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Energy security risk in the age of economic uncertainty: The role of environmental policy stringency

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Abstract

Energy is used as a vital input in the production and function of almost every sector of the economy, and hence, it is the fundamental component of the development process of the economies. Due to the rising energy demand, the issue of energy security has become crucial for economic stability. Thus, it is crucial to estimate the factors that can contribute to mitigating risks related to energy security. This analysis aims to investigate the influence of environmental policy stringency and economic policy uncertainty on energy security risk by utilizing the cross sectional autoregressive distributed lag. The findings reveal that economic policy uncertainty helps enhance the energy security risk in the short and long-run. In contrast, environmental policy stringency enhances the energy security risk only in the long-run. In contrast, technological, economic, and financial development hurt the energy security risk in the long run, while these factors enhance the energy security risk in the short run. In the context of these findings, we suggest that policymakers should focus on reducing economic uncertainties and implementing environmental policies with great caution to enhance energy security.

Keywords: Environmental policy stringency, economic uncertainty, energy security risk

JEL Classification: Q50, Q43, O33

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1. Introduction

In the era of industrialization and modernization, energy is widely acknowledged as the engine of growth. Therefore, a reliable, affordable, clean, and sustainable energy supply has become crucial for the world's sustainable future. This makes energy security a top concern in the modern global economy, particularly during times of economic uncertainty and the global transition towards low-carbon development. Energy security is an important dimension of national security and economic stability, confirming that a country has reliable, affordable, and sustainable energy resources. Energy security has increasingly become an important research theme in the contemporary world as global energy demand continues to rise owing to rapid population growth and economic expansion. The energy supply of primary energy sources belongs to less than twenty countries while demand is linked to the rest of the world, making energy balance an issue on a global scale (Thanh *et al*., 2023). The recent geopolitical tensions and the COVID-19 crisis have created additional stress on energy security owing to transportation disruption and energy market instability. Meanwhile, the overuse of energy has led to numerous environmental and climatic-related problems, posing a significant threat to the achievement of sustainable development agendas (UNEP, 2029). Against this milieu, understating the driving forces of energy security is increasingly becoming vital. In this respect, environmental regulations can significantly influence energy supply and demand patterns.

Environmental policy stringency (EPS) is an important avenue that has a significant potential to influence energy security risks through diverse paths. On the one hand, EPS has the potential to tackle environmental problems by formulating policies against environmentally damaging economic activities. On the other hand, it can also create an energy security issue by limiting the use of conventional energy sources. In a recent study, Usman *et al*. (2024) provided firm evidence about the negative effects of EPS on trade in conventional energy sources for top polluting economies. However, an opposing school of thought claims that EPS can encourage trade in energy sources, particularly clean energy sources. Recently, Sun *et al*. (2023) confirmed the favorable role of environmental regulations on the trade of clean energy-related products.

Besides, EPS can undermine energy security by increasing operational costs and creating geopolitical risks. EPS requires energy producers to invest in clean energy or adopt pollution-controlling measures, enhancing operation costs. That is, the implementation of EPS increases regulatory and compliance costs. EPS can also change energy trade dynamics. In this situation, if energy or technological requirements for complying with EPS depend on foreign sources, geopolitical risks may arise, particularly if those sources are located in unstable regions. Conversely, EPS can change energy market dynamics by shifting the energy mix from primary energy sources to clean energy and by disturbing the energy supply chain. Stringent policies trigger innovations, potentially lowering long-term energy security risks. Such policies, however, create short-term energy security risks when rapid technological changes are not adopted smoothly. Thus, EPS influences energy security through a complex interplay of economic, technological, regulatory, and social factors. While EPS can help lower environmental impacts and boost sustainable energy, it can present various challenges that can serve as a barrier to energy security.

Another important source through which energy security risk (ESR) can be influenced is economic policy uncertainty (EPU). The literature on EPU and energy security is progressing from various perspectives. The literature delineates the following mechanisms through which EPU can contribute to ESR. Firstly, EPU can create energy price fluctuations that can change the balance of demand and supply for energy, creating energy security issues. Scarcioffolo and Etienne (2021) showed for the USA that EPU created a disturbance in the energy markets. In the case of China, Wang *et al*. (2024) highlighted that EPU exerted a negative influence on coal prices over the study time period. In the case of G7 economies, Apostolakis *et al*. (2021), however, demonstrated that EPU is not associated with oil prices and does not affect energy security from a price perspective. Meanwhile, Gong *et al*. (2024) ascertained that the potential association between EPU and oil price varies across EPU regimes. In the low EPU regime, both variables are mutually beneficial while in the high EPU regime, this association is inhibited.

Secondly, EPU can influence energy security by inhibiting investment in energy infrastructure such as power plants, pipelines, and clean energy projects. This situation can lead to a shortage of energy capacity and supply. Chen *et al*. (2024) demonstrated that oil-producing economies disproportionally receive more negative effects of EPU than oil-consuming economies. He *et al*. (2021) indicated that EPU created the energy sector's volatility in China. The degree of volatility, however, varies between oil exporters and importers. That is, oil exporters face more volatility. Dai *et al*. (2023) found out that Russian EPU exerted a short-term and risk-seeking influence on China's energy future (CEF) investors. Similarly, results are found in the case of Australian EPU on CEF. However, in the case of Brazil EPU played risk-seeking CEF investors with a short position. Thirdly, EPU can influence energy security risks by changing geopolitical links. Disputes or tensions between nations can disrupt energy supply, energy prices, and other energy-related issues (Wang *et al*., 2023).

Fourthly, EPU can determine energy security risks by influencing the pace of energy-related technological developments. The new energy technology can demonstrate a high sensitivity to EPU. That is, EPU can hinder energy-associated innovation that, in turn, can affect the availability and diversity of diverse energy sources, thereby impacting energy security. Many studies have highlighted the importance of EPU for innovations (Liu and Ma, 2020; Bloom *et al*., 2007; Zhu *et al*., 2021). However, the literature on EPU and innovation nexus provides conflicting evidence. The firms become more cautious when facing the challenge of external demand shock Bloom *et al*. (2007).

The real options theory (Folta and O'Brien, 2004; Quigg, 1993) suggests that the economic value of 'wait and see' is higher, and companies prioritize delaying the innovation process (Xu, 2020) to mitigate the potential investment risks and losses, suggesting a negative link between EPU and innovations. Kyaw (2022) found that policy-related uncertainties discourage environmental innovations. In a comparative setting, innovative firms find it a more suitable option to delay the present investment as it becomes a more valuable option (Gulen and Ion, 2016). In effect, the challenge of investment irreversibility is not completely ineversible in the case of innovation investment, therefore the value of deferred investment increases in the presence of high EPU. Thus, EPU leads to lower performance of innovations.

Contrary to this, other energy experts highlight that innovations are helpful in tackling the issues arising in response to policy uncertainties (He *et al*., 2020). That is, EPU serves as a source of grabbing innovation opportunities (He *et al*., 2020). The theoretical underpinning behind this approach can be traced from the growth options theory (Kulatilaka and Perotti, 1998; Bloom, 2014). Thus, a higher EPU leads to the value for the growth options. Hence, growth options theory suggests that EPU and innovations are positively linked. In the presence of high risks and market uncertainties, companies can expand early investment to harness future potential gains and a competitive advantage.

The growth options encourage firms to boost their innovation investment (Tajaddini and Gholipour, 2020). For instance, He *et al*. (2020); Shen *et al*. (2020) elucidated that a higher EPU led to more corporate innovation output. Feng and Zheng (2022) provided international evidence on EPU and energy innovations for 22 countries during the period 1985–2019. Their findings suggest that EPU supports energy innovations. However, this positive effect is only significant for economies having higher institutional quality than that of low institutional economies. Li *et al*. (2021) demonstrated a negative effect of EPU on green innovation. Meanwhile, some studies disregard a linear association between EPU and green innovation. For example, Xu and Yang (2021) and Zhu *et al*. (2021) showed a non-monotonic impact of EPU on green innovations.

Due to rising global geopolitical tensions, disruptions in energy markets, and uncertain ecological policies, it is crucial to understand how these dynamics shape energy security risks. At the same time, nations are striving to develop a low-carbon economic framework, thereby making environmental policies more stringent, which can have both stabilizing and disruptive effects on energy systems. Prior literature on ESR has mostly focused on its impact on environmental quality (Rabbi *et al*., 2022) and energy efficiency (Gökgöz and Güvercin, 2018), while some other studies have confirmed the role of clean energy and digitalization as determinants of energy security (Hache, 2018; Wang and Ullah, 2024; Thanh *et al*., 2023). However, despite the importance of EPS and EPU for energy security, empirical evidence in this context is limited, leaving a significant gap in the literature. This gap motivates us to conduct an analysis aimed at investigating the influence of EPS and EPU on ESR. Thus, the basic research question this study tries to address is whether EPU and EPS are vital in shaping ESR in advanced and emerging economies, both in the short and the long run. This analysis is crucial for enhancing our comprehension of the opportunities and threats for global energy security.

This study extends the existing research on energy security in the following dimensions. First, the present study investigates the influence of EPU on ESR. Second, the study also elucidates the role of stringent environmental policies in impacting ESR. Third, inclusion of EPU and EPS within the framework of energy security is another novel contribution of the study. Fourth, analysing advanced and emerging economies helps us understand the complex relationship between ESR, EPU, and EPS within varying political and socioeconomic environments. The analysis clarifies how EPU and EPS contribute to achieving the highest level of energy security in countries with varying social, economic, and governance structures. Fifth, this study focused on those economies that are important in the context of energy security. The findings of the study are useful for sampled economies and other economies with similar profiles. This approach aids stakeholders and governments in promoting energy security. Finally, for policymakers and stakeholders, this research provides valuable policy advice. The analysis emphasises the importance of policy certainty in supporting energy security by highlighting its beneficial effects in promoting endeavours toward green energy and energy mix.

2. Literature review

The national security of a country is strongly related to its energy security. Energy security measures during World War II were mostly based on the preservation of military applications; however, this trend changed when in the 1970s the two-oil crisis hit the world and several new ideas related to energy security emerged. In the contemporary global context, the definition of energy security is also changing, and it has now expanded by including several dimensions regarding supply, ecosystem, economics, and society (Augutis *et al*., 2012). The IEA (2000) defines energy security as "uninterrupted access to energy at a reasonable price". In a bid to define energy security more effectively, several empirics have analyzed energy security in quantitative terms, and most of them have done this by using single-indicator and composite index methodologies. Some of the famous indexes are the energy efficiency index and the energy dependence index (Chuang and Ma, 2013). On the other hand, some multi-factor indices of energy security have been proposed by Augutis (2012) and Song *et al*. (2019).

Currently, empirics have started examining the determinants of energy security. For instance, Radovanović *et al*. (2017) revealed that energy security is determined by three key elements, such as energy intensity, carbon intensity, and affluence. Wang *et al*. (2021) underscore the significance of urban population, population density, and manufacturing activities in impacting regional energy security. Lee *et al*. (2022) confirmed an inverse U-shaped nexus between ICT and energy security. Zhang *et al*. (2022) shed light on the favorable role of industrial expansion on security, whereas the favorable connection between information technologies and energy security.

In addition to the above-stated factors, environmental regulations have gained popularity as a crucial factor in enhancing the quality of the ecosystem and energy system, and the empirics have estimated the link between energy efficiency and environmental regulations. According to Mandal (2010), environmental-related regulations play a key role in enhancing energy efficiency in the cement sector of India but with visible heterogeneous impacts across several regions. Guo and Yuan (2020) revealed that the association between environmental regulations and energy efficiency is favorable but asymmetric. Further, an empirical work by Yan *et al*. (2023) stated that EPS help reduces the energy demand, as well as help mitigate fossil-fuel-based energy demand. Numerous researchers have also revealed that strict environmental policies cause energy intensity, and this happens because firms are bound to innovate their production techniques and enhance innovations (Lee and Ho, 2022).

Understanding the role of EPU in impacting different energy types, such as renewable energy, oil, and coal, is a renowned topic in energy finance. For example, as per Feng *et al*. (2020), EPU is a crucial tool in the crude oil industry. As per the observations of Rakpho and Yamaka (2021), EPU has the ability to forecast energy demand and supply. Furthermore, Ahmed *et al*. (2021) observed that with a reduction in uncertainty in economic policies, carbon footprints also reduce. Wang *et al*. (2022) stated that uncertainty can anticipate renewable energy volatility. Wei *et al*. (2021) estimated the connection between EPU and energy generation in China and confirmed that EPU and energy production move together. Shafiullah *et al*. (2021) analyzed the USA's EPU and renewable energy nexus. The outcomes of the causality analysis highlighted that a two-ways asymmetric causal connection exists between EPU and renewable energy. As per the nonparametric regressions, an inverse connection exists between EPU and renewable energy usage in the long run, suggesting that a more uncertain economic policy hinders clean energy use and vice versa. These factors, energy production, renewable energy, and carbon emissions, are all important determinants of energy security. Since EPU has a significant and close connection with these factors, EPU indirectly affects energy security by impacting these factors.

As far as literature on EPU and ESR, not enough literature is available apart from few exceptions. For instance, Dagar *et al*. (2024) estimated the impact of EPU on energy diversification, which is used as a measure of energy security. Diverse energy types generated from various artificial or natural sources may enhance energy security while fostering sustainable and environmentally beneficial alternatives. The results show that higher EPU reduces energy source diversity, weakening energy security. Zhang *et al*. (2024) examined the role of EPU and geopolitical risk on energy import security. Both EPU and geopolitical risk hinder energy imports and threaten China's energy security. In order to check the robustness, they employed three different variables as a measure of energy security import, i.e., coal import, oil import, and gas import. The impacts of EPU and geopolitical risk on coal imports and natural gas imports vary significantly from those on oil imports, principally owing to the substitution effect and geopolitical characteristics.

3. Theoretical framework and model

Environmental policies and rules have the ability to impact industrial prices by facilitating more equitable energy use and restricting emissions. *EPS* can influence energy security in both negative and positive ways. In the short run, strict environmental rules raise energy production costs, curb fossil fuel use, and heighten energy security risks (Aslam *et al*., 2025). However, in the long-run, when the environmental policies are stable and consistent, they are more likely to support innovation and investment in clean and eco-friendly technologies. According to growth option theory, firms always prefer to respond to sustainable and predictable policies by developing eco-friendly technologies, improving efficiency, and diversifying energy sources (Bian and Luo, 2025). As time passes, these efforts by the firms reduce reliance on imported fossil fuels, enhancing the sustainability and stability of the energy system and ultimately reducing *ESR*.

Nations with better environmental performance are more proactive in implementing strict environmental policies and forcing polluting businesses to restrict their output (Fan *et al*., 2021). Firms and businesses that comply with strict environmental policies and rules are in a better position to expand their client base by considering themselves as frontrunners in environmental conservation efforts. This gives them a competitive edge over other businesses and enhances their sustainable development (Aidara *et al*., 2021). The significance of Porter's hypothesis (Porter and Linde, 1995) increased manifold since 1990 after it was used to estimate the effects of stringent environmental policies on economic output. This idea posits that strict environmental regulations are helpful in steering the ecosystem to preserve a harmonious equilibrium between the ecology and the economy. As a result, this leads to a strengthened market position and improved benefits derived from possessing a unique r*EPU*tation (Perino and Pioch, 2017).

The proponents of Porter Hypothesis suggest that following the stringent environmental policies, more ecologically conscious firms are more likely to be involved in innovative activities and develop more energy-efficient and clean technologies, which in turn help them reduce their demand on conventional and dirty fossil fuels and improve the energy security situation. Due to stringent environmental policies, these firms enhance their investment in clean energy sources, which are crucial for diversifying the energy mix and stabilizing supply, making the energy systems more capable of bearing external shocks. In other words, a more efficient and sustainable energy structure can become a reality due to strict environmental policies. Thus, we can state that stringent environmental policies, within the framework of Porter's Hypothesis, catalyze the development of energy-efficient technologies and promote energy diversification, which are crucial for achieving energy security.

A phrase used to characterize policy-related uncertainty is *EPU* (Pirgaip and Dinçergök, 2020). These uncertainties are related to fiscal and monetary issues that impact the business climate in which enterprises flourish. *EPU* has the ability to influence investment decisions and the mechanisms of law implementation, both of which have a significant effect on the energy sector (Jackson and Orr, 2019). People and businesses are more likely to cut their investment in the energy sector when faced with uncertainties about possible energy shortages that might jeopardize energy security (WB, 2016). As the economy deviates from its normal course, it may also impact the price and amount of energy. According to Zakeri *et al*. (2022), these kinds of situations happen when market participants try to protect themselves against any unforeseen incident that can increase costs and limit access to energy. Any incident that brings uncertainty in economic policy may limit energy investments, such as the COVID-19 pandemic or international conflicts. This might jeopardize supply security and the capacity to retain reliable energy supplies. Reduced consumer spending may alter the cost and availability of energy supplies, and switching to renewable energy sources may become more challenging due to unstable policies (Li *et al*., 2023). *EPU* has an impact on conventional energy firms, which in turn has an effect on renewable energy investments (Su *et al*., 2023).

When government policies are unstable or change frequently, businesses and investors become uncertain about the future of their activities and significantly reduce overall investment (Montes and Nogueira, 2022). The growth option theory posits that firms and enterprises view investment in energy projects as somewhat risky and long-term, yet profitable under stable economic policies. As a result of uncertain economic policies, investors are postponing or even abandoning risky investments, including those in clean energy ventures, oil exploration, and energy storage (Shahnazi, 2025). Consequently, the risk related to energy security significantly increases due to enhanced unpredictability in energy supply and instability in energy prices. Furthermore, under unstable economic policies, the government has found it difficult to implement long-term strategies for energy imports and infrastructure development, thereby exacerbating energy security risks. Following the literature review and theoretical framework, we have developed the following model:

$$ESR_{it} = \partial_0 + \partial_1 EPU_{it} + \partial_2 EPS_{it} + \partial_3 TECH_{it} + \partial_4 EG_{it} + \partial_5 FD_{it} + \varepsilon_{it} \quad (1)$$

In Equation (1), energy security risk (*ESR*) is dependent on environmental policy stringency (*EPS*), economic policy uncertainty (*EPU*), technology (*TECH*), financial development (*FD*), economic growth (*EG*), and error term (ε_{it}). *EPU* is expected to have a positive effect on *ESR*. *EPU* tends to reduce investment in renewable energy projects, as investors perceive greater risks and are less willing to invest resources under uncertain policy conditions. This can slow the transition to energy sources and increase energy security risks. Conversely, *EPS* is expected to reduce *ESR*. As *EPS* stimulates the diversification of energy sources by promoting investments in energy technologies and energy efficiency measures. This diversification reduces energy security risks.

4. Econometric methodology

4.1 CSD and slope homogeneity test

In order to empirically test the relation between *EPS*, *EPU*, *ESR*, initially, it is crucial to check the cross-sectional dependency (CSD) across the panel entities, as a preliminary test before doing the regression analysis. The phenomenon of common shocks in longitudinal or panel data can be identified when these shocks have uniform effects across multiple panel entities, particularly due to their similar socioeconomic and ecological attributes. Consequently, if the CSD is not taken care of while performing the regression analysis, the estimates and their interpretation become biased and unreliable. Within our selected panel framework of 18 advanced and emerging economies, given the trade contacts and complex geopolitical ties among these nations, it is highly likely that these economies have to deal with a common macroeconomic shock of any kind. Given the significance of CSD during regression analysis, we have employed the Pesaran (2004) CSD test to ensure that our results are reliable and error-free. The generic equation of this test is as follows:

$$CSD_{test} = \sqrt{\frac{2T}{N(N-1)}}\left(\sum_{i=1}^{N-1}\sum_{k=i+1}^{N}\hat{\tau}_{ik}\right) \tag{2}$$

Secondly, the examination of slope heterogeneity is conducted because each panel entity has different characteristics within a specific panel data set, potentially leading to the estimation of slope heterogeneous for the corresponding panel entity. The varying levels of national income, environmental regulations, economic uncertainty, and *ESR* in the context of advanced and emerging economies suggest that the slope coefficients obtained from regression analyses may not be uniform across these nations. Consequently, statistical estimates may turn out to be biased and inconsistent. Thus, to counter this issue, we have employed the slope heterogeneity test of Pesaran and Yamagata (2008), based on the following equations:

$$\widetilde{\Delta}_{HPY} = (N)^{\frac{1}{2}}(2k)^{-\frac{1}{2}}\left(\frac{1}{N}\widetilde{S} - k\right) \tag{3}$$

$$\widetilde{\Delta}_{ASH} = (N)^{\frac{1}{2}}\left(2k\left(\frac{T-k-1}{T+1}\right)^{-\frac{1}{2}}\left(\frac{1}{N}\widetilde{S} - 2k\right)\right) \tag{4}$$

4.2. Unit root test

Thirdly, the stationarity test is performed to determine whether the data series in this research has a unit root. Conducting stationarity analysis by using the unit root test is crucial, since non-stationary data may lead to false outcomes. Furthermore, not every econometric technique is suitable for data that is not stationary or data that has the variables exhibiting varying orders of integration. To establish stationarity (*i.e.*, to verify the absence of a unit root), the data points within a certain variable must return to its mean value; otherwise, the variable would be deemed non-stationary. Thus, this study tests variable stationarity using Pesaran's (2007) CIPS unit root test. This approach is selected for its efficiency in mitigating CSD-related issues in the data. This test relies on the cross-sectional averages to take care of the "common factor effects" represented by the following equation:

$$\Delta V_{i,t} = \alpha_i + \alpha_i Y_{i,t-1} + \alpha_i X_{t-1} + \sum_{l-0}^{p} \alpha_{i1} \Delta \overline{V_{t-1}} + \sum_{i-1}^{p} \alpha_i \Delta X_{i,t-1} + \mu_{it} \tag{5}$$

where $\overline{V}_t$ signifies the cross-sectional average. The CIPS statistics is estimated by using the average of individual CADF statistics for every panel entity, as shown below:

$$\widehat{CIPS} = \frac{1}{N} \sum_{i=1}^{n} C_{ADF}^{i} \tag{6}$$

4.3 Westerlund cointegration test

The analysis of cointegration is conducted to determine if the annual *ESR* in advanced and emerging economies exhibits long-run (LR) associations with *ESR*, *EPU*, *EPS*,*TECH*, *EG*, and *FD*. The *ESR* series and at least one series from the *EPU*, *EPS*, *TECH*, *EG*, *FD* must move together to confirm a valid LR link between the variables, known as cointegration. In situations where cointegration among the relevant variable series cannot be established, the LR relation becomes absurd and less relevant. Therefore, when cointegration is not confirmed, the short-run (SR) analysis becomes more significant and appropriate. This work used the panel cointegration methodology proposed by Westerlund (2008). Compared to Pedroni (2004), which is a residual-based test, Westerlund (2008) is an error-correction-based test that can estimate the valid LR connection between variables, even in the presence of the CSD. Furthermore, Westerlund (2008) provides comparably superior finite-sample results than the test proposed by Pedroni (2004). The error-correction equation of Westerlund is based on the following equation:

$$\Delta x_{it} = \varphi_i d_t + \varrho_i \left(x_{it-1} - \beta_i \, y_{it-1} \right) + \sum_{j=1}^{ki} \varphi_{ij} \, \Delta x_{it-j} + \sum_{j=-qi}^{ki} \vartheta_{ij} \, \Delta \, y_{it-j} + \varepsilon_{it} \tag{7}$$

In order to prove the cointegration, Westerlund (2008) offers two Group statistics and two Panel Statistics, which are based on the following equations (8–11):

$$G_\tau = N^{-1} \sum_{i=1}^{N} \frac{\theta_i}{SE(\theta_i)} \tag{8}$$

$$G_\alpha = N^{-1} \sum_{i=1}^{N} \frac{T\theta_i}{\theta_i(1)} \tag{9}$$

$$P_\tau = \frac{\theta_i}{SE(\theta_i)} \tag{10}$$

$$P_\alpha = T\theta_i \tag{11}$$

4.4 Methods of estimation

After completing all requisite tests, we used the CS-ARDL established by Chudik and Pesaran (2015) to examine the SR and LR connection between the variables. The CS-ARDL offers comprehensive estimates of autoregressive distributed lag models while considering cross-dependence in analysis. This method uses normalized coefficients generated by variable averaging. The CS-ARDL is a distinguished third-generation econometric approach that accounts for structural breaks and other variables to mitigate estimation bias. The CS-ARDL model outperforms alternative cointegration approaches due to its assumptions for managing slope heterogeneity, cross-sectional dependence, endogeneity, and structural breakdowns. Significantly, CS-ARDL encompasses both SR variations and LR equilibrium associations, making it suitable for analyzing the SR and LR connection between *ESR*, *EPU*, *EPS*, *TECH*, *EG*, and *FD*. In addition, the CS-ARDL can efficiently handle the variables with varying orders of cointegration, making it suitable for macroeconomic analysis where the variables are either I(0) or I(1). The equation of the CS-ARDL model is articulated as follows:

$$\Delta ESR_{i,t} = \varphi_i + \sum_{l=1}^{p} \theta_{il}\Delta ESR_{i,t-l} + \sum_{l=0}^{p} \partial'_{il}X_{i,t-l} + \sum_{l=0}^{1} \delta'_{il}\bar{Z}_{i,t-l} + \varepsilon_{i,t} \tag{12}$$

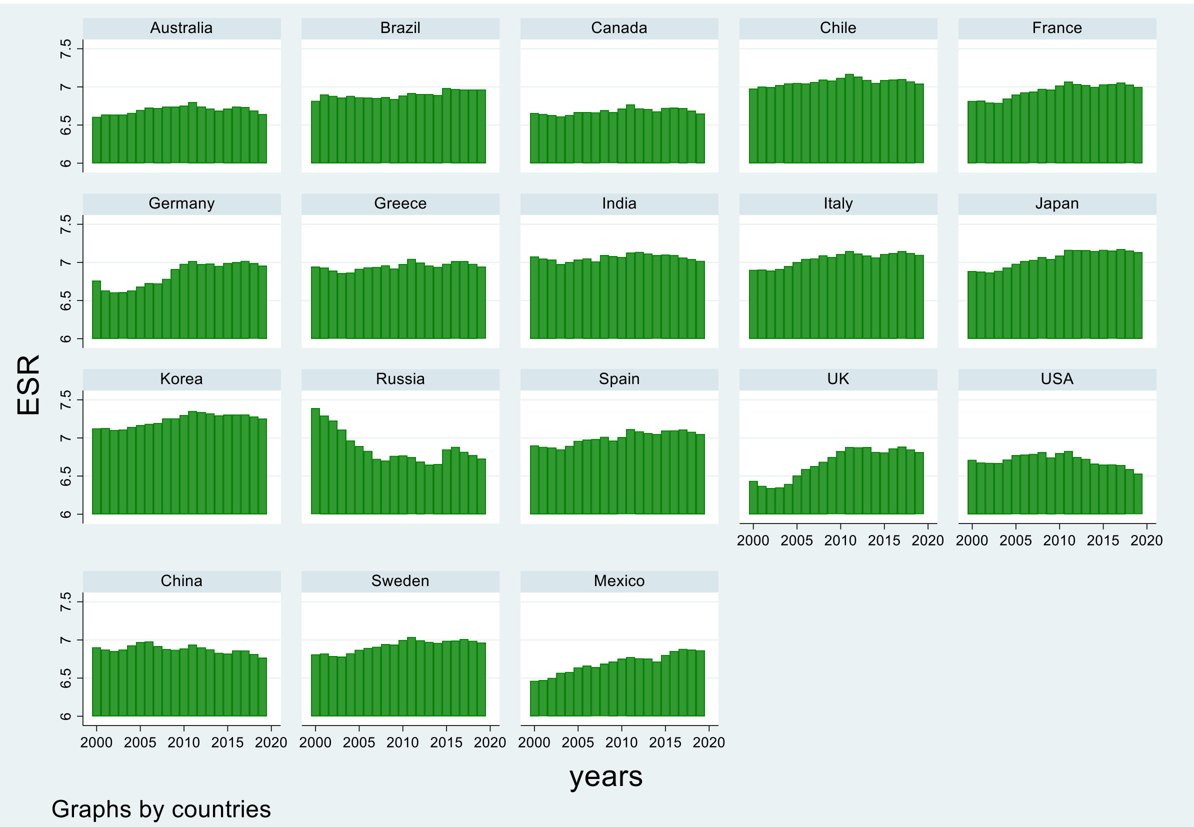
where $\Delta ESR_{i,t}$ is our outcome variable, and X_{it} represents all regressors in the LR, t represents the time period, and i indicates the panel entity (country in our case). The mean values of the outcome variable and the regressors are represented by $\bar{Z}_{i,t-l}$, $\varepsilon_{i,t}$ is a randomly distributed error term.

The pooled mean group autoregressive distributed lag (PMG-ARDL) approach offers important benefits when used as a robustness technique alongside the CS-ARDL estimator. It allows for SR heterogeneity across cross-sections while assuming LR homogeneity, making it especially suitable for panel data with diverse units but common LR relationships (Pesaran *et al.*, 1999). Unlike traditional methods, the PMG-ARDL efficiently manages mixed-order variables (I(0) and I(1)) without requiring transformation or differencing. One of PMG-ARDL's main advantages is its ability to estimate SR dynamics and LR equilibrium connections concurrently within a single framework (Alsagr *et al.*, 2025). Thus, PMG-ARDL also provides efficient and consistent estimates of LR parameters while accounting for dynamic adjustments in the SR (Yang *et al.*, 2025).

5. Data and descriptive analysis

The study explores the nexus between environmental policy stringency, economic uncertainty, energy security risk using 18 advanced and emerging economies from 1997 to 2019. Data for the three key variables – environmental policy stringency, economic uncertainty, and energy security risk – are available for only 18 economies, so the sample is limited to these 18 economies. Energy security risk is the dependent variable, while economic policy uncertainty (*EPU*) and environmental policy stringency (*EPS*) are independent variables. All three variables are assessed through indexes. Data series for the energy security index is obtained from the Global Energy Institute. *ESR* trend is shown in Figure 1. Baker, Bloom and Davis provide the data for the *EPU* index, while *EPS* index data series is taken from the OECD. The Global Energy Institute created the energy security risk index variable, which we used as the dependent variable in our investigation. This is the most comprehensive measure of energy security risk, and it is preferred over other measures as it covers 29 indicators. This variable is commonly used in energy economics research. *ESR* data are only available up to 2019 and are not available from any other source.

Figure 1: Trend of energy security risk



Source: Authors' own elaboration

Technology, economic growth, and financial development role is incorporated as control variables in the model. Prior studies justify these control variables in the context of energy security. For instance, technological developments improve the efficiency of energy production and reducing dependence on fossil fuels (Chen *et al*., 2021). Technology (*TECH*) is determined through total patent applications. Literature shows that economies with higher economic growth tend to invest more in energy infrastructure, thus strengthening energy security (Ullah *et al*., 2024). Economic growth (*EG*) is assessed through annual percent of GDP growth. The data series for technology and economic growth are taken from the World Bank. Financial development enhances energy security by providing access to capital for promoting investments in renewable energy infrastructure (Zeng *et al*., 2024). Financial development index is used to measure this variable, which the IMF calculates. Table 1 summarizes the variable's description and sources.

Table 1: Variables and data sources

Variables	**Symbol**	**Definitions**	**Sources**
Energy security risk	*ESR*	Energy security risk index	Global Energy Institute
Economic policy uncertainty	*EPU*	Economic policy uncertainty index	Baker, Bloom and Davis
Environmental policy stringency	*EPS*	Environmental policy stringency index	OECD
Technology	*TECH*	Patent applications, total	World Bank
Economic growth	*EG*	GDP growth (annual %)	World Bank
Financial development	*FD*	Financial development index	IMF

Source: Authors' own elaboration

Table 2 provides summary statistics. The mean score of *ESR* is 6.886, with a S.D 0.199. It shows a slightly negative skewness (−0.115). *EPU* has a mean score of 4.688 and a higher S.D of 0.456. It is positively skewed (0.365). *EPS* shows a mean of 2.030 and a S.D of 1.127. *TECH* has a mean of 10.07 and S.D of 1.801. *EG* has a mean of 2.847 but S.D of 3.119. Its distribution is slightly negatively skewed (−0.125). Finally, *FD* has a mean of 0.676, a S.D of 0.184, and is negatively skewed (−0.387). The Jarque–Bera statistic shows that *ESR* and *TECH* follow normal distribution, whereas *EPU*, *EPS*. *EG*, and *FD* are non-normally distributed series.

Table 2: Summary statistics

	Mean	Median	Max	Min	S.D	Skewness	Kurtosis	Jarque–Bera	Prob.
ESR	6.886	6.887	7.540	6.341	0.199	−0.115	3.055	0.971	0.615
EPU	4.688	4.666	6.297	3.296	0.456	0.365	3.568	14.73	0.001
EPS	2.030	2.028	4.722	0.000	1.127	0.041	1.845	23.12	0.000
TECH	10.07	10.11	14.24	5.737	1.801	−0.058	2.767	1.171	0.557
EG	2.847	2.688	14.23	−10.14	3.119	−0.125	4.955	67.02	0.000
FD	0.676	0.736	0.967	0.261	0.184	−0.387	1.823	34.22	0.000

Source: Authors' own calculations

Table 3: Correlation matrix

	ESR	***EPU***	***EPS***	***TECH***	***EG***	***FD***
ESR	1					
EPU	0.060	1				
EPS	0.279	0.345	1			
TECH	−0.071	0.128	0.101	1		
EG	0.017	−0.273	−0.360	0.172	1	
FD	−0.067	0.229	0.624	0.249	−0.293	1

Source: Authors' own calculations

Table 3 displays the correlation matrix. The *ESR* shows a moderate positive correlation with *EPS* (0.279) and a weak positive correlation with *EPU* (0.060). *TECH* has a slight negative correlation with *ESR* (−0.071). *EPU* is positively correlated with *EPS* (0.345) and *TECH* (0.128). Conversely, *EPU* has a negative correlation with *EG* (−0.273). *EPS* exhibits a strong positive correlation with *FD* (0.624) and a moderate negative correlation with *EG* (−0.360). *TECH* shows positive correlations with *FD* (0.249) and *EG* (0.172). However, *TECH* correlation with *EPS* (0.101) is relatively weak. *EG* has a negative correlation with *FD* (−0.293). Lastly, *FD* has a weak negative correlation with *ESR* (−0.067).

Table 4 presents the results of the VIF test, which is used to check the multicollinearity among the variables in the model. A VIF score below 10 generally indicates no significant multicollinearity issues. The VIF scores for the variables range from 1.17 to 1.83. The mean VIF score is 1.46, further confirming that multicollinearity is not an issue in our analysis.

Table 4: VIF results

Variable	VIF	1/VIF
EPS	1.83	0.545
FD	1.78	0.560
EG	1.29	0.772
EPU	1.20	0.835
TECH	1.17	0.851
Mean VIF	1.46	

Source: Authors' own calculations

6. Empirical results and discussion

Tables 5 and 6 report CSD and slope heterogeneity results, respectively. Table 5 confirms cross-sectional dependence among all indicators. Next, slope homogeneity tests assess whether parameter slopes are consistent across the selected economies. Table 6 reports slope heterogeneity test outcomes. The rejection of the null confirms slope heterogeneity.

Table 5: CSD results

	ESR	***EPU***	***EPS***	***TECH***	***EG***	***FD***
Pesaran's test	8.998***	12.69***	10.38***	0.001	17.57***	11.13***
Friedman's test	82.07***	103.2***	85.13***	28.27**	88.76***	75.19***

Note: **, *** denote statistical significance at the 5%, and 1% levels, respectively.
Source: Authors' own calculations

Table 6: Slope heterogeneity results

	ESR	*EPU*	*EPS*	*TECH*	*EG*	*FD*
$\hat{\Delta}$	11.16***	9.863***	10.56***	12.38***	2.111**	11.79***
$\hat{\Delta}_{adj}$	13.38***	11.82***	12.65***	14.85***	2.531**	14.13***

Note: **, *** denote statistical significance at the 5%, and 1% levels, respectively.
Source: Authors' own calculations

Table 7 shows unit root test results using second-generation methods due to CSD. The CIPS test is employed. The CIPS indicate that *ESR*, *EPS*, and *TECH* are non-stationary at their levels, while they turned out to be stationary at their first differences. Other indicators, namely *EPU*, *EG*, and *FD* become stationary at their levels. The results indicate a mixed order of integration. In this scenario, the ARDL model is the best choice for analysis as it takes care of the mixed order of integration given that no series is integrated of order two. Moreover, our data has the issue of CSD, therefore, we employ CS-ARDL. In the next step, the cointegration of the series is tested using the Westerlund test. Table 8 shows that Pt, Gt, and Pa are significant at the 1% level, indicating the presence of cointegration among the series.

Table 7: CIPS results

	I(0)	**I(1)**
ESR	−1.078	−4.205***
EPU	−1.940**	
EPS	−1.078	−4.205***
TECH	−1.535	−4.506***
EG	−3.122***	
FD	−1.991***	

Note: **, *** denote statistical significance at the 5%, and 1% levels, respectively.
Source: Authors' own calculations

Table 8: Westerlund cointegration test results

Statistic	Value	z-value	p-value
G_t	–2.247***	3.504	0.000
G_a	–7.524*	1.319	0.093
P_t	–8.209***	3.186	0.001
P_a	–6.187***	3.193	0.001

Note: *, *** denote statistical significance at the 10%, and 1% levels, respectively.
Source: Authors' own calculations

Table 9 reports the empirical outcomes based on CS-ARDL and PMG-ARDL. In LR, *EPU* results indicate that *EPU* has a positive and significant effect on energy security. The parameter estimate indicates that a 1% incline in *EPU* will lead to a 0.21 percent rise in energy security. The SR results suggest *EPU* positively affects energy security, but the effect is insignificant, implying its impact emerges in the LR. This finding is consistent with real options theory (Quigg, 1993). This theory suggests that the economic value of 'wait and see' is higher, and companies prioritize delaying the innovation process (Xu, 2020) to mitigate the potential investment risks and losses, suggesting a negative link between *EPU* and innovations. Kyaw (2022) found that policy-related uncertainties discourage environmental innovations. In a comparative setting, innovative firms find it a more suitable option to delay the present investment as it becomes a more valuable option (Gulen and Ion, 2016). *EPU* creates *ESR* by creating energy price fluctuations that can change the balance of demand and supply for energy, creating energy security issues. This finding is consistent with Scarcioffolo and Etienne (2021) and Wang *et al*. (2024) who demonstrated that *EPU* created a disturbance in the energy markets in the USA and China, respectively. Besides, *EPU* can increase energy security risks by influencing the pace of energy-related technological developments. The new energy technology can demonstrate a high sensitivity to *EPU*. That is, *EPU* can hinder energy-associated innovation that, in turn, can affect the availability and diversity of diverse energy sources, thereby impacting energy security (Zhu *et al*., 2021; Bloom *et al*., 2007).

Table 9: CS-ARDL and PMG-ARDL estimates

	CS-ARDL	PMG-ARDL (robustness)
Long-run		
EPU	0.211*** (0.041)	0.407*** (0.101)
EPS	0.097* (0.050)	0.106 (0.094)
TECH	−0.267** (0.095)	−0.442** (0.190)
EG	−0.104*** (0.004)	−0.131*** (0.044)
FD	−0.818* (0.488)	−2.289*** (0.876)
Short-run		
D(EPU)	0.011 (0.024)	0.015** (0.007)
D(EPS)	−0.012 (0.021)	−0.003 (0.010)
D(TECH)	0.082* (0.045)	0.103* (0.058)
D(EG)	0.001 (0.002)	0.004*** (0.001)
D(FD)	0.015 (0.155)	0.160** (0.080)
C		0.512*** (0.190)
Number of countries	18	18
ECM(−1)	−0.758*** (0.074)	−0.341*** (0.013)
Post estimation tests		
LM	1.689	
BP	1.914	

Note: *, **, *** denote statistical significance at the 10%, 5%, and 1% levels, respectively.

Source: Authors' own calculations

Similarly, the LR coefficient on *EPS* indicates that environmental policy has a positive and significant effect on *ESR*. The parameter estimate indicates that a 1% increase in *EPS* will lead to a 0.09 percent rise in *ESR*. Usman *et al*. (2024) asserted that *EPS* can create an energy security issue by limiting the use of conventional energy sources. They provided firm evidence about the negative effects of *EPS* on trade in conventional energy sources for top polluting economies. Moreover, *EPS* can undermine energy security by increasing operational costs and creating geopolitical risks. *EPS* requires energy producers to invest in clean energy or adopt pollution-controlling measures, enhancing operation costs. That is, the implementation of *EPS* increases regulatory and compliance costs. *EPS* can also change energy trade dynamics. In this situation, if energy or technological requirements for complying with *EPS* depend on foreign sources, geopolitical risks may arise, particularly if those sources are located in unstable regions. Alsagr (2023) suggests that *EPS* can paradoxically increase energy security risks by discouraging the necessary technological advancements and infrastructure improvements required for advancements in green energy.

All control variables *TECH*, *EG*, and *FD* have a negative and significant influence on energy security risks. The coefficient on *TECH* suggests that a one percent increase in *TECH* will lead to a 0.27 percent decline in energy security. A similar result is observed in the SR. The control variable *TECH* is measured by the total number of patents. The increasing number of patents indicates innovations and technological growth. In such a scenario, especially in the energy sector, energy efficiency and energy diversification tend to increase, therefore enhancing energy security. The coefficient on *EG* also indicates that a 1% incline in *EG* will lead to a decline of 0.10% in energy security. Growing economies have more potential to afford the adoption of green energy sources and support energy diversification, thereby improving their energy security. Finally, the coefficient on *FD* shows that a 1% incline in *FD* will lead to a decline of 0.82 percent in energy security. This finding is consistent with the findings of Lee and Wang (2022) who found a favorable role of financial development in China. The PMG-ARDL results also support findings based on CS-ARDL. That is both *EPU* and *EPS* have a positive and significant effect on energy security in the LR. However, the coefficient on *EPS* is not robustly positive indicating that comparatively the effect of *EPU* is more robust in enhancing LR energy security. In short, Table 9 highlights distinct dynamics. In the LR, *EPU* exerts a strong influence on energy security. In contrast, the SR results reveal weaker and mostly insignificant effects. While *EPU* has a positive but statistically insignificant SR effect, its impact becomes meaningful only in the LR. Similarly, *EPS* also demonstrates a significant positive LR impact on *ESR*. However, *EPS* shows an insignificant SR coefficient. The LR effects are comparatively larger and more significant than the SR effects. The effects of control variables are robust across both estimators. The Lagrange Multiplier (LM) test is applied to check for autocorrelation in the models. The results show that there is no autocorrelation problem. The Breusch–Pagan (BP) test results also indicate that the models are free from heteroscedasticity issues.

Two additional panel data estimators are employed to assess the robustness of results. In this respect, Table 10 reports the empirical outcomes based on FMOLS and DCCE estimators. The LR coefficients for both *EPU* and *EPS* indicate a positive and significant influence on *ESR* in the selected economies. The parameter estimate indicates that a one percent increase in *EPU*/*EPS* leads to a 0.031/0.077 percent rise in energy security.

Table 10: FMOLS and DCCE estimates (robustness)

Variables	FMOLS	DCCE
EPU	0.031** (0.015)	0.028** (0.013)
EPS	0.077** (0.037)	0.045** (0.020)
TECH	−0.221* (0.135)	−0.179*** (0.068)
EG	−0.004 (0.004)	−0.002 (0.003)
FD	−2.851*** (0.514)	−1.162*** (0.183)
Constant	4.309** (1.760)	
Number of countries	18	18

Note: *, **, *** denote statistical significance at the 10%, 5%, and 1% levels, respectively.
Source: Authors' own calculations

7. Conclusions and policy recommendations

Indeed, the significance of energy for running the day-to-day affairs of society can't be underestimated. Energy is primarily responsible for the higher standards of living people are enjoying in this current age, as almost every sector of the economy requires energy to operate, such as health, education, transportation, housing, agriculture, and manufacturing.

However, the current trends have shown that the high demand for energy, the depletion of conventional energy resources, and the slow transition to renewable energy sources are impacting the pace of economic growth, particularly in developing economies. Therefore, researchers and academics must look for the determinants of energy security, which is crucial for making more informed decisions regarding improved energy security by providing continuous and sustainable energy sources. This analysis aims to examine the impact of EPS and EPU on ESR by utilizing the CS-ARDL and PMG. The results reveal that EPU helps enhance the ESR in the LR and SR. On the other hand, EPS enhances the ESR only in the LR. In contrast, technological, economic, and financial development hurt the ESR in the LR, while these factors enhance the ESR in the SR.

Based on these outcomes, we recommend the following main policies for decision-makers. Energy security rises as a result of strict environmental rules and policies; thus, a balanced policy must be created and implemented by the government to ensure that energy is available, affordable, and accessible to everyone. In addition to other environmental protection measures, such as the creation of green funds, technical advancements, and setting aside a budget specifically for environmental preservation, policymakers must develop and implement moderate ecological laws and restrictions to conserve the environment. With the help of these combined policy measures, not only the environmental performance of the nation will improve but also the energy security due to the enhanced energy efficiency and diversification of the energy mix. As stringent environmental policies increase the long-run risks related to energy security, it is suggested that emerging economies should design these policies with a focus on the specific industry's requirements to avoid disruptions in energy commodity trade and production. We also suggest that emerging economies should focus on promoting technological, financial, and economic development, as these factors significantly reduce energy security risks in the short run while countering long-term risks through innovation and efficiency gains. Further, aligning the objectives of clean energy justice with stringent environmental policies promotes equitable access, cost-effectiveness, and fair distribution, resulting in sustainable and more inclusive energy transitions.

In addition, EPU is detrimental to energy security; thus, it fosters risks related to energy security. In order to counter the detrimental impacts of EPU on energy security risks, policymakers should develop a stable and long-term policy structure. Further, it is suggested that policymakers should work for stable and transparent governance frameworks, which are crucial for enhancing investor confidence and long-term resilience, resulting in a more reliable and robust energy structure. Specifically addressing standard practices, which may be seen as a proactive measure to reduce the risks associated with short-term energy security-related EPU. Further, the policymakers should prioritize the diversification of the energy mix, enhance investment in domestic energy production, and boost the efficiency of the energy sector, reducing the reliance on the volatile global energy markets. This tactical change may make the energy system more robust by reducing the risks brought on by price volatility and supply interruptions. Moreover, the establishment of stable and long-term policies, specifically addressing standard practices, may be seen as a proactive measure to reduce the risks associated with short-term energy security-related EPU.

One key limitation of this study is that the dataset ends in 2019, as there is no data available on our dependent variable of ESR beyond this year. Due to this data limitation, this analysis can't capture major global disruptions that occurred after 2019, such as the COVID-19 pandemic, the Russia-Ukraine conflict, and the tensions in the Middle East, which play a critical role in shaping the dynamics of the global energy markets, supply chains, and policy environments. Thus, future studies should extend the dataset beyond 2019 to 2024 by employing alternative measures of energy security, which would provide more in-depth and accurate information regarding the nexus between ESR, EPU, and EPS. Moreover, the sample of 18 economies is relatively small and may be sensitive to outliers, especially when comparing energy exporters with importers. This problem can be resolved in future studies by collecting data across more countries and increasing the data volume. This approach makes it less vulnerable to econometric issues, including outliers, and thereby offers reliable and robust estimates. This study overlooks post-2019 developments in EPS, which have supported energy transitions in OECD countries but hindered progress in BRICS due to trade-offs. Future research should consider EPS–geopolitical risk interactions, particularly their amplification through EPU, to better understand impacts on energy security and transition pathways.

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