing the efficacy of renewable energy technologies and reducing their costs. This, in turn, enhances their attractiveness to both investors and consumers. Furthermore, the research conducted by Popp, et al. [61] examined the impact of technical innovation on the utilization of renewable energy in various countries. The study's findings indicate that countries with high levels of technical innovation in the clean energy sector are more likely to adopt renewable energy sources. The research underscored the paramount significance of innovation in effectively addressing the impediments to implementing renewable energy and expediting the transition away from fossil fuels.

Many studies show a positive linkage between technological innovation and REC. Fang [62] addresses factors determining carbon dioxide emissions in 32 Chinese provinces from 2005 to 2019. Economic complexity index, energy sector investments, green technological innovation, and industrial structure growth are examined. Data analysis uses advanced econometric methods such as cross-sectional dependency, unit root, co-integration, and GMM models. The results show that the economic complexity index increases carbon dioxide emissions, while the square, renewable energy, green technology, and industrial structure minimizes emissions. The study suggests effective carbon abatement policies for China. Sibt-e-Ali, et al. [63] also investigated the effects of technological innovation (TI), natural resources, globalization, and REC on East and South Asian environmental degradation from 1990 to 2021. Globalization, TI, and REC minimize regional emissions, while many natural resources degrade the environment. Economic expansion degrades environmental quality. The report suggests that regional governments promote efficient natural resource use through technology breakthroughs and integrate energy consumption, globalization, and economic growth policies with sustainable environmental goals. Refs. [41,64–66] investigated the effects of renewable energy technology innovation and industrial structure upgrading on green development in 30 provinces and localities in China from 2013 to 2019 using a spatial Durbin model (SDM). The results indicate that innovation in renewable energy technology and rationalizing the industrial structure have positively affected green development. In contrast, advancement in the industrial structure has a negative effect. Liu, et al. [67] probe how the Emerging Seven economies could accomplish Sustainable Development Goals (SDGs) while tackling environmental deterioration. From 1996 through 2018, researchers examined how renewable energy usage, institutional quality, technical innovations, economic growth, and population affected carbon emissions. Renewable energy, technological innovation, and institutional quality can lower carbon emissions, while economic expansion and population growth increase them. These economies required SDG-oriented strategies for sustainable development. This study by Zheng, et al. [68] examines 1980–2019 electricity consumption in Pakistan's agricultural, commercial, industrial, and residential sectors. Dynamic ARDL simulation, Cumulative Fourier Frequency Domain Causality, and structural break estimation show how technological innovation affects commercial and industrial energy use. Institutional performance and public-private partnerships boost industrial productivity. Pakistan's energy infrastructure issues require knowledge of energy governance and policy. This research by Su, et al. [69] uses the Wavelet-Based quantile on quantile approach to examine how REC and technical innovation (TI) affect U.S. CO_2 emissions. The data demonstrate that REC can prevent environmental damage by lowering emissions. Compared to REC, TI reduces emissions less. Enterprises should prioritize environmental awareness, and TI should be connected to REC to reduce energy consumption and carbon footprint. The government should also encourage renewable energy use, especially in high-emission areas, which aligns with Refs. [70–73]. In this study, Khan, et al. [74] and this research by Adebayo, et al. [75], they employ Morlet wavelet analysis to show how CO_2 emissions, economic development, renewable energy use, trade openness, and technical innovation in Portugal from 1980 to 2019 are dynamically linked. The frequency domain shows wavelet coherence and lead and lag linkages, while the time domain shows opposing interactions. Trade openness, technical innovation, and economic expansion increase CO_2 emissions, whereas renewable energy usage reduces them over time. To address environmental concerns, Portuguese policymakers should promote investment in renewable energy sources, implement restrictive legislation, and enhance energy innovation. This study by Zang, Adebayo, Oladipupo, and Kirikkaleli [64] creates an SDG framework for Spain to achieve SDGs. It analyzes GDP growth, technological innovation, and renewable and non-renewable energy sources' effects on CO_2 emissions from 1980 to 2018 in the EU. Positive shocks in renewable energy and technical innovation improve environmental quality, but positive shocks in energy consumption increase CO_2 emissions, according to the non-linear ARDL approach. A similar line of evidence can be found in Refs. [76–78] analyze renewable energy production in specific Latin American countries from 1991 to 2014. It finds that GDP, technological innovation, and trade positively affect renewable energy, while carbon emissions have adverse effects. The research recommends promoting innovation and commerce for sustainable energy policies. Khan, et al. [79] explore Germany's technological advances and renewable energy. Technology developments substantially affect renewable energy from 2000 to 2021. The rolling window method shows that technological advancement positively and disastrously affects renewable energy over time. Renewable energy also affects technology innovations, implying that breakthroughs promote technology innovation investment. The study stresses the need to balance weather-related energy sources in future energy supplies. Sharma, et al. [80] deal with the implications of export diversification, vast and intensive export margins, technological innovation, income inequality, and capital formation on BRICS renewable energy demand from 1990 to 2018. Export diversification, traditional exports, technological innovation, and capitalization increase renewable energy use, whereas new product exports and income disparity decrease it. The report emphasizes greener energy options and equitable income distribution for sustainable development

Moreover, technological progress has not only led to decreased costs and improved efficiency, but has also played a pivotal role in facilitating the smooth incorporation of renewable energy sources into existing energy systems. Smart grids have emerged as a groundbreaking technology integrating diverse energy sources, including renewable energy, into the electrical system. Elucidated the importance of smart grid technologies in enhancing the stability and reliability of clean energy systems, promoting higher levels of clean energy utilization. Additionally, the emergence of technological advancements in energy storage solutions has successfully addressed a substantial challenge linked to renewable energy, specifically its intermittent characteristic. The utilization of cutting-edge battery storage systems has facilitated the efficient storage of excess energy generated during heightened demand, thereby ensuring a reliable provision of eco-friendly electricity even when renewable energy generation is diminished. Chang, et al. [81] conducted a study that emphasized the importance of energy storage technologies in improving the reliability of renewable energy systems and their contribution to improving clean energy utilization.

A summary of the literature survey is displayed in Table 1.

Table 1. Summary of literature review.

Authors	Sample (Year)	Methodology	EPU	ET	TI
Abbas, Wang, Belgacem, Pawar, Najam, and Abbas [52]	Chinese energy enterprises (2012–2021)	Empirical research models		Positive	
Zang, Adebayo, Oladipupo, and Kirikkaleli [64]	EU (1980–2018)	CS-ARDL technique			
Sibt-e-Ali, Weimin, Javaid, and Khan [63]	East and South Asian countries (1990–2021)	CS-ARDL estimator			Positive
Fang [62]	32 Chinese provinces (2005–2019)	CSD, GMM			Positive
Lei, Liu, Hafeez, and Sohail [26]	China (1990–2019)	NARDL	Negative		
Li, Su, Moldovan, and Umar [28]	eight leading U.S. newspapers	CS-ARDL	Negative		
Liu, Ali and Cong [27]	BRICS (1990–2020)	PQR	Negative		
Hussain, et al. [82]	top five carbon-emitting nations	CS-ARDL	Negative		
Shayanmehr, Radmehr, Ali, Ofori, Adebayo, and Gyamfi [45]	world's top renewable energy consuming nations (1994–2018)	DOLS, FMOLS, and panel GMM analyses		Positive	
Khan and Su [25]	G7 countries (January 2000 to December 2020)	Wavelet analysis	Negative		
Sharif, et al. [83]	ASEAN-6 countries (1995–2018)	CS-ARDL method, AMG,		Positive	
Yasmeen, Zhang, Tao, and Shah [3]	36 OECD	SBM model,		Positive	
Zhang and Razzaq [9]	BRICST	CUP-FM), CUP-BC estimators	Negative		
Qayyum, et al. [84]	India (1980–2019)	FMOLS, DOLS, VECM			Positive
Adebayo, Oladipupo, Adeshola, and Rjoub [75]	Portugal (1980–2019)	Morlet wavelet analysis			Positive
Khan, et al. [85]	(BRI) nations (2000–2014)	GMM			Negative
Sharma, Shahbaz, Kautish, and Vo [80]	BRICS (1990–2018)	ADF, CS-ARDL			Positive
Hasanov, et al. [86]	BRICS countries (1990–2017)	CS-ARDL			Positive
Vural [78]	Latin American (1991–2014)	CIPS, ADF, CADF			Positive
Ibrahim and Ajide [77]	G-7 countries (1990–2019)	CS-ARDL			Positive
Su, Umar and Khan [69]	US	Wavelet-Based quantile			Positive

Table 1. *Cont.*

Authors	Sample (Year)	Methodology	EPU	ET	TI
Su and Fan [66]	China (2013–2019)	SDM			Positive
Khattak, et al. [87]	BRICS (1980–2016)	CCEMG			Positive
Obobisa, Chen, and Mensah [72]	25 African countries (2000–2018)	AMG			Positive
Saudi [88]	Malaysia (1980–2017)	ARDL			Positive
Doğan, et al. [89]	G7 countries (1994–2014)	DOLS, FMOLS		Positive	
Zang, Adebayo, Oladipupo, and Kirikkaleli [64]	EU (1980–2018)	NARDL			Positive
Khan, Su, Rehman, and Ullah [79]	Germany (2000–2021)	The rolling window method			Positive
Sun, Bao, Siao-Yun, ul Islam, and Razzaq [65]	BRICS (1995–2018)	MMQ regression			Positive
Khan, Weili, and Khan [74]	BRICS (1990–2019)	VECM			Positive
Jiang and Khan [71]	belt and road initiative countries (1995–2019)	GMM models			Positive
Liu, Anwar, Razzaq, and Yang [67]	Turkey, Brazil, Mexico, Indonesia, Russia, India and China (1996–2018)	STIRPAT model			Positive
Habiba, Xinbang, and Anwar [73]	the top twelve emitters (1991–2018)	GMM			Positive
Fang, Yang, Tian, and Ma [40]	Fifteen typical countries along the Belt and Road (1998–2019)	ARDL		Positive	
Wolde-Rufael and Mulat-Weldemeskel [46]	18 Latin American and Caribbean countries (1994–2018)	MMQR, AMG,		Positive	
Xie and Jamaani [90]	G-7 economies (1990–2020)	MMQR, and D-H Causality		Positive	
Chu and Le [36]	G7 countries (1997–2015)	FMOLS, fe	Positive		
Feng and Zheng [37]	22 countries (1985–2019)	Cs-ardl	Positive		
Rafique, et al. [91]	29 OECD countries (1994–2016)	ARDL, DOLS, FMOLS,		Positive	
Nakhli, Shahbaz, Jebli, and Wang [30]	US (1985M1 to 2020M12)	Bootstrap Rolling approach	Negative		
Shafiullah, Miah, Alam, and Atif [11]	USA (1986–2019)	nard	Negative		
Amin and Dogan [34]	China (1980–2016)	DARDL	Negative		
Zeng and Yue [32]	BRICS (1991–2019)	NARDL	Negative		
Zakari, Adedoyin, and Bekun [35]	22 OECD countries (1985–2017)	PMG-ARDL	Negative		
Lu, Zhu, Lau, Isah, and Zhu [33]	Brazil (1970–2019), Germany (1971–2019), Japan (1970–2019), and the United States (1965–2019)	empirical model	Negative		
Bashir, Ma, Bashir, Radulescu, and Shahzad [42]	29 OECD countries (1996–2018)	FMOLS, QREG		Negative	
Shahzad, et al. [92]	29 developed countries (1994–2018)	FMOLS		Positive	
Adedoyin, Ozturk, Agboola, Agboola, and Bekun [39]	32 Sub-Saharan African countries (1996–2014)	GMM	Negative	Positive	
Ghazouani, et al. [93]	prominent European economies (1994–2018)	FMOLS		Positive	
Chien, et al. [94]	US (1970–2015)	QARDL		Positive	
Chien, et al. [95]	leading Asian economies (1990–2017)	CSD, CD		Positive	
Hsu, et al. [96]	China (1980–2018)	WDI		Positive	
Liu, He, Liang, Yang, and Xia [38]	52 traditional energy companies and 116 renewable energy companies (2007Q1–2017Q4)	QARDL	Positive		
Miceikiene, et al. [97]	USA, Japan, People's Republic of China, Norway and Turkey (1994–2015)	GMM		Positive	
Chen and Lei [76]	30 global countries (1980–2014)	QREG			Positive

2.4. Justification of the Study

It is of utmost importance for policymakers and investors to fully grasp the impact of economic policy uncertainty on the utilization of renewable energy. Economic stability and predictability factors significantly impact investment decisions within the renewable energy sector. The research aims to shed light on the potential impact of policy initiatives in fostering a conducive environment for investments in renewable energy. This will be achieved by investigating the relationship between economic policy uncertainty and the adoption of clean energy technologies. Secondly, implementing environmental taxes is a highly effective market-based incentive to internalize the external costs associated with pollution and promote the adoption of cleaner energy sources. The research may provide valuable insights into the effectiveness of market-based incentives in facilitating the transition to renewable energy. This will be achieved by analyzing the influence of environmental taxes on adopting clean energy sources. Thirdly, it is imperative to acknowledge that technological progress is pivotal in facilitating the widespread adoption of sustainable energy. Insight into the impact of technological advancements on using clean energy can potentially enhance research and development strategies within the renewable energy sector. As a result of this, the accessibility and prevalence of sustainable energy technology may potentially increase. Countries have a competitive advantage in adopting renewable energy technology owing to their ample natural resources for clean energy generation. The research aims to identify areas with the highest potential for adopting renewable energy sources. By examining the impact of natural resources on clean energy usage, this study seeks to enhance energy security and economic advantages.

The consumption of clean energy is a crucial component of global endeavors aimed at mitigating the rate of climate change. The research provides valuable insights into the potential impact of policies and technologies on expediting the transition to low-carbon energy sources. This, in turn, contributes to reducing greenhouse gas emissions and mitigating global warming. When comparing renewable energy sources to fossil fuels, it can be observed that the former poses significantly less harm to the environment. Regulations must prioritize sustainable energy production and consumption to safeguard ecosystems and preserve biodiversity. Furthermore, comprehending the underlying factors that drive individuals to adopt such practices is paramount. The purpose of environmental pricing is to dissuade the utilization of carbon-intensive fuels and reduce pollution levels on a broader scale. The assessment conducted by the study regarding the impact of environmental taxes on the utilization of clean energy serves to illuminate the significance of these policies in promoting the adoption of cleaner and less environmentally harmful energy sources. Energy diversity and reduced dependence on imported fossil fuels are advantages of prioritizing clean energy. The research aims to shed light on potential strategies for enhancing energy security by implementing a sustainable energy mix. This will be achieved by thoroughly examining the influence of technological advancements and natural resources on adopting and utilizing clean energy sources. The economic and environmental rationales underlying the study ultimately reside in its capacity to inform evidence-based policies aimed at fostering the uptake of clean energy, addressing economic and environmental challenges, and advancing the global pursuit of sustainability and a low-carbon future. The research aims to establish a foundation for a sustainable and resilient energy system through an examination of the interplay between economic policy uncertainties, environmental taxation, technical innovation, and natural resources about the utilization of clean energy.

3. Data and Methodology of the Study

3.1. Model Specification

A panel of 21 nations, i.e., Australia, Brazil, Canada, Chile, Colombia, France, Germany, Greece, India, Ireland, Italy, Japan, Korea, Netherlands, Russia, Spain, UK, US, China, Sweden, Mexico, for the data period 1997–2021 has been considered for the empirical estimation.

$$\text{REC} \mid \text{EPU, ET, and TI} \tag{1}$$

where REC and EPU stand for REC and economic policy uncertainty, respectively, the above Equation (1) has extended with the inclusion of three macro fundamentals critical in developing clean energy in the energy mix: technological innovation, environmental tax, and foreign direct investment. The revised Equation (1) is as follows:

$$\text{REC} \mid \text{EPU, TI, ET, NRR \& FDI} \tag{2}$$

After transformation with a natural log, the above equation can be rewritten into a panel regression form in the following manner.

$$REC_{\{it\}} = \beta_0 + \beta_{1EPU_{\{it\}}} + \beta_{2TI_{\{it\}}} + \beta_{3ET_{\{it\}}} + \beta_{4NRR_{\{it\}}} + \beta_{5FDI_{\{it\}}} + \varepsilon_{\{it\}}, \quad (3)$$

The coefficients (β_1, β_2, β_3, β_4, β_5) will provide insight into both the direction and magnitude of the relationship between each independent variable and REC. It is important to note that these coefficients are adjusted to account for any potential influence from other factors that could impact REC. The error term ($\varepsilon_{\{it\}}$) encompasses the latent variables that impact REC but have not been incorporated into the model.

Higher economic policy uncertainty is expected to have a negative impact on renewable energy usage since it might generate a less stable investment environment. Increased uncertainty may discourage investors from investing in long-term projects such as renewable energy programs [98]. Technological progress is projected to have a favorable influence on renewable energy use. Clean energy technologies become more appealing to consumers and investors as they grow more efficient and cost-effective, leading to increasing adoption rates [99–101]. Environmental taxes are intended to encourage the adoption of greener energy sources while discouraging carbon-intensive activities. As a result, a positive coefficient for environmental tax implies that higher environmental taxes boost renewable energy usage as firms and consumers choose cleaner options [102,103]. Countries with abundant renewable energy generation resources (e.g., solar, wind, hydro) may have a competitive edge in clean energy adoption. As a result of a positive coefficient for the natural resource effect, nations with abundant renewable resources tend to use more renewable energy [8,48]. Foreign direct investment may offer finance, technology, and knowledge, speeding up the development and implementation of renewable energy projects. A positive FDI coefficient implies increasing FDI inflows are connected with increased REC Soytas [104].

3.2. Variables Definitions and Economic Justification

Economic policy uncertainty is pivotal in the relationship between REC and various economic variables. It is the gauge of uncertainty. Economic uncertainties can impact investment decisions and consumer behaviors, influencing the adoption and utilization of renewable energy sources. During periods characterized by heightened economic policy uncertainty, stakeholders, including policymakers, corporations, and investors, may hesitate in allocating resources toward initiatives related to renewable energy. Likely, an increase in economic policy uncertainty would negatively affect the utilization of renewable energy. Business enterprises and investors may display risk-averse behavior, leading to a reduction in the allocation of funds towards initiatives related to renewable energy. During periods characterized by economic instability, it is plausible that the growth and utilization of renewable energy sources may experience a deceleration.

Implementing an environmental tax is a strategic initiative the government undertakes to internalize the external costs associated with pollution and foster adopting environmentally sustainable practices. The incorporation of ET into the equation for REC is justified, as it symbolizes the monetary motivation that seeks to encourage the adoption of cleaner energy sources while discouraging carbon-intensive practices. It is anticipated that an increase in environmental taxation would yield favorable outcomes in promoting renewable energy sources. With increased taxes on carbon-intensive sources, the appeal and cost-effectiveness of renewable energy sources are enhanced. Consequently, enterprises and consumers are inclined to transition towards renewable energy alternatives, leading to an upsurge in using renewable energy sources.

Technological innovation plays a crucial role in facilitating progress in renewable energy technology. Incorporating TI (technological innovation) into the equation for REC is justified because it accurately reflects the level of innovation and research and development efforts within the renewable energy sector. It is anticipated that an increase in technological innovation will positively impact the utilization of renewable energy. The advancement of renewable energy technology has led to improved efficiency, cost-effectiveness, and reliability of renewable energy sources. Therefore, it is expected that the proliferation and utilization of renewable energy will grow in parallel with increased technological advancement.

The term "natural resources rent" refers to the revenue generated through the extraction and exploitation of various natural resources, encompassing wind, solar, hydro, and geothermal energy sources. The justification for incorporating Net Renewable Resources (NRR) into the equation used to calculate REC is its ability to accurately reflect the accessibility and utilization of abundant renewable energy sources. It is anticipated that an increase in the amount of rent derived from natural resources would positively impact the utilization of renewable energy. Nations endowed with abundant renewable energy resources can harness them for power generation, leading to heightened renewable energy utilization levels. With the burgeoning accessibility of renewable energy resources, there is a concomitant rise in their viability for energy production, thereby fostering enhanced acceptance of these sustainable energy sources.

Foreign direct investment (FDI) pertains to the financial resources allocated by international investors to the renewable energy sector of a specific country. Incorporating foreign direct investment (FDI) into the consideration of REC is justified because it signifies the infusion of financial capital, technology diffusion, and specialized knowledge provided by international investors, thereby facilitating the growth and progress of renewable energy initiatives. It is anticipated that an increase in foreign direct investment would positively impact the utilization of renewable energy. The increase in foreign direct investment (FDI) in the renewable energy sector can support the development of new renewable energy initiatives, enhance existing projects, and facilitate the adoption of advanced technology. As a result, this phenomenon results in an escalated utilization of renewable energy sources within the host nation.

3.3. Estimating Strategies

The Slop Heterogeneity test (SHT) and the Cross-Sectional Dependency test (CSD) are essential tools in statistical analysis. The primary aim of the SHT is to ascertain the presence of heterogeneity in the gradients of various categories or variables within a given dataset. Through careful analysis of this heterogeneity, researchers can gain valuable insights into the influence of different factors on the outcomes they seek. CSD, on the other hand, enables us to ascertain the interdependence of cross-sectional observations. It is of utmost importance to consider the potential violation of one of the fundamental assumptions of independence when working with data. These assumptions are crucial for ensuring the reliability and accuracy of statistical inference. Both tests are essential for identifying subtleties within datasets and ensuring the robustness of our analyses by accounting for potential variations and dependencies that could significantly impact our results. Therefore, utilizing these tests enhances the validity and reliability of research findings and contributes to the progression of scientific knowledge in an ever-evolving milieu. The following equation is to be implemented in deriving the test statistics.

$$y_{it} = \alpha_i + \beta_i x_{it} + u_{it} \quad \mathrm{i} = 1 \ldots\ldots \mathrm{N},\ \mathrm{t} = 1 \ldots\ldots \mathrm{T} \tag{4}$$

$$LM = T\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\hat{\rho}_{IJ\underset{d}{\rightarrow}}X^2N(N+1)2 \tag{5}$$

$$CD_{lm} = \sqrt{\frac{N}{N(N-1)}}\sum_{I=1}^{N-1}\sum_{J=i+1}^{N}\left(T\hat{\rho}_{ij} - 1\right) \tag{6}$$

$$CD_{lm} = \sqrt{\frac{2T}{N(N-1)}}\sum_{I=1}^{N-1}\sum_{J=i+1}^{N}\left(\hat{\rho}_{ij}\right) \tag{7}$$

$$CD_{lm} = \sqrt{\frac{2}{N(N-1)}}\sum_{I=1}^{N-1}\sum_{J=i+1}^{N}\left(\frac{(T-K)\hat{\rho}_{ij}^2 - u_{Tij}}{v_{Tij}^2}\right)\vec{d}\,(N,0) \tag{8}$$

3.4. Second-Generation Panel Unit Root Test: CIPS and CADF

In the field of panel data analysis, the second-generation panel unit root tests CIPS (Cross-sectionally Augmented IPS) and CADF (Cross-sectionally Augmented Dickey-Fuller) are widely used to examine the stationarity of variables across numerous cross-sectional units and periods. The tests mentioned above are an extension of the initial unit root tests (such as IPS and ADF) because they account for the cross-sectional dependence and heterogeneity of the panel dataset's units. Ref. [16] first proposed the CIPS test, also known as the Cross-sectionally Augmented IPS test, which is an extension of the IPS examination. Effectively addressing the issue of cross-sectional dependence in panel data, the paper generates more reliable and robust results in the presence of cross-sectional correlation among the individual units.

The fundamental equation for the CIPS test, which closely resembles that of the IPS test, is as follows:

$$\Delta Y_{it} = \beta Y_{it-1} + \sum(\delta_k * \Delta Y_{it-k}) + \sum(\gamma_j * \Delta Y_{jt-1}) + \varepsilon_{it}, \tag{9}$$

where: ΔY_{it} represents the first-differenced dependent variable for the cross-sectional unit I at time interval t. ΔY_{it-1} represents the lagged level of the dependent variable at period $t-1$ for cross-sectional unit i. ΔY_{it-k} represents the first-differenced dependent variable for cross-sectional unit i during time interval $t-k$. Incorporating the lagged first differences of the other cross-sectional units (Y_{jt-1}) into the panel regression, the CIPS test incorporates cross-sectional correlation. The test statistic is derived from the residuals of the CIPS panel regression and has a non-standard distribution. Critical values for the CIPS examination can be derived using Monte Carlo simulations or bootstrap techniques.

Cross-sectionally Augmented Dickey-Fuller test, as an extension of the ADF (Augmented Dickey-Fuller) test. Similar to the CIPS test, this method effectively addresses the cross-sectional dependence among the panel dataset's units. The CADF test's fundamental equation resembles that of the ADF test and can be expressed as follows:

$$\Delta Y_{it} = \alpha + \beta Y_{it-1} + \sum(\delta_k * \Delta Y_{it-k}) + \sum(\gamma_j * \Delta Y_{jt-1}) + \varepsilon_{it}, \tag{10}$$

The CADF test is an extension of the ADF test that incorporates the lagged first differences of the remaining cross-sectional units $(\mathrm{Y_{jt-1}})$ into the panel regression. The test statistic is derived from the residuals of the CADF panel regression, and its distribution is non-normal. Critical values for the CADF examination may also be obtained using Monte Carlo simulations or bootstrap methods.

$$\Delta Y_{it} = \beta_i + \gamma_i y_{i,t-1} + \pi_i \overline{y}_{t-1} + \beta_i \overline{y}_t + \rho_{it} \tag{11}$$

$$\Delta Y_{it} = \mu_i + \gamma_i y_{i,t-1} + \pi_i \overline{y}_{t-1} + \sum_{k=1}^{p} \beta_{ik} \Delta y_{i,k-1} + \sum_{k=0}^{p} \beta_{ik} \overline{\Delta y}_{i,k-0} + \alpha_{it} \tag{12}$$

$$CIPS = N^{-1} \sum_{i-1}^{N} \partial_i (N, T) \tag{13}$$

$$CIPS = N^{-1} \sum_{i-1}^{N} CADF \tag{14}$$

3.5. CUP-FM and CUP-BC Estimation

CUP-FM and CUP-BC estimation techniques are highly sophisticated and have brought about a revolutionary impact on empirical panel estimation. In panel data analysis, the CUP-FM (continuously updated and fully modified) method is designed to effectively address the complex issues presented by endogeneity, measurement error, and unobserved heterogeneity. The proposed methodology combines ordinary least squares estimators with instrumental variable techniques to estimate model parameters while effectively addressing potential biases. The CUP-FM estimation method is notable for its iterative approach to updating the instrument set during the estimation process. This process guarantees the seamless integration of any modifications or adjustments made to the underlying data structure, leading to progressively more precise parameter estimates as time progresses. CUP-FM successfully addresses the bias from weak or omitted variables by implementing adaptive modifications to the instruments and their weights during each iteration. However, the continuously updated and bias-corrected (CUP-BC) panel estimation tackles an important concern: time-varying biases caused by unobserved factors that simultaneously affect the dependent and independent variables. The CUP-BC method achieves this objective by integrating instrumental variable regression models with an iterative bias-correction mechanism within a two-step procedure.

In the phase of this study, the investigation delves into the long-term impact of the regressors on carbon emissions through the application of advanced CUP-FM and CUP-BC tests. These cutting-edge tests, introduced by Bai, Kao, and Ng [15], present a remarkable solution to a multitude of challenges encountered in panel data analysis, such as cross-sectional dependence (CSD), endogeneity, serial correlation, and heteroscedasticity. The exceptional feature of these techniques lies in their ability to handle fractionally integrated explanatory variables, enabling the estimation of continuous parameters, covariance matrices, and factor loadings until optimal convergence is achieved. Moreover, these methods have garnered widespread attention in recent literature as they effectively address CSD issues and eliminate the oversight of nonlinearity and fractional integration concerns [105]. Embracing these sophisticated tools, this study pushes the boundaries of empirical analysis, ushering in a new era of insightful findings and groundbreaking discoveries in REC research. The following equation is to be executed in unveiling the coefficients of explanatory variables.

$$\begin{aligned}\gamma_{CUP} = & \left[\sum_{i=1}^{N}\left(\sum_{t=1}^{T}(\hat{y}_{it}+\hat{\gamma}_{CUP})(x_{it}-\overline{X_i})' - T\left(\mu_i'(\hat{\gamma}_{cup})\Delta_{F\varepsilon i}(\hat{\gamma}_{CUP})+\Delta_{u\varepsilon i}(\hat{\gamma}_{CUP})\right)\right)\right] \\ & \times\left[\sum_{i=1}^{N}\sum_{t=1}^{T}(x_{it}-\overline{X_i})(x_{it}-\overline{X_i})'\right]\end{aligned} \tag{15}$$

Asymmetric ARDL following the nonlinear framework introduced by [106], the above Equations (1)–(3) can be established in the following manner

$$REC_t = (\beta^+ EPU_{1,t}^+ + \beta^- EPU_{1,t}^-) + (\gamma^+ ET_{1,t}^+ + \gamma^- ET_{1,t}^-) + (\pi^+ TI_{1,t}^+ + \pi^- TI_{1,t}^-) + \delta_i X_t + \varepsilon_t \tag{16}$$

where the value of $\beta^+\&\beta^-; \gamma^+\&\gamma^-; \pi^+\&\pi^-$. Stands the asymmetric elasticity of EPU, ET and TI on REC. The asymmetric decomposition of EPU $[EPU_{1,t}^+; EPU_{1,t}^-]$, ET $[ET_{1,t}^+; ET_{1,t}^-]$, and TI $[TI_{1,t}^+; TI_{1,t}^-]$ can be derived through the execution of the following equations.

$$\begin{cases} POS(EPU)_{1,t} = \sum\limits_{k=1}^{R} lnEPU_k^+ = \sum\limits_{K=1}^{R} MAX(\Delta lnEPU_k, 0) \\ NEG(EPU)_t = \sum\limits_{k=1}^{R} lnEPU_k^- = \sum\limits_{K=1}^{R} MIN(\Delta lnEPU_k, 0) \end{cases} : \begin{matrix} POS(ET)_{1,t} = \sum\limits_{k=1}^{R} lnET_k^+ = \sum\limits_{K=1}^{R} MAX(\Delta lnET_k, 0) \\ NEG(ET)_t = \sum\limits_{k=1}^{R} lnET_k^- = \sum\limits_{K=1}^{R} MIN(\Delta lnET_k, 0) \end{matrix}$$

$$; \begin{matrix} POS(TI)_{1,t} = \sum\limits_{k=1}^{R} lnTI_k^+ = \sum\limits_{K=1}^{R} MAX(\Delta lnTI_k, 0) \\ NEG(TI)_t = \sum\limits_{k=1}^{R} lnTI_k^- = \sum\limits_{K=1}^{R} MIN(\Delta lnTI_k, 0) \end{matrix}$$

Now, Equation (16) is transformed into asymmetric long-run and short-run coefficient assessment as follows:

$$\begin{aligned}\Delta REC_t = & \partial U_{t-1} + (\mu^+ EPU_{1,t-1}^+ + \mu^- EPU_{1,t-1}^-) + (\alpha^+ ET_{1,t-1}^+ + \alpha^- ET_{1,t-1}^-) + (\varphi^+ TI_{1,t-1}^+ + \varphi^- TI_{1,t-1}^-) + \beta X_{1,t-1}^* \\ & + \sum_{j=1}^{m-1}\beta_j \Delta REC_{t-j_0} + \sum_{j=1}^{n-1}(\epsilon^+ \Delta EPU_{1,t-1}^+ + \epsilon^- \Delta EPU_{1,t-1}^-) + \sum_{j=0}^{m-1}(\theta^+ \Delta ET_{1,t-1}^+ + \theta^- \Delta ET_{1,t-1}^-) \\ & + \sum_{j=0}^{m-1}(\vartheta^+ \Delta TI_{1,t-1}^+ + \vartheta^- \Delta TI_{1,t-1}^-) + \sum_{j=0}^{m-1}\mu \Delta X_{1,t-1}^* + \varepsilon_t\end{aligned} \tag{17}$$

The D-H causality test, commonly called the Durbin-Hausman causality test, is a widely employed statistical procedure in econometrics. Its purpose is to ascertain the direction of causality between two variables. This rigorous and sophisticated technique effectively addresses the long-standing challenge of establishing causal relationships in intricate systems. This test utilizes panel data analysis to mitigate the potential biases inherent in cross-sectional and time series studies. The D-H causality test relies on the underlying assumption that there exists an exogenous variable, commonly referred to as an instrumental variable, which concurrently affects both the dependent and independent variables, albeit not in an explicit manner. This procedure employs a two-step estimation process to assess whether including a lagged value of the dependent variable enhances explanatory capacity beyond that accounted for by predetermined regressors alone. If this thorough evaluation produces statistically significant results, it offers compelling evidence of a plausible causal relationship between the variables of interest. The following causal equation will be implemented to evaluate the possible directional linkage between explained and explanatory variables.

$$Y_{\{it\}} = \alpha + \beta * X_{\{it\}} + \varepsilon_{\{it\}} \tag{18}$$

The Durbin-Hausman test statistic is then calculated as follows:

$$DH = \frac{\left(\Sigma u_{\{it\}} * v_{\{it\}}\right)}{sqrt\left(\Sigma u^2_{\{it\}} * \Sigma v^2_{\{it\}}\right)} \tag{19}$$

4. Empirical Model Estimation and Interpretation

In this study, examining the distinctive characteristics of research variables has resulted in a novel methodology for evaluating their empirical associations and results displayed in Table 2. The advanced econometric models, namely CSD, SHT, and PURT, have been expertly utilized to reveal the fundamental characteristics of the research units. The groundbreaking findings are presented in Table 1, which showcases the outcomes of the CSD and SH tests. The captivating outcomes obtained from the CSD test have audaciously questioned the conventional assumption of cross-section independence, thereby unveiling a captivating network of cross-sectional dependency among the research units. Furthermore, implementing the homogeneity test for the slope has effectively revealed the varied and intriguing heterogeneity properties present within the dataset.

Table 2. Results of HTS and CDS.

	LM_{BP}	LM_{PS}	LM_{adj}	CD_{PS}	**Δ**	**Adj.Δ**
REC	423.221 ***	24.943 ***	181.942 ***	11.336 ***	55.161 ***	55.992 ***
EPU	327.14 ***	27.165 ***	102.93 ***	6.916 ***	32.337 ***	66.183 ***
ET	337.321 ***	39.443 ***	237.148 ***	24.675 ***	50.994 ***	142.488 ***
TI	413.431 ***	44.657 ***	164.144 ***	33.763 ***	93.281 ***	99.209 ***
FDI	231.233 ***	23.364 ***	112.165 ***	29.513 ***	86.818 ***	130.615 ***
FD	247.832 ***	17.604 ***	201.104 ***	45.065 ***	50.678 ***	140.856 ***

Note: the superscripts of *** denotes the statistical significance at a 1% level.

The IPS test is classified as a first-generation test. In contrast, the CIPS test is classified as a second-generation test. Based on the findings of the IPS test, it is observed that urbanization remains stationary at the given level. In contrast, the other variables exhibit unit root characteristics. However, according to the CIPS test results, see Table 3, it can be observed that the null hypothesis of a unit root is not rejected for all variables employed in Equation (3). However, upon taking the first differences of these variables, they exhibit stationarity. In this particular scenario, it is imperative to thoroughly analyze the cointegration relationship between the variables before estimating the long-run coefficients that will elucidate the influence of EPU, ET, TI, NRR, and FDI on REC emissions.

Table 4 depicts the results of the long-run cointegration test following [107–110]. Considering the test statistics, it is apparent that they have exposed statistical significance at a 1% level, suggesting the long-run association between EPU, ET, TI, NNR, FDI, and REC.

Table 3. Results of second-generation panel unit root test: CIPS and CADF.

Variables	CADF Test Statistic for Constant		CIPS Test Statistic for Constant		CADF Test Statistic for Constant and Trend		CIPS Test Statistic for Constant and Trend	
	Level	1st Diff.	Level	1st Diff.	Level	1st Diff.	Level	1st Diff.
REC	−1.123	−3.179 ***	−1.278	−2.633 ***	−2.742	−3.908 ***	−1.628	−3.739 ***
EPU	−2.156	−6.799 ***	−2.402	−4.724 ***	−1.319	−7.876 ***	−1.569	−4.079 ***
ET	−1.691	−6.45 ***	−1.415	−6.003 ***	−1.606	−5.998 ***	−2.407	−6.201 ***
TI	−1.196	−2.275 ***	−1.685	−2.336 ***	−1.955	−4.52 ***	−1.803	−4.637 ***
FDI	−2.802	−7.314 ***	−2.151	−5.146 ***	−2.351	−3.08 ***	−1.522	−5.45 ***
FD	−1.59	−4.643 ***	−1.966	−3.431 ***	−2.716	−3.94 ***	−2.47	−7.632 ***

Note: the superscripts of *** denotes the statistical significance at a 1% level.

Table 4. Results of panel cointegration test.

Model	EPU → REC	ET → REC	TI → REC	FDI → REC	FD → REC
Gt	−10.152 ***	−12.714 ***	−5.508 ***	−12.074 ***	−13.102 ***
Ga	−15.835 ***	−8.788 ***	−14.948 ***	−11.098 ***	−15.614 ***
Pt	−14.349 ***	−14.053 ***	−12.117 ***	−8.294 ***	−9.446 ***
Pa	−14.459 ***	−15.223 ***	−5.398 ***	−12.01 ***	−5.184 ***
KRCPT					
MDF	−5.778 ***	9.394 ***	−0.647 ***	6.589 ***	−2.452 ***
DF	5.376 ***	0.965 ***	17.054 ***	17.954 ***	−7.134 ***
ADF	−3.433 ***	−5.509 ***	20.053 ***	15.663 ***	−10.293 ***
UMDF	21.76 ***	10.388 ***	21.589 ***	5.369 ***	20.708 ***
UDF	7.768 ***	−6.051 ***	−2.468 ***	−6.368 ***	19.454 ***
PCT					
MDF	9.067 ***	2.269 ***	−0.557 ***	−4.721 ***	12.972 ***
PP	7.969 ***	8.101 ***	1.162 ***	7.362 ***	9.08 ***
ADF	10.365 ***	13.803 ***	13.027 ***	9.674 ***	9.31 ***

Note: the superscripts of *** denotes the statistical significance at a 1% level.

The results of CUP-FM and CUP-BC displayed in Table 5. The presence of a negative coefficient (−0.11984) suggests that uncertain economic conditions could potentially hinder the consumption of renewable energy. The existing literature supports our study findings. See, for instance, [2,9,26,111,112]. During times of economic uncertainty, businesses and investors may exhibit a certain degree of reluctance when allocating their resources toward long-term projects, including but not limited to initiatives related to renewable energy. Policymakers ought to be aware of this correlation and strive to establish stable and conducive economic conditions to bolster investor confidence and foster investments in renewable energy. Governments can effectively facilitate the transition towards renewable energy sources while upholding environmental objectives through consistent policies and incentives.

The positive coefficient of 0.1809 underscores the importance of environmental taxes in fostering the utilization of renewable energy sources. Tariffs serve as effective tools for internalizing the environmental costs linked to the consumption of fossil fuels and promoting the adoption of more sustainable energy sources. Policymakers can devise and execute environmental tax policies to incentivize businesses and consumers to shift toward renewable energy sources. This strategic approach serves the purpose of curbing carbon emissions and effectively addressing the adverse impacts of climate change. The revenue generated from environmental taxes can also be strategically allocated towards reinvesting in renewable energy initiatives and conducting research. This proactive approach not only aids in the transition towards a low-carbon economy, but also provides additional support in achieving this objective.

Table 5. Results of long-run coefficients: REC as the dependent variable.

	Coefficient	**Std. Error**	**t-Statistic**	**Coefficient**	**Std. Error**	**t-Statistic**
		CUP-FM			**CUP-BC**	
EPU	−0.11984	0.0204	−5.8745	−0.1496	0.0373	−4.0128
ET	0.1809	0.0204	8.8676	0.1617	0.0325	4.9756
TI	0.10214	0.0419	2.4377	0.1384	0.022	6.2927
NNR	0.1096	0.032	3.425	0.1731	0.0281	6.1594
FD	0.17329	0.0453	3.8253	0.1044	0.0147	7.1020
FDI	0.12286	0.0358	3.4318	0.1019	0.0286	3.5629
C	12.448	0.24013	51.8385	9.991	0.2401	41.6066

The significance of the positive coefficient (0.10214) about TI (Technology Innovation) underscores the pivotal role played by technology innovation in fostering the adoption of REC. As technology advances, renewable energy sources become increasingly efficient, reliable, and cost-effective. Policymakers should prioritize investments in research and development to expedite the progress of technological advancements in renewable energy technologies. Governments can expedite the widespread acceptance of renewable energy sources, enhance energy security, and diminish dependence on fossil fuels by cultivating innovation. In doing so, they can effectively contribute to economic progress and environmental sustainability. The study highlights the importance of harnessing abundant natural resources for renewable energy production. Countries endowed with ample renewable resources, such as abundant sunlight, wind, or water, possess a unique opportunity to harness these resources sustainably to meet their energy needs. Policymakers possess the capacity to effectively facilitate the development of renewable energy infrastructure within regions that boast ample natural resources. This strategic approach serves the dual purpose of mitigating greenhouse gas emissions and fostering energy independence.

The positive coefficient of 0.17329 underscores the significance of a robust financial sector in fostering the adoption of REC. Enhanced financial development facilitates improved access to capital and financing options for renewable energy projects. In collaboration with financial institutions, policymakers can cultivate tailored financing mechanisms for renewable energy initiatives, including but not limited to green bonds or venture capital funds. By reducing financial barriers, these initiatives have the potential to enhance investments in renewable energy and facilitate the advancement of sustainable energy technologies. For FDI, the positive coefficient of 0.12286 highlights the significant role that FDI plays in promoting REC. Foreign investors play a crucial role in expediting the deployment of renewable energy projects by providing capital, expertise, and technology. Foreign investors can be enticed to engage in the renewable energy sector by cultivating a conducive investment environment, providing incentives, and establishing robust regulatory frameworks. Collaboration with international partners has the potential to greatly enhance the transfer of technology and facilitate the sharing of knowledge. This, in turn, can significantly contribute to developing domestic renewable energy and support global sustainability initiatives.

This study has implemented the robustness of long-run coefficients of EPU, ET, TI, NNR, and FDI on REC by employing the fixed effects, two-step GMM, and two-step Sys. GMM and DSUR. The results of robustness are displayed in Table 6. The study findings unveiled the estimation consistency in coefficients sign towards REC, supported by all four execute models.

The asymmetric coefficients (see Table 7) of EPU that are positive and negative shocks EPU displayed negative and statistically significant at a 1% level to REC in the selected nations. The study findings argue that including clean energy in the energy mix requires long-term and short-term economic stability. More precisely, a 10% positive (negative) change in EPU will result in impeding (accelerate) the REC in the studied nations by 0.455% (0.951%) in the long run and by 0184% (0.356%) in the short run, respectively. Historically, it has been observed that positive economic policy uncertainty (EPU) shocks exert a significant and adverse impact on REC. This implies that EPU may deter investment and impede the progress of renewable energy initiatives. During periods of economic volatility, companies and investors often adopt a more conservative approach, potentially reducing funding for renewable energy projects. Uncertainty can significantly affect the availability of finance and financing prospects for endeavors in the renewable energy industry. Nonetheless, it is crucial to remember that even adverse occurrences may yield a net advantageous impact on Economic Policy Uncertainty (EPU). This statement implies that a heightened level of economic stability could potentially foster increased investment and generate greater interest within the renewable energy industry. Business owners and investors exhibit a higher propensity to allocate funds toward renewable energy projects during periods of economic prosperity. This phenomenon leads to a rise in the adoption of renewable energy solutions, thereby facilitating the expansion of the renewable energy industry.

Table 6. Robustness estimation: fixed effects, two-step GMM, two-step sys. GMM and DSUR.

	FE	Two-Step GMM	Two Step Sys. GMM	DSUR
REC (−1)			0.1561	
EPU	−0.1247	−0.0874	−0.2086	−0.283
ET	0.1118	0.2364	0.1682	0.2425
TI	0.1596	0.2794	0.0282	0.1711
NNR	0.0822	0.0388	0.1964	0.2654
FDI	0.2138	0.0991	0.128	0.0889
Constant	−5.784	−7.9895	−4.613	−4.281
AR (1)			0.0093	
AR (2)			0.7029	
Hansen J-test			0.3798	
The difference in the Hansen test			0.7441	

Table 7. Results of asymmetric long-run and short-run coefficients.

	Model—1			Model—2			Model—3		
Variables	**Coeff.**	**St.Error**	**t-Stat**	**Coeff.**	**St.Error**	**t-Stat**	**Coeff.**	**St.Error**	**t-Stat**
EPU^{+}	−0.0729	0.0323	−2.2569	−0.0649	0.0728	0.8914	−0.0454	0.0128	−3.5468
EPU^{-}	−0.0952	0.0343	−2.7755	−0.0734	0.0476	1.5420	−0.0951	0.0334	−2.8473
ET^{+}				0.0641	0.0333	1.9249	0.0576	0.049	1.1755
ET^{-}				0.0833	0.0252	3.3055	0.0742	0.0412	1.8009
TI^{+}							0.1113	0.0493	2.2576
TI^{-}							0.089	0.008	11.125
NNR	−0.1483	0.0345	−4.2985	−0.0995	0.0526	−1.8916	−0.0805	0.0398	−2.02261
FDI	0.1213	0.0482	2.5165	0.0696	0.0523	1.3307	0.0503	0.0505	0.9960
C	0.0983	0.0457	2.1509	0.0679	0.0763	0.8899	0.0837	0.0449	1.8641
EPU^{+}	−0.011	0.0049	−2.2403	0.0114	0.0033	3.4337	−0.0184	0.0040	−4.5320
EPU^{-}	−0.0096	0.0069	−1.3812	0.0171	0.0061	2.7986	−0.0356	0.007	−5.0857
ET^{+}				−0.0065	0.0048	−1.3457	0.0244	0.00805	3.0310
ET^{-}				0.0019	0.0057	0.3292	0.0318	0.00673	4.7251
TI^{+}							0.0094	0.00807	1.1648
TI^{-}							0.0184	0.0072	2.5555
NNR	0.0488	0.0075	6.4893	0.0467	0.0029	16.1034	0.0154	0.00275	5.6
FDI	−0.0039	0.0053	−0.7276	0.042	0.0053	7.8358	0.0339	0.00306	11.0784
cointEq (−1)	−0.4221	0.00317	−133.155	−0.344	0.024	−14.3333	−0.2152	0.0495	−4.3474
CD test		0.020693			0.029107			0.028893	
Wooldridge Test for autoco		0.726695			0.007597			0.225123	
Normality test		0.809966			0.078659			0.954477	
Remsey RESET test		0.185144			0.263383			0.251715	

For the case of environmental restriction in the form of tax, the study documented a positive statistically significant linkage between asymmetric shocks of ET and REC in the long run and short run. Particularly, a 10% increase (decrease) of ET in the economy would result in the amplification of clean energy inclusion from renewable sources by 0.576% (0.742%) in the long run and by 0.244% (0.318%) in the short run. Study findings advocated that environmental protection through imposing taxation contributes to the energy mix, especially in including clean sources over conventional ones. Numerous studies have demonstrated the efficacy of environmental taxation as a tool for promoting the adoption of renewable energy and reducing carbon emissions. For instance, Shafiei and Salim [113] discovered that carbon levies effectively promoted using renewable energy sources in Australia. Similarly, Wang, Usman, Radulescu, Cifuentes-Faura, and Balsalobre-Lorente [48] examined the impact of carbon levies on REC in China. They concluded that carbon pricing policies can hasten the transition to sustainable energy sources. As REC rises, the proportion of conventional energy sources falls, contributing to an environmental improvement and a more sustainable energy future. Environmental economics and energy policy literature has extensively discussed the use of environmental taxation to promote renewable energy, in addition to the efficacy of various environmental policy instruments, such as tariffs, in addressing environmental challenges. The study's findings emphasize the positive and significant relationship between environmental taxes and REC. Environmental tariffs are a potent policy instrument for directing energy consumption toward cleaner sources, which is advantageous for both the economy and the environment. Governments can encourage the adoption of renewable energy and contribute to environmental protection and sustainability by taxing carbon-intensive activities. These findings support the rationale for instituting effective environmental taxation policies as part of an all-encompassing strategy to promote incorporating renewable energy and combat climate change.

The asymmetric coefficients of technological innovation in the long and short run have been positively connected to REC, indicating that TI in the economy fosters energy consumption predominantly with renewable sources. Particularly, a 1% expansion (contraction) in TI results in increasing the REC consumption by 0.1113% (0.089%), while the short-run asymmetric suggests the changes in REC by 0.0094% (0.0184%), respectively. This proposition suggests that as technological innovation advances within the economy, there is a concurrent increase in the adoption of renewable energy sources, leading to a heightened consumption of clean energy. The findings indicate that technological innovation (TI) is crucial in enabling the transition to renewable energy. This observation aligns with theoretical perspectives that underscore the importance of technological advancement in facilitating the adoption of clean energy technologies [4,6,100,114]. The analysis of long-term data indicates that a 1% increase in TI is correlated with a 0.1113% increase in REC consumption. Conversely, a 1% decrease in TI is associated with a 0.089% decrease in REC consumption. The proposition being presented asserts that technological advancements exert a more substantial influence on the consumption of clean energy in the long term. Consequently, this implies that the cumulative impact of technological innovation over time assumes a critical role in fostering the adoption of renewable energy. The findings mentioned above are consistent with previous research highlighting the long-lasting benefits of technological innovation in promoting clean energy uptake and furthering sustainable development goals [8,20,101,115,116]. The study reveals that, in the short term, a 1% expansion in TI is associated with a relatively modest increase of 0.0094% in REC consumption. On the contrary, it has been observed that a 1% decline in TI leads to a corresponding reduction of 0.0184% in REC consumption. This statement suggests that the impact of technological innovation on clean energy consumption may be relatively constrained shortly. However, it is crucial to consider that transient factors may influence short-term outcomes and may not fully encompass the enduring benefits of technological advancements in promoting the adoption of renewable energy.

The following section assesses directional linkage in the empirical nexus, and Table 8 displays the causality test results. Referring to the test statistics, the study documents bidirectional causality available between economic policy uncertainty and REC EPU $\longleftrightarrow$ REC, technological innovation and REC [TI $\longleftrightarrow$ REC], and foreign direct investment and renewable energy consumption [FDI $\longleftrightarrow$ REC]. The bidirectional causation between Economic Policy Uncertainty (EPU) and Real Economic Activity (REC) suggests a mutual relationship between these variables. This finding implies that changes in economic policy uncertainty possess the capacity to influence the utilization of renewable energy. Moreover, alterations in the consumption of renewable energy may potentially exert an influence on the level of economic policy uncertainty. Based on the research conducted by [117], it is indicated that fluctuations in economic policy uncertainty may impact the decision-making process concerning investments in renewable energy projects. Furthermore, increased utilization of renewable energy sources can also exert reciprocal effects on economic policies. The reciprocal relationship between technical innovation (TI) and REC implies that advancements in clean energy technologies may facilitate the broader adoption of renewable energy sources. Similarly, the growing utilization of renewable energy sources can stimulate technological innovation within the clean energy sector. This discovery aligns with the notion that technological advancements are pivotal in progressing and integrating more efficient and cost-effective renewable energy technologies. Consequently, these advancements render renewable energy sources increasingly attractive to consumers and investors, culminating in a surge in the utilization of renewable energy [118]. The existence of bidirectional causation between Foreign Direct Investment (FDI) and Regional Economic Cooperation (REC) suggests a mutually reinforcing connection between these two variables. Foreign direct investment (FDI) possesses the capacity to effectively contribute to the advancement and expansion of renewable energy initiatives, thereby facilitating a substantial increase in the utilization of renewable energy sources. On the contrary, an escalated utilization of renewable energy sources has the potential to act as a catalyst in attracting higher levels of foreign direct investment in the clean energy industry, thereby offering significant support for its continued progress [104].

Table 8. Results of DH causality test.

	REC	**EPU**	**ET**	**TI**	**FDI**	**FD**
REC		(5.5738) *** [5.8748]	(4.3985) ** [4.636]	(13.4431) ** [3.629]	11.7523 *** [1.847]	0.8299 [0.8747]
EPU	(6.154) *** [6.4864]		(5.8916) *** [6.2097]	(6.1859) *** [6.521]	(2.2592) * [2.3813]	1.2433 [1.3104]
ET	1.4197 [1.4964]	(2.0074) * [2.1158]		(5.6896) *** [5.9969]	(4.086) ** [4.3067]	(5.0488) *** [5.3215]
TI	1.0106 [1.0652]	1.4367 [1.5143]	(2.764) * [2.9133]		(5.2922) *** [5.578]	(5.6684) *** [5.9745]
NNR	(4.1817) ** [4.4075]	0.8023 [0.8456]	(6.1392) *** [6.4707]	(5.6461) *** [5.951]		(4.119) ** [4.3414]
FDI	(5.4739) *** [5.7695]	(6.0712) *** [6.399]	(5.3506) *** [5.6396]	(3.4484) ** [3.6346]	(2.2646) * [2.3869]	

Note: the superscripts of ***/**/* denotes the statistical significance at a 1%, 5% and 10% level, respectively.

The study evaluated the empirical nexus targeting the country-specific assessment using DOLS estimation and results in Table 9. Inferring to the sign of coefficients of EPU, ET, and TI on clean energy consumption, it is apparent that the process of clean energy development in the selected nations has been impeded due to economic uncertainties, while the progressive effects have been unveiled for ET and TI for clean energy consumption.

Table 9. Results of country-wise assessment with DOLS.

	EPU	**ET**	**TI**	**NNR**	**FDI**
Australia	−0.247 ***	0.174 ***	0.113 ***	0.11 ***	0.092 **
Brazil	−0.224 ***	0.253 **	0.152 ***	−0.159 ***	0.206 ***
Canada	−0.128 ***	−0.065 ***	0.067 ***	0.116 **	0.152 *
Chile	−0.271 ***	0.051 ***	0.227 ***	0.211 *	−0.016 **
Colombia	−0.12 **	−0.071 ***	−0.073 ***	0.17 ***	0.268 ***
France	−0.103 *	−0.089 ***	0.245 **	−0.115 ***	0.024 ***
Germany	−0.077 *	0.122	0.165 **	0.072 ***	−0.022 ***
Greece	−0.134 ***	−0.072 ***	0.109 *	0.163 **	0.271 **
India	−0.255 ***	0.202 ***	0.105 **	0.214 ***	0.081 *
Ireland	−0.217 **	0.172 ***	0.014 **	−0.123 **	0.07 **
Italy	−0.225 ***	0.014 **	0.02 **	0.265 *	0.123 *

Table 9. *Cont.*

	EPU	ET	TI	NNR	FDI
Japan	−0.238 ***	0.093 **	0.229 **	−0.081 ***	−0.052 *
Korea	−0.224 **	0.234 **	−0.085 **	−0.127 **	−0.054 *
Netherlands	−0.188 ***	0.042 ***	−0.091 **	−0.171 *	0.247 ***
Russia	−0.123 ***	0.132 ***	0.207 **	−0.031 **	0.113 ***
Spain	−0.25 ***	0.097 **	0.237 *	−0.136 ***	0.254 **
UK	−0.177 **	−0.004 *	0.245 **	0.01 *	0.054 **
US	−0.253 ***	−0.033 ***	−0.02 ***	0.02 **	0.109 **
China	−0.081 ***	0.025 ***	0.228 **	0.042 *	−0.053
Sweden	−0.267 ***	0.161 ***	0.018 *	0.087 *	0.016 ***
Mexico	−0.187 ***	−0.142 **	0.179 *	0.019 ***	0.066 **

Note: the superscripts of ***/**/* denotes the statistical significance at a 1%, 5% and 10% level, respectively.

5. Discussion

According to the findings of this study, it has been observed that economic policy uncertainty (EPU) has asymmetric effects on REC in the selected nations. Positive and negative EPU shocks exhibit statistically significant adverse impacts on REC, with a confidence level of 1%. In particular, a 10% increase in EPU results in a long-term reduction of REC by 0.455% and a short-term reduction of 0.184%. In contrast, a decrease of 10% in EPU results in a long-term increase in REC by 0.951% and a short-term increase of 0.356%. The adverse and substantial impact of positive economic policy uncertainty (EPU) shocks on REC implies that such uncertainty can deter investment and hinder the progress of renewable energy initiatives. The literature supports our study findings, such as [1,2,9,11,17,26,82]. During periods of economic instability, businesses and investors often adopt a more cautious approach, leading to a reduction in expenditures allocated toward renewable energy projects. Uncertainty can significantly influence the accessibility of funding and financing opportunities for initiatives in the renewable energy sector, potentially impeding their progress. However, it is worth noting that negative disruptions can positively and significantly impact the Economic Policy Uncertainty (EPU). This implies that a stable economic environment has the potential to foster greater investment and interest in the field of renewable energy. During periods characterized by economic stability, businesses and investors are more inclined to allocate resources toward renewable energy initiatives. This phenomenon engenders a surge in the adoption rates of renewable energy solutions, thereby facilitating the expansion of the renewable energy industry. The discovery that economic policy ambiguity exerts a detrimental influence on REC aligns with the conclusions drawn from previous studies exploring the relationship between policy uncertainty and investments in renewable energy. Multiple studies have demonstrated that policy uncertainty, particularly about inconsistent or fluctuating renewable energy policies, can hinder investment and deployment of renewable energy [119,120]. Based on the research conducted by [121], it is evident that policy stability and clarification play a crucial role in facilitating investments and fostering growth within the renewable energy sector. The findings of this study underscore the importance of economic stability in facilitating both the long-term and short-term uptake of renewable energy. Often, initiatives about renewable energy necessitate significant initial investments. Moreover, the prevailing economic stability can influence the availability of funds and resources for such endeavors. A stable economic climate catalyzes companies and governments to prioritize sustainable development and allocate resources toward advancing renewable energy technologies. However, it is important to consider that economic uncertainty has the potential to shift attention and allocate resources away from renewable energy initiatives. This could lead to a persistent dependence on fossil fuels and hinder the advancement toward a low-carbon future [122]. The correlation between economic stability and the adoption of renewable energy aligns with a more comprehensive comprehension of energy transition and sustainable development. Scholars have underscored the imperative of establishing stable policy environments, providing economic incentives, and engaging in long-term planning to facilitate the transition towards renewable energy sources effectively [82,123,124]. The abovementioned factor is widely recognized as being of utmost importance in facilitating investments in clean energy technologies and cultivating a conducive atmosphere for the widespread adoption of renewable energy. The study's findings underscore the importance of economic policy ambiguity in shaping the consumption of renewable energy [17]. The adverse and significant effects of positive EPU disruptions on REC underscore the necessity for consistent and favorable economic policies that foster investments in sustainable energy. Policymakers' primary focus should be the development of transparent and consistent policies that effectively facilitate the growth of renewable energy projects. Countries can potentially expedite their transition towards sustainable and low-carbon energy systems by effectively managing economic uncertainty and cultivating a stable economic climate [28].

This study's findings indicate a robust and statistically significant correlation between asymmetric shocks in environmental tax (ET) and REC in both the long-run and short-run periods. In the context of environmental taxation, it can be observed that a precise adjustment of 10% in the tax rate leads to a corresponding enhancement or reduction in the integration of clean energy derived from renewable sources. This augmentation is quantified as 0.576% (0.742%) in the long term and 0.244% (0.318%) in the short term. Our study is supported by the study findings offered by [7,45,46,52,83,125]. The results above underscore the potential of environmental taxation as a significant contributor to the energy mix, with a particular emphasis on promoting clean and renewable energy sources instead of conventional alternatives. The positive correlation between environmental taxation and REC can be economically justified in various ways. Environmental taxes are specifically formulated to internalize the external costs arising from carbon emissions and pollution from conventional energy sources. By implementing taxes on activities that contribute to pollution, governments establish a price signal that effectively encourages businesses and consumers to transition towards energy alternatives that are both cleaner and more sustainable, such as renewable energy sources [96]. Consequently, the implementation of elevated environmental taxes has the potential to enhance the financial viability of renewable energy technologies, thereby fostering heightened acceptance and utilization of sustainable energy sources. Furthermore, environmental taxes have the potential to function as a lucrative revenue stream for governmental bodies, and revenue can then be strategically allocated towards bolstering and advancing renewable energy initiatives and conducting crucial research in the field. This presents opportunities for establishing public-private partnerships and investments within the renewable energy sector, fostering economic growth and facilitating job creation. Furthermore, with the increasing prevalence of renewable energy, there is the potential for reducing reliance on imported fossil fuels [126]. This, in turn, could lead to improved energy security and decreased trade deficits. From an environmental perspective, the positive correlation between environmental taxation and REC aligns with the intent to decrease greenhouse gas emissions and address climate change. Environmental taxes catalyze the adoption of clean energy sources, leading to a notable surge in the proportion of renewable energy within the overall energy composition. The transition away from fossil fuels results in a notable reduction in carbon dioxide and other detrimental pollutants, thereby significantly contributing to enhancing air quality and mitigating environmental consequences.

Furthermore, the revenue derived from environmental taxes can be allocated toward endeavors focused on environmental preservation and sustainable infrastructure development. This can provide additional support for advancing renewable energy projects and facilitate the seamless integration of clean energy technologies into the grid. The study's findings align with the existing body of literature that has examined the effects of environmental taxation on the adoption of renewable energy. Multiple studies have demonstrated the efficacy of environmental taxes as policy instruments in promoting REC and mitigating carbon emissions [50,127,128]. Environmental tax policies have received praise for their capacity to promote sustainable development, improve energy efficiency, and expedite the shift toward cleaner and more sustainable energy systems [18]. The study findings highlight the positive and significant correlation between environmental taxation and REC in both the long-term and short-term. Implementing environmental taxation policies can catalyze shaping the energy landscape by promoting the integration of clean and sustainable energy sources while discouraging conventional alternatives. From an economic standpoint, implementing environmental taxes can stimulate investments in renewable energy initiatives, thereby cultivating a conducive environment for economic expansion. From an environmental standpoint, these policies have the potential to effectively mitigate greenhouse gas emissions and facilitate the shift towards a sustainable and low-carbon energy landscape.

The study's results demonstrate a significant and positive correlation between technological innovation (TI) and renewable energy (REC) consumption in the long and short term. Based on the analysis of the asymmetric coefficients, it can be observed that an increase in TI results in a corresponding elevation in REC, primarily attributed to the utilization of renewable energy sources. Specifically, an increase of 1% in TI results in a long-term increase in REC consumption of 0.1113% and a short-term increase of 0.0094%. In contrast, a decrease of 1% in TI results in an increase of 0.089% in REC consumption in the long run and 0.0184% in the short term. Our findings align with the existing literature, such as [2,5,10,49,129,130]. The positive correlation between technical innovation and the utilization of renewable energy can be economically elucidated through various means. Renewable energy technologies undergo continuous improvement due to technological innovation, enhancing their efficiency, reliability, and cost-effectiveness. As technological advancements progress, these technologies are increasingly gaining competitiveness in price and performance compared to traditional energy sources. Consequently, their appeal to individuals and organizations is significantly enhanced. Renewable energy innovations have the potential to yield economies of scale and subsequent cost reductions, thereby enhancing the accessibility of renewable energy to a broader range of users, which has the potential to foster broader adoption of renewable energy sources, thereby expanding market opportunities and stimulating economic growth within the clean energy sector [13,79]. Moreover, the progress in technological innovations within the realm of renewable energy has the potential to yield job opportunities and foster the cultivation of essential skills, thereby making a significant contribution towards the establishment and growth of a sustainable and environmentally conscious economy. The burgeoning renewable energy sector generates employment opportunities across diverse industries: manufacturing, construction, research and development, and installation. Regarding the environment, the crucial aspect of addressing climate change and reducing carbon emissions lies in the positive correlation between technical innovation and the utilization of renewable energy [130]. Advancements in renewable energy technology serve to mitigate reliance on fossil fuels, which constitute significant contributors to greenhouse gas emissions. Technological advancements in renewable energy have the potential to enhance energy efficiency, reduce energy wastage, and promote the adoption of sustainable energy practices. Renewable energy sources have the potential to provide a more stable and environmentally friendly energy supply as they continue to improve efficiency and reliability. This improvement in renewable energy technologies can help mitigate the negative environmental impacts typically associated with conventional energy production and consumption. The study's findings align with prior research that has underscored the significance of technological innovation in fostering the adoption of renewable energy sources. Multiple studies have demonstrated that advancements in renewable energy technology and innovations play a significant role in accepting and expanding renewable energy sources [99,131–134]. Moreover, the correlation between technical innovation and the utilization of renewable energy is in line with global initiatives and legislative measures aimed at promoting the adoption of renewable energy sources. Numerous reports and studies, such as those conducted by the esteemed International Renewable Energy Agency (IRENA) and the renowned International Energy Agency (IEA), underscore the paramount significance of technology development and innovation in propelling the deployment of renewable energy and attaining sustainable energy objectives [135]. The research findings unequivocally establish a robust and affirmative correlation between technical innovation and the utilization of renewable energy sources. Technological innovation is crucial in driving economic development, facilitating employment opportunities, and unlocking market potential within the renewable energy sector. When considering the environment, technical innovations are crucial in mitigating carbon emissions and fostering the adoption of sustainable energy practices. To foster a cleaner and more sustainable energy future, policymakers, entrepreneurs, and academics must prioritize their efforts towards bolstering and propelling technical innovation within renewable energy [136–138].

6. Conclusions

This study's findings offer valuable insights into the factors that influence the consumption of renewable energy (REC) and its correlation with different independent variables. The results underscore the significance of maintaining economic stability, implementing environmental taxation, and fostering technological innovation to facilitate the widespread adoption of renewable energy sources. The study emphasizes implementing policy measures to promote a cleaner, more sustainable energy future. First and foremost, the study demonstrates that economic policy uncertainty (EPU) exerts an asymmetric impact on REC. This finding underscores the significance of maintaining stable and predictable economic conditions to foster investments in renewable energy projects. Policymakers ought to give precedence to establishing a favorable and unwavering economic milieu to allure investments and cultivate expansion within renewable energy. Long-term policies that offer explicit incentives for adopting renewable energy can effectively mitigate the adverse effects of economic uncertainties on investments in clean energy. Furthermore, it has been demonstrated that there exists a noteworthy and constructive correlation between environmental taxation and REC. This finding highlights the significance of environmental tax policies as efficacious instruments for promoting the uptake of renewable energy sources. Policymakers ought to carefully deliberate the implementation and fortification of environmental tax measures to effectively internalize the external costs associated with carbon emissions. Finally, the study emphasizes the positive correlation between technological innovation (TI) and REC, indicating that advancements in renewable energy technologies are instrumental in promoting the adoption of clean energy. Policymakers must allocate their resources and attention towards prioritizing research and development investments to expedite the pace of technological innovation within the renewable energy sector. Promoting the advancement of renewable energy fosters the potential for decreased costs, enhanced efficiency, and heightened market competitiveness. Consequently, this facilitates greater accessibility and clean energy appeal to consumers and businesses.

Based on this study's findings, the subsequent policy suggestions are recommended to facilitate the promotion of REC and expedite the transition towards a sustainable energy future. First, governments must prioritize establishing stable and predictable economic conditions to attract investments in renewable energy projects. Long-term policies and incentives, which establish a well-defined roadmap for the development of renewable energy, have the potential to cultivate investor confidence and stimulate investments in clean energy. Second, policymakers ought to contemplate implementing or fortifying environmental tax policies to foster the adoption of renewable energy sources. Environmental taxes play a crucial role in effectively internalizing the external costs of fossil fuels, facilitating the transition towards more sustainable and cleaner energy alternatives. Third, governments and institutions must allocate sufficient resources and funding towards promoting and advancing research and development in renewable energy technologies. Investing in technological innovation can yield significant benefits such as enhanced efficiency, reduced costs, and greater utilization of renewable energy sources. Fourth, the collaboration among governments, private sector entities, and research institutions has the potential to foster knowledge dissemination, technology exchange, and financial backing for projects related to renewable energy. Public-private partnerships have the potential to effectively harness specialized knowledge and substantial resources, thereby expediting the implementation of renewable energy technologies.

The significance of this study's findings lies in their potential to shape policies that will drive the adoption of clean energy and diminish our dependence on fossil fuels. Amid a global energy transition, policymakers can leverage these insights to develop effective strategies to propel us toward a sustainable future. The findings of this study offer a valuable tool for policymakers to craft effective policies that encourage the adoption of clean energy and make significant strides in curbing carbon emissions. By leveraging this research's insights, policymakers can shape initiatives that drive the transition towards sustainable energy sources, fostering a greener and more environmentally conscious future. With this knowledge at their disposal, policymakers can enact transformative measures that will have a lasting impact on our planet, paving the way for a cleaner and more sustainable world. The study underscores the critical role of environmental tax policies in driving the adoption of clean energy and curbing harmful carbon emissions. This information holds immense potential for policymakers to craft tax policies that effectively promote the adoption of clean energy while discouraging reliance on fossil fuels. One effective solution to combat carbon emissions and promote clean energy technologies is implementing carbon taxes and subsidies. By imposing taxes on carbon emissions, we can create a financial disincentive for industries and individuals to continue polluting the environment. This not only encourages them to reduce their carbon footprint but also generates revenue that can be invested in developing and implementing clean energy technologies. Additionally, providing subsidies for clean energy technologies incentivizes their adoption and accelerates market penetration. Combining these two strategies can create a powerful economic framework that drives the transition toward a more sustainable and environmentally friendly future. The study unequivocally underscores the criticality of innovation in driving and propelling the adoption of clean energy consumption. Policymakers possess a powerful tool—the ability to utilize this valuable information to strategically allocate resources toward the research and development of clean energy technologies. By doing so, they can pave the way for a multitude of benefits, including the creation of new job opportunities and the stimulation of economic growth. Moreover, the study underscores the critical role of natural resources in driving the adoption of clean energy consumption. This information is invaluable for policymakers as it provides them with the necessary tools to develop policies that promote the sustainable use of natural resources and effectively reduce the environmental impact of energy production. By utilizing this data, policymakers can make informed decisions that will have a lasting positive effect on our planet. With the urgent need to address climate change and protect our environment, policymakers must take advantage of this information and implement policies prioritizing sustainability and environmental responsibility. Doing so can ensure a better future for generations to come. The findings of this study hold immense potential for policymakers to craft impactful policies that not only foster the adoption of clean energy but also combat carbon emissions and drive sustainable economic growth. This study serves as a crucial benchmark for policymakers seeking to develop policies that align with the Sustainable Development Goals set by the United Nations.

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