GENDER-RELATED ENERGY INSECURITY: EXAMINING THE NEXUS BETWEEN ENERGY SECURITY RISKS AND GENDER EQUALITY

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Nezahat DOĞAN

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Nezahat DOĞAN [1]

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ABSTRACT

Energy is widely recognized as a fundamental driver of economic growth and sustainable development. However, uncertainties in energy supply and demand pose significant challenges to global energy security. This study investigates whether gender equality can mitigate energy security risks by examining the case of the United States over the period 1989–2019. Using an Autoregressive Distributed Lag (ARDL) framework, the study explores the long-run relationship between gender equality (SDG 5) and energy security (SDG 7), measured by the Gender Inequality Index (GII) and the Energy Security Risk Index (ESRI), respectively. The analysis also incorporates key control variables, including real GDP per capita, urban population, and the share of women female investors. The findings provide evidence of a significant long-termrun association relationship between gender equality and energy security risk. By integrating gender dynamics into the analysis of energy security, this study contributes to the literature by offering a more comprehensive perspective and provides policy-relevant insights for promoting inclusive and resilient energy systems.

ÖZ

Enerji, ekonomik büyümenin ve sürdürülebilir kalkınmanın temel belirleyicilerinden biri olarak geniş ölçüde kabul edilmektedir. Ancak enerji arz ve talebine ilişkin belirsizlikler, küresel enerji güvenliği açısından önemli zorluklar yaratmaktadır. Bu çalışma, 1989–2019 dönemi için Amerika Birleşik Devletleri örneğini inceleyerek, toplumsal cinsiyet eşitliğinin enerji güvenliği risklerini azaltıp azaltamayacağını araştırmaktadır. Çalışmada, Otoregresif Dağıtılmış Gecikmeli (ARDL) yaklaşımı kullanılarak, toplumsal cinsiyet eşitliği (SKA 5) ile enerji güvenliği (SKA 7) arasındaki uzun dönemli ilişki analiz edilmektedir. Bu kapsamda, toplumsal cinsiyet eşitsizliği Birleşmiş Milletler tarafından geliştirilen Toplumsal Cinsiyet Eşitsizliği Endeksi (GII) ile, enerji güvenliği ise Enerji Güvenliği Risk Endeksi (ESRI) ile ölçülmektedir. Analize ayrıca kişi başına reel gelir, kentsel nüfus ve kadın yatırımcıların payı gibi temel kontrol değişkenleri de dahil edilmiştir. Elde edilen bulgular, toplumsal cinsiyet eşitliği ile enerji güvenliği riski arasında anlamlı bir uzun dönemli ilişki olduğunu ortaya koymaktadır. Bu çalışma, enerji güvenliği analizine toplumsal cinsiyet dinamiklerini entegre ederek literatüre daha bütüncül bir bakış açısı kazandırmakta ve kapsayıcı ve dirençli enerji sistemlerinin geliştirilmesine yönelik politika yapıcılara önemli çıkarımlar sunmaktadır.

[1] Prof. Dr. Nezahat DOĞAN, Arkın University of Creative Arts and Design (ARUCAD), Faculty of Communication, nezahat.dogan@arucad.edu.tr, ORCID: 0000-0002-7357-6030

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INTRODUCTION

The U.S. Energy Information Administration projects that global energy demand is expected to increase by approximately 50% by 2050, driven by factors such as population growth, economic development, and urbanization (U.S. Energy Information Administration, 2023). In contrast, energy demand in the United States is projected to grow at a more modest pace, with an estimated increase of around 8% over the same period. This divergence between global and U.S. energy demand trends highlights the importance of addressing energy security challenges in the United States, particularly within an increasingly complex global energy landscape. Although the U.S. has taken several steps to strengthen its energy security, partly in response to past vulnerabilities such as the 1973 oil crisis, various risks persist. For instance, policies such as the Energy Independence and Security Act of 2007 have encouraged investment in renewable energy and contributed to improving energy resilience. Despite these efforts, the United States continues to face a range of energy security risks with important implications for sustainable development. According to the Energy Security Risk Index (2020) published by the U.S. Chamber of Commerce's Global Energy Institute, the country's energy security risk score has shown an upward trend in recent years. While the overall index score was 68.1 in 2021, it is projected to rise to 70.4 by 2040. Notably, the report also indicates that the United States achieved its strongest energy security performance in 2019 since 1970. Traditionally, energy security has been primarily concerned with ensuring a reliable supply of energy and safeguarding economic interests, often with limited attention to environmental and social dimensions. However, as the United States increasingly moves toward more sustainable energy systems, the environmental and social implications of energy security have gained greater importance. Much of the existing literature conceptualizes energy security by focusing on a single dimension within the energy–environment–economic development nexus. Nevertheless, a more comprehensive understanding of energy security requires a broader perspective that incorporates sustainability as a guiding principle, including its social dimension. In this context, factors such as gender equality become particularly relevant. The United States continues to face challenges in addressing energy security risks, especially when considering the role of gender inequality within this broader framework.

Energy security is a multidimensional concept that extends beyond simple supply and demand conditions, encompassing factors such as price volatility, system reliability, affordability, and institutional resilience. Within this broader framework, gender equality represents an important yet often underexplored dimension. Gender-related inequalities in political representation, labor market participation, financial decision-making, and access to education can influence household energy vulnerability, shape institutional responses to energy shocks, and affect investment priorities. As a result, even in high-income countries such as the United States, where physical energy shortages are relatively limited, gender inequality may still play a critical role in underlying social and institutional vulnerabilities, ultimately shaping energy security risks.

Gender equality in the United States remains a complex and multifaceted issue, characterized by progress in certain areas alongside persistent challenges. Compared to other developed countries, the United States lags behind several European Union nations in terms of gender equality performance. For example, according to the Gender Inequality Index, the U.S. ranks 44th globally, while countries such as Denmark, Norway, and Switzerland consistently perform among the top in terms of women's empowerment and equality (2022). At the same time, the United States performs relatively better than some other major economies, such as China, Brazil, and Türkiye, where female participation in leadership positions and the labor market remains comparatively lower. However, gender equality outcomes in the U.S. are not uniform and vary significantly across regions and demographic groups, with some states and communities making more progress than others. Despite legislative efforts, such as equal pay laws, and increased female participation in political processes, deeply rooted cultural norms and structural barriers continue to constrain the achievement of full gender equality.

The gender equality landscape in the United States presents both opportunities and challenges when considered within the framework of energy security. To address a gap in the literature, this study examines the intersection between gender and energy security, with particular attention to the disproportionate burden of energy insecurity on women and the potential of gender-focused approaches to improve energy outcomes.

The primary objective of the study is to analyze the relationship between gender equality and energy security risk in the United States over the period 1989–2019. As a high-income economy with an advanced energy infrastructure, energy insecurity in the U.S. is less associated with physical scarcity and more closely linked to institutional, structural, and distributional factors. At the same time, gender equality has evolved over time, particularly in areas such as labor market participation, financial inclusion, and political representation. This context provides a suitable framework for examining how the socio-economic and institutional dimensions of gender equality interact with energy security in a mature energy system. In addition, the study explores the long-run relationship between gender equality and energy security risk within an ARDL–ECM framework, allowing for a clearer understanding of their dynamic interaction over time. This approach contributes to the literature by highlighting the structural role of gender equality in shaping long-term energy security outcomes.

LITERATURE REVIEW

Defining energy security is inherently challenging due to its broad and multidimensional nature. It has become a central concern for countries, not only in the context of energy policy but also within broader national security strategies. Luft and Korin (2009) conceptualize energy security differently for energy-exporting and energy-importing countries. For exporting countries, ensuring stable demand and access to diverse international markets is essential, whereas for importing countries, the reliability and continuity of energy supply are of primary importance. Similarly, the International Energy Agency (International Energy Agency, 2022) defines energy security as the uninterrupted availability of energy sources at an affordable price. Beyond the traditional supply–demand distinction, Blum and Legey (2012) emphasize that energy security also encompasses additional dimensions, including the sustainability of energy supply.

Energy security risks can be classified into several dimensions, including geopolitical, economic, environmental, and technological factors (Alshwawra & Almuhtady, 2020; Blum & Legey, 2012; Mansson, 2014; Nawaz & Alvi, 2018; Soliman, Lopez, & Biona, 2019; Sovacool, 2012). Geopolitical risks may arise from political tensions and conflicts, either within countries or between them, which can disrupt energy supply and distribution systems. For example, tensions between the United States and other countries over access to fossil fuel resources or control of strategic energy infrastructure, such as oil and gas pipelines, may lead to supply chain disruptions and price volatility in energy markets (Axon & Darton, 2021; Fija & Grigorie, 2021; Paravantis & Kontoulis, 2020; Zhilkina, 2019). Economic risks include energy price volatility, imbalances between supply and demand, insufficient investment in energy infrastructure, and affordability challenges, particularly for low-income households and marginalized groups (Fija & Grigorie, 2021; Jessel, Sawyer, & Hernandez, 2019; Sovacool, 2012).

Environmental risks, such as hurricanes, wildfires, and droughts in the United States, can also threaten energy security by damaging infrastructure, disrupting supply, and increasing demand, thereby intensifying fluctuations in both availability and prices. Technological risks are associated with failures or inefficiencies in energy systems, including grid disruptions, equipment malfunctions, and cybersecurity threats. Such risks may interrupt energy distribution and availability, while also reflecting the challenges of technological obsolescence and the need to adapt to emerging energy innovations.

An increasing body of research has highlighted the gendered dimensions of energy security risks. Geopolitical conflicts and environmental disasters often have disproportionate effects on women, as they may face greater vulnerability due to socio-economic and cultural factors (Standal, Wither, & Danielsen, 2018). In conflict-affected settings, women are more likely to experience forced displacement, gender-based violence, and limited access to essential services such as clean water and energy. These challenges are often intensified by structural inequalities, as women typically have fewer financial resources and more limited decision-making power within households and communities. As a result, gender disparities can exacerbate the impact of energy-related risks and constrain adaptive capacity.

Women are disproportionately affected by environmental disasters, including natural hazards and climate change-related events (Fordham, 2011; Kundo, Brueckner, Spencer, & Davis, 2023; Scott, et al., 2023; United Nations International Strategy for Disaster Reduction, 2008). For example, women may face increased risks of gender-based violence in the aftermath of such disasters. In addition, disruptions in access to essential energy resources, such as those required for lighting, cooking, and heating, can further exacerbate their vulnerability. These challenges are often compounded by economic constraints, as women typically have more limited control over financial resources and household decision-making. As a result, they may encounter greater barriers to accessing reliable and affordable energy services.

Women often bear primary responsibility for securing household energy, as well as food and water resources, and any disruption in these services can significantly increase their workload. These responsibilities are typically labor-intensive and time-consuming, which may limit women's access to education, income-generating opportunities, and participation in public life. At the same time, access to modern energy services can substantially improve women's well-being and overall living conditions. Expanding access to energy can reduce the time and effort required for household tasks, thereby enabling women to engage more actively in productive and social activities. In this regard, improved energy access can contribute to both economic empowerment and social inclusion (Standal, Wither, & Danielsen, 2018; United Nations International Strategy for Disaster Reduction, 2008). Therefore, access to energy should be understood not only as a development issue but also as a key dimension of gender equality. In particular, progress toward Sustainable Development Goal 5 (SDG 5) on gender equality and Sustainable Development Goal 7 (SDG 7) on affordable and reliable energy can be supported through gender-responsive policies and programs aimed at reducing energy poverty (European Parliament, 2019).

The adoption of new energy technologies and systems may have important gender-related implications. Women continue to be underrepresented across the energy sector, ranging from production processes to policymaking roles (European Parliament, 2019; Feenstra, 2022; Habersbrunner & Kuschan, 2024). As a result, energy solutions may fail to fully address the specific needs and challenges faced by women. The transition toward clean energy technologies, such as solar power, requires a shift away from fossil fuels and carries broader social, economic, and political implications. In this context, it is essential to consider the role of gender equality and to promote women's active participation in energy transitions. Doing so can help ensure that the benefits of clean energy systems are distributed more equitably and that policy outcomes are more inclusive.

Likewise, energy transition policies and programs should take into account the specific needs and concerns of women, who may be disproportionately affected by changes in energy availability and costs (Feenstra, 2022; Standal, Wither, & Danielsen, 2018). The energy transition and gender justice framework emphasizes the active participation of women in shaping policies, technologies, and investment decisions. Incorporating women into energy governance can contribute to more resilient and secure energy systems by ensuring that diverse needs and perspectives are adequately represented. For instance, although the transition toward renewable energy may create new employment opportunities within the energy sector, women remain significantly underrepresented in STEM (Science, Technology, Engineering, and Mathematics) fields and related careers. Therefore, initiatives aimed at increasing women's participation in the renewable energy sector, such as expanding access to education, training, and mentorship programs, are essential for addressing gender disparities and promoting more inclusive energy transitions.

In summary, the existing body of literature suggests that gender equality influences energy security through multiple interconnected channels. As illustrated in Figure 1, gender equality may affect energy security risk through several pathways, including: (i) inclusive energy policies and governance (Blanka, Bardhan, & Haquec, 2019; Shakya & Buchy, 2024; Sumarno, Yusgiantoro, Fitriyanti, & Khusna, 2024; Søraaa, et al., 2020); (ii) improved energy access and efficiency (Dutta & Sahu, 2024; Hirmer, Mazzone, Leonard, & Conforti, 2022; Opoku, Kufuor, & Manu, 2021; Osunmuyiwaa & Ahlborga, 2019; Pueyo & Maestre, 2020); (iii) enhanced community resilience and adaptive capacity (Glemarec, Bayat-Renoux, & Waissbein, 2016); (iv) increased economic participation (Feenstra, 2022; Osunmuyiwaa & Ahlborga, 2019; Sumarno, Yusgiantoro, Fitriyanti, & Khusna, 2024; Tadadjeua, Tadadjeu, Njangang, & Djeunankana, 2023); (v) reduction in energy poverty (Dutta & Sahu, 2024; Musango, et al., 2020; Tadadjeua, Tadadjeu, Njangang, & Djeunankana, 2023); (vi) improved health and environmental outcomes (Blanka, Bardhan, & Haquec, 2019; Fordham, 2011; United Nations International Strategy for Disaster Reduction, 2008); and (vii) climate change mitigation and adaptation (Jessel, Sawyer, & Hernandez, 2019; Kundo, Brueckner, Spencer, & Davis, 2023; Scott, et al., 2023; United Nations International Strategy for Disaster Reduction, 2008). Despite these contributions, much of the existing research focuses primarily on developing country contexts and tends to examine either a single dimension of gender equality or a specific aspect of energy security. However, the relationship between gender equality and energy security extends beyond developing economies and involves multiple, interrelated dimensions. Moreover, empirical evidence on the long-run relationship between gender inequality and aggregate energy security risk remains limited, particularly in high-income countries. To address this gap, the present study investigates the impact of gender equality on energy security in the United States, a developed economy, by employing the Gender Inequality Index (GII) developed by the United Nations and the Energy Security Risk Index (ESRI) developed by the U.S. Chamber of Commerce's Global Energy Institute. By doing so, the study adopts a more comprehensive and integrated approach. In this respect, the study contributes to the literature by explicitly incorporating gender equality into the long-term analysis of energy security risk and by providing empirical evidence from a high-income country context.

Overall, Figure 1 illustrates the multiple pathways through which gender equality may influence energy security risk at the country level. These include governance structures, energy access and efficiency, economic participation, community resilience, the reduction of energy poverty, as well as health, environmental, and climate-related outcomes.

Taken together, these channels highlight that gender equality affects energy security not through a direct or mechanical relationship, but by reinforcing the underlying institutional and social foundations of energy systems.

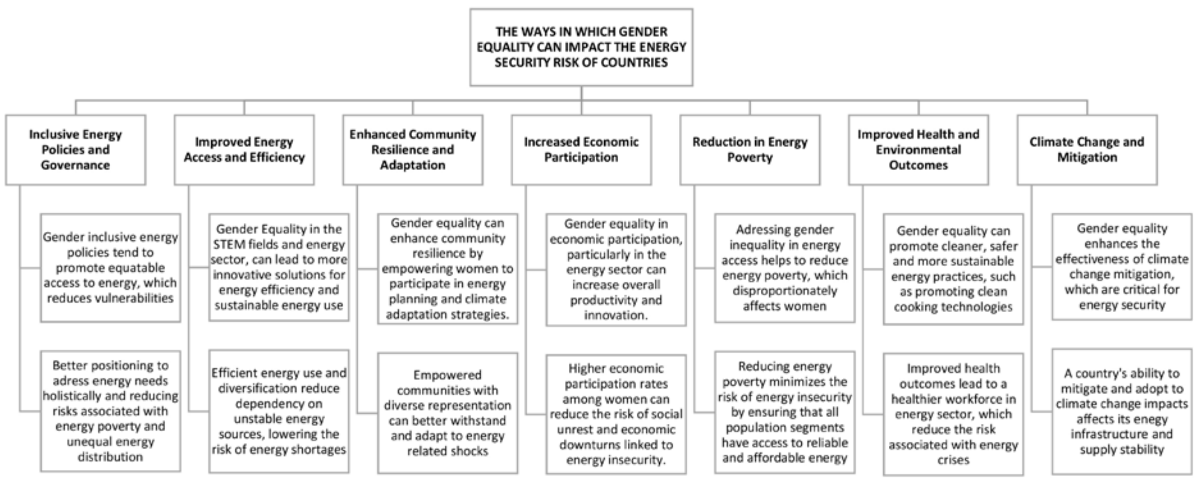

Figure 1. Exploring the connection between gender equality and energy security risk (Source: Author's own work)

DATA AND METHOLOGICAL FRAMEWORK

To examine the nexus between gender equality and energy security, a comprehensive analytical approach is required rather than focusing on a single dimension of these variables. Accordingly, this study employs two composite indices: The Energy Security Risk Index (ESRI) as the dependent variable and the Gender Inequality Index (GII) as the main explanatory variable. The Gender Inequality Index, developed by the United Nations, captures key dimensions of gender disparities, including;

a. Empowerment, measured by the share of parliamentary seats held by each gender and levels of secondary and higher educational attainment;

b. labor market participation, proxied by women's participation in the workforce; and

c. reproductive health, assessed through indicators such as the maternal mortality ratio and the adolescent fertility rate.

The GII ranges from 0 to 1, where lower values indicate greater gender equality, reflecting fewer disparities between men and women across these dimensions.

The Energy security risk index (ESRI), developed by the U.S. Chamber of Commerce's Global Energy Institute, is a comprehensive indicator composed of eight categories and a total of 37 metrics. These categories include:

a. energy use intensity (six metrics),

b. global fuel (six metrics),

c. fuel import (four metrics),

d. price and market volatility (four metrics),

e. energy expenditure (four metrics),

f. electric power sector (three metrics),

g. transportation sector (three metrics),

h. environmental impact (four metrics) and

i. research and development (three metrics).

The index is further structured around four sub-indices that capture key dimensions of energy security risk in the United States: economic (30%), geopolitical (30%), reliability (20%), and environmental (20%) factors. Each of the 37 underlying metrics is linked to one or more of these sub-indices, reflecting the multidimensional nature of energy security. Higher values of the ESRI indicate greater energy security risk, corresponding to increased vulnerability within the energy system.

Over the sample period, the Energy Security Risk Index (ESRI) exhibits notable fluctuations that closely correspond to major structural developments in the U.S. energy system. Energy security risk was relatively high during the late 1970s and early 1980s, followed by a decline throughout the 1990s. After increasing again in the mid-2000s, the index shows a significant reduction in the period after 2012. This pattern aligns with key energy and economic developments, including oil price shocks, the global financial crisis, the shale oil revolution, and the broader transition toward renewable energy sources. In contrast, the Gender Inequality Index (GII) demonstrates a steady and sustained decline over time, reflecting gradual improvements in gender-related socio-economic outcomes in the United States. These improvements are particularly evident in areas such as political representation, educational attainment, and labor force participation.

To examine the nexus between gender equality and energy security, the Gender Inequality Index (GII) is employed as the main explanatory variable, while the Energy Security Risk Index (ESRI) serves as the dependent variable. Rather than modeling ESRI as a structural representation of the energy system, this study treats it as a composite outcome indicator that captures overall energy security risk. Accordingly, the empirical specification focuses on the long-run relationship between ESRI and selected institutional, demographic, and economic variables, rather than attempting to model the internal composition of the index. This approach allows for a more holistic assessment of how broader socio-economic dynamics relate to energy security outcomes. Importantly, concerns regarding mechanical endogeneity are minimized, as the Gender Inequality Index is not a component of the ESRI, and the control variables included in the analysis are not directly embedded within the index's construction. Finally, given the emphasis on long-run equilibrium relationships within the ARDL–ECM framework, the estimated coefficients should be interpreted as long-run associations and co-movements, rather than as evidence of strict causal relationships.

In addition to the main variables, real GDP per capita (in U.S. dollars) (GDPPC), urban population (URB), and the share of women investors (%) (WINV) are included as control variables. The urban population variable captures the proportion of individuals residing in urban areas and is expected to have a positive coefficient, as higher levels of urbanization are typically associated with increased energy demand, which may elevate energy security risk. Similarly, real GDP per capita is anticipated to have a positive relationship with energy security risk, as it reflects the level of economic activity and production within the country. Higher income levels are generally linked to greater energy consumption, which may increase pressure on energy systems and contribute to higher risk levels. Data for real GDP per capita and urban population are obtained from the World Bank's World Development Indicators (WDI) database. The share of women investors (WINV) is sourced from the OECD database and is included to capture the role of gender participation in financial and investment activities. Consistent with the central argument of this study, the coefficient of WINV is expected to be negative, suggesting that a higher share of women investors may contribute to reducing energy security risks.

The share of women investors (WINV) may be correlated with the Gender Inequality Index (GII). However, these variables capture distinct dimensions of gender-related dynamics. While WINV reflects women's participation in financial and investment decisions, GII represents broader, aggregated disparities within the socio-institutional framework. Therefore, the inclusion of both variables allows for a more nuanced analysis by distinguishing between women's economic agency within the energy–investment nexus and broader patterns of socio-institutional gender inequality.

The inclusion of additional control variables in a long-run time-series framework is constrained by data availability, degrees of freedom, and the risk of over-parameterization. Although variables such as population growth, industrial structure, trade openness, interest rates, and policy uncertainty may influence energy security outcomes, their inclusion is limited in the present study due to the relatively small sample size. To ensure robust and reliable long-run estimates, the model prioritizes theoretically relevant and statistically sound variables. Rather than incorporating controls that are mechanically linked to the components of the ESRI, the selected variables capture key dimensions related to energy demand, urbanization, institutional dynamics, and investment behavior.

The study employs annual data for the United States covering the period 1989–2019. The model specification is presented below to examine the long-run associations among the variables:

$$ESRI_t = f(GII_t, GDPPC_t, URB_t, WINV_t) \qquad Eq.\ 1$$

All variables are transformed into their natural logarithmic forms to mitigate potential heteroskedasticity and to stabilize variance. The model is specified in a log–log functional form, allowing the estimated coefficients to be interpreted as elasticities of ESRI with respect to the explanatory variables. The empirical model is expressed as follows:

$$LESRI_t = \beta_0 + \beta_1 LGII_t + \beta_2\, LGDPPC_t + \beta_3\, LURB_t + \beta_4\, LWINV_t + \varepsilon_i \qquad Eq.\ 2$$

The error term, , s assumed to be normally distributed. The parameters represent the elasticities of energy security risk (ESRI) with respect to gender inequality (GII), GDP per capita (GDPPC), urban population (URB), and the share of women investors (WINV), respectively, while denotes the constant term. Although Equation (2) is specified as a single-equation long-run relationship, potential concerns related to weak exogeneity and simultaneity are explicitly addressed within the empirical framework. In principle, energy security risk may influence gender-related outcomes through its effects on labor market conditions and broader socio-economic structures. To account for these dynamics, the study employs the Autoregressive Distributed Lag (ARDL) approach, which incorporates lagged values of both dependent and independent variables, thereby mitigating potential reverse causality concerns. One of the key advantages of the ARDL framework is its applicability to variables with mixed orders of integration, allowing for a flexible modeling strategy in the presence of both I(0) and I(1) series. Moreover, the ARDL approach captures both short-run dynamics and long-run equilibrium relationships, providing a robust framework for analyzing time-series data that may exhibit cointegration. This flexibility is particularly important when examining complex socio-economic phenomena, such as gendered energy insecurity, where variables may display heterogeneous time-series properties (Usman, Özkan, Alola, & Ghardallou, 2024). In addition, ARDL models offer superior small-sample properties compared to multivariate cointegration techniques, making them especially suitable for single-country time-series analyses with limited data availability. By incorporating lagged structures, the ARDL framework also helps to alleviate issues related to endogeneity and serial correlation, contributing to more reliable and consistent estimates (Elmassah & Hassanein, 2025).

Although Equation (2) is specified as a single-equation long-run relationship, potential concerns related to weak exogeneity and simultaneity are addressed within the empirical framework. In principle, energy security risk may influence gender-related outcomes, particularly through its effects on labor market conditions. To account for these dynamics, the study employs the Autoregressive Distributed Lag (ARDL) approach, which incorporates lagged values of both the dependent and independent variables, thereby helping to mitigate potential reverse causality concerns.

A key advantage of the ARDL framework is its applicability to variables with mixed orders of integration. Moreover, it effectively captures both short-run dynamics and long-run equilibrium relationships, providing a robust approach for analyzing time-series data that may exhibit cointegration among variables. This methodological flexibility is particularly important for modeling complex socio-economic phenomena, such as gendered energy insecurity, where variables may exhibit heterogeneous time-series properties (Usman, Özkan, Alola, & Ghardallou, 2024). The ARDL framework also offers superior small-sample properties compared to multivariate cointegration techniques, making it especially suitable for analyses with limited data availability and single-country time-series contexts. Furthermore, by incorporating lagged values of both dependent and independent variables, the ARDL model helps to mitigate potential endogeneity and serial correlation issues, thereby enhancing the reliability and consistency of the estimated coefficients (Elmassah & Hassanein, 2025).

METHODOLOGY AND RESULTS

While examining the relationship between gender equality and energy security risk in the long-term perspective, ARDL method were conducted. The analysis starts with examining the descriptive statistics given in Table 1. To investigate the long-term relationship between gender inequality and energy security risk, the ARDL method was employed. The analysis starts with examining the descriptive statistics given in Table 1. The results indicate that all variables exhibit relatively low volatility, with standard deviations ranging from 0.043 to 0.069, suggesting stable time series properties over the 1989-2019 period. The mean and median values for each variable are closely aligned, indicating symmetric distributions. Specifically, LESRI has a mean of 1.917 and a median of 1.905, while LGII shows a mean of 8.365 and a median of 8.371, reflecting consistent patterns in energy security risk and gender inequality over time. The Jarque-Bera normality test results reveal that all variables fail to reject the null hypothesis of normality at the 5% significance level. The p-values for LESRI (0.288), LGDPPC (0.304), LURB (0.204), LGII (0.379), and LWINV (0.084) all exceed the critical threshold, confirming that the data series are normally distributed. This finding is particularly important for the ARDL methodology, as it supports the validity of subsequent statistical inference and model estimation. Following the descriptive analysis, unit root tests were conducted as a prerequisite to confirm the order of integration for each variable, ensuring the applicability of the ARDL bounds testing approach to cointegration. The results from these tests confirmed that none of the variables were integrated of order two, thus satisfying a key assumption for the ARDL methodology.

To evaluate the stationarity properties of the variables, Augmented Dickey-Fuller and Phillips-Perron unit root tests were performed, with the results reported in Table 2. Lag lengths were selected based on the Akaike Information

Criterion, which is preferred for small samples as it helps avoid underfitting. The PP and ADF test results indicate a mixed order of integration among the variables. According to the PP test, LESRI, LGDPPC and LGII are found to be integrated of order one, while LURB is stationary at level. The results for LWINV are mixed across specifications. Initially, alternative long-run estimation techniques such as FMOLS and CCR were considered. However, unit root test results revealed a mixed order of integration among the variables. Therefore, these methods were deemed inappropriate, and the ARDL bounds testing approach was adopted as the primary estimation technique. The results from these tests confirmed that none of the variables were integrated of order two, thus satisfying a key assumption for the ARDL methodology.

After confirming that none of the variables are integrated of order two, the analysis proceeds to examine the existence of a long-run relationship among the variables using the ARDL bounds testing approach. The results of the F-test for cointegration are presented in Table 3. The results show that the computed F-statistic of 4.980 is significantly higher than the upper bound critical value I(1) at both the 10% (3.560) and 5% (4.223) significance levels. Specifically, since the F-statistic exceeds the 5% critical value of 4.223, the null hypothesis of "no levels relationship" is rejected. This provides strong empirical evidence of a stable, long-run equilibrium relationship or cointegration among energy security risk, gender inequality, economic growth, urbanization, and women's financial participation. The existence of this cointegrating relationship suggests that although these variables may deviate from each other in the short run, they move together in a synchronized manner over the long term. From a policy perspective, this implies that the nexus between gender equality and energy security is not merely a transitory phenomenon but a structural component of the U.S. energy-economic system. The statistical significance at the 5% level justifies the subsequent estimation of long-run coefficients and the error correction model to determine the speed of adjustment toward equilibrium.

The ARDL model selected based on the Akaike Information Criterion is ARDL(1,0,0,2,0). The results of the ARDL model, selected based on the Akaike Information Criterion, are presented in Table 4. The model exhibits high explanatory power, with an R-squared of 0.906, indicating that approximately 90.6% of the variations in the U.S. energy security risk index are explained by the independent variables. The F-statistic (27.74) is highly significant ($p < 0.001$), confirming the overall validity of the model. Furthermore, the Durbin-Watson statistic (1.76) suggests the absence of significant serial correlation in the residuals.

The coefficient for real GDP per capita (LGDPPC) is positive and statistically significant at the 1% level (1.434, $p = 0.0012$). This result suggests that a 1% increase in economic growth leads to a 1.43% increase in energy security risk in the United States. This finding aligns with the literature suggesting that rapid economic expansion often increases total energy demand, which, in the absence of complete transition to renewables, can exacerbate supply-side vulnerabilities and price volatility (Usman, Özkan, Alola, & Ghardallou, 2024). It highlights that despite technological advancements, economic growth in the U.S. remains intrinsically linked to heightened energy security challenges. While one might typically expect growth to lead to better energy security, the positive sign here indicates that countries with higher income levels, like the USA, may have higher energy risks due to having increased industrialization resulting higher energy demands and energy consumption in turn. Especially, if the countries are highly energy dependent and have environmental impacts from energy production. In this case, higher energy consumption rates may lead higher energy risks due to having vulnerabilities, price volatilities or supply disruptions in developed countries. This perspective is echoed in a 2016 World Bank report, which notes that economic growth boosts energy consumption and security challenges, even while improving energy access. This paradox underscores that while developed economies can typically absorb short-term energy shocks, their extensive energy consumption patterns, often reliant on fossil fuels, inherently elevate long-term security risks such as environmental degradation and supply instability (Kartal, 2022). Moreover, the dynamic interplay between economic growth and energy security suggests that increased GDP, while potentially enabling greater investment in diverse energy portfolios, can paradoxically heighten energy insecurity if diversification efforts do not keep pace with escalating demand (Dagar, Dagher, Rao, Doytch, & Kagzi, 2024). Urbanization (LURB) also yields a positive coefficient (0.703), though it does not reach statistical significance in this specific level representation. This positive sign, however, remains consistent with the theoretical expectation that increasing urban density places additional pressure on energy infrastructure and reliability (Elmassah & Hassanein, 2025). Normally, some can expect that urban areas have better energy access, energy networks and infrastructure, which help mitigate energy security risk. However, rapid urbanization without corresponding infrastructure improvements may also lead energy shortages, higher energy costs or increase environmental pollution due to greater population density and industrialization, all of which rise energy security risks. For example, in developed countries, such as the USA, the increase in population and industrial activities can increase in electricity demand for heating/cooling purposes, industrial activities, and transportation etc. These activities may result in creating extra burden on energy systems and exacerbate energy security risk, if it is not managed properly with sustainable energy policies. Therefore, net effect may change depending on how countries manage these challenges.

A key finding in the level model is the impact of women's financial participation. The coefficient for the share of women investors (LWINV) is negative and statistically significant at the 5% level (-0.582, $p = 0.0119$). This indicates that a 1% increase in women's financial participation is associated with a 0.58% reduction in energy security risk. This finding supports the theoretical proposition that women tend to prioritize long-term sustainability and risk mitigation in investment portfolios (Gbolonyo, Obeng, Nunoo, & Armah, 2025; Saha, 2024). Increased female participation in the financial nexus of the energy sector likely promotes investments in diversified and decentralized energy systems, thereby enhancing national energy resilience (Elmassah & Hassanein, 2025; Saha, 2024). This inverse relationship among the variables could reflect underlying structural barriers or market dynamics that limit the occupation of women in energy sector, particularly in investment roles. As a result, regions with lower female participation in energy investments may experience slower adaptation of clean and innovative energy systems, which could contribute to a higher security. At this point, equality in accessing the same business and financial networks for women plays very crucial role to drive forward energy initiatives that could reduce the risk. Policies developed with more diverse group of investors might better balance sustainable development with social and environmental considerations, leading better energy policies and outcomes. By supporting ventures and start-ups that focus on energy efficiency and usage, women investors can motivate both peers in the sector and the next generations to foster more sustainable energy future but also enhance their economic participation. As mentioned by Feenstra (2022), Osunmuyiwaa & Ahlborga (2019), Sumarno, Yusgiantoro, Fitriyanti, & Khusna (2024), this increased involvement of women in the economic cycle and in energy sector may contribute to both energies related goals and sustainable growth through inclusive and participative policies.

The coefficient for the lagged dependent variable, LESRI(-1), is positive and statistically significant at the 5% level (0.415, $p = 0.0173$). This indicates a significant degree of path dependency in the United States' energy security profile. Current energy security risks are heavily influenced by the previous year's risk levels, reflecting the structural inertia and institutional configurations of the national energy system (Usman, Özkan, Alola, & Ghardallou, 2024). This result underscores that any policy intervention to mitigate energy risk will have a cumulative effect over time rather than a purely instantaneous impact.

Regarding the Gender Inequality Index (LGII), the model incorporates its current value and two lags (LGII, LGII(-1), LGII(-2)). While these individual components exhibit p-values greater than 0.10, their coefficients are consistently positive and substantial (ranging from 0.288 to 0.691). Within the ARDL framework, these variables represent the distributed lag impact of socio-institutional gender disparities. The positive signs across all lags suggest that gender inequality acts as a risk-augmenting factor for the energy system (Kaur, Yadav, Ansari, & Jena, 2024; Saha, 2024). This lack of individual significance often stems from the distributed lag structure, where the total impact is partitioned across multiple periods (Gbolonyo, Obeng, Nunoo, & Armah, 2025). Briefly, in the ARDL specification, the contemporaneous and lagged coefficients of LGII are not statistically significant, suggesting that gender inequality does not exert an immediate short-run impact on LESRI. This finding indicates that the effects of gender inequality are not instantaneous but rather evolve gradually over time, reflecting structural and institutional dynamics.

To confirm the structural nature of this relationship, the long-run elasticities will be calculated, followed by an analysis of the Short-Run Error Correction Model to evaluate the speed of adjustment and immediate dynamics of the system (Kaur, Yadav, Ansari, & Jena, 2024; Saha, 2024). Following the estimation of the level model, the Long-Run Coefficients are presented to reveal the steady-state impact of the independent variables on energy security risk. Subsequently, the Error Correction Model is estimated to determine the short-run responses and the Error Correction Term, which indicates how quickly the energy security risk returns to its long-run equilibrium following a shock. The Error Correction Model is given as below;

$$EC = LESRI - (2.4522*LGDPPC + 1.2030*LURB + 2.7031*LGII - 0.9953*LWINV - 17.0470) \quad \text{Eq. 3}$$

The short-run dynamics of the model are examined using the error correction representation of the ARDL model and the results are provided in Table 5. The coefficient of the error correction term (ECT(-1)) is negative and statistically significant at the 1% level, confirming the existence of a stable long-run equilibrium relationship among the variables. This confirms long-run causality running from the explanatory variables (LGDPPC, LURB, LGII, and LWINV) to LESRI. Due to the limited sample size and the dynamic structure of the ARDL specification, short-run causality could not be robustly established through Wald tests. The estimated coefficient (-0.585) indicates that approximately 58% of short-run disequilibrium is corrected within one period, suggesting a relatively rapid adjustment toward long-run equilibrium. In the short run, economic growth (LGDPPC) has a positive and statistically significant effect on LESRI. Similarly, the lagged value of gender inequality (LGII) exerts a positive and significant impact. In contrast, investment (LWINV) has a negative and significant effect. The results for urbanization (LURB) and the differenced terms of LGII are not statistically significant. These short-run dynamics are consistent with the long-run results, which indicate that economic growth and gender inequality positively influence LESRI, while investment has a negative long-run effect. The statistical significance and correct sign of the error correction term further validate the robustness and stability of the ARDL model.

The results reveal that gender inequality (LGII) does not have a statistically significant short-run effect on LESRI in the ARDL specification. However, the error correction model provides strong evidence of a significant long-run relationship. The lagged level of LGII is positive and highly significant, indicating that gender inequality exerts a substantial long-term impact on LESRI. This suggests that the influence of gender inequality operates through structural and institutional channels, which require time to materialize. Therefore, the effects of gender inequality are not immediate but accumulate over time, ultimately shaping long-run outcomes. The delayed impact of gender inequality can be interpreted within the framework of structural transformation. Inequality in education, labor market participation, and access to resources may not immediately affect outcomes but gradually influence economic and social dynamics. Over time, these disparities accumulate, leading to significant long-run effects.

This finding suggests that societies with higher levels of gender inequality may not utilize their resources-including energy-efficiently, which can, over time, weaken overall energy security. As illustrated in Figure 1, gender inequality can influence energy systems through multiple pathways. For instance, when women are underrepresented in education or decision-making processes, energy-related policies may lack diverse perspectives, potentially leading to less efficient outcomes and increased vulnerability to energy-related risks.

The results align with previous studies emphasizing the importance of gender-inclusive approaches in energy policy (Blanka, Bardhan, & Haquec, 2019; Shakya & Buchy, 2024; Sumarno, Yusgiantoro, Fitriyanti, & Khusna, 2024; Søraaa, et al., 2020). Encouraging gender equality in energy governance, supporting women's participation in initiatives, and increasing female representation in STEM fields may help ensure more efficient use of energy resources and more equitable access to energy services. Importantly, the empirical findings indicate that these effects are not immediate but emerge gradually, highlighting the structural and long-term role of gender equality in shaping energy security outcomes. When the dimensions of the Gender Inequality Index (GII) are considered separately, the policy implications can be discussed under three main categories:

a. Empowerment: Greater female representation in political decision-making and higher educational attainment among women can contribute to more inclusive and well-informed energy policies. Increasing women's participation in parliament and supporting their access to education, particularly in STEM fields, may foster more innovative and sustainable approaches to energy use. Although these contributions may not be immediately visible, they are likely to strengthen energy governance and policy effectiveness over time (Standal, Wither, & Danielsen, 2018; United Nations International Strategy for Disaster Reduction, 2008).

b. Labor market: Women's participation in the labor force, especially in energy and environmental sectors, can enhance productivity and improve the adaptive capacity of societies facing energy-related challenges. A more inclusive labor market may also strengthen community resilience and support more sustainable energy practices. Therefore, policies that facilitate women's access to employment opportunities in these sectors can play a meaningful role in improving long-term energy security (European Parliament, 2019; Feenstra, 2022; Habersbrunner & Kuschan, 2024).

c. Reproductive health: Health-related aspects of gender equality can indirectly contribute to energy security by improving overall socio-economic stability. Healthier populations are more productive and better positioned to adopt sustainable energy practices, such as cleaner cooking technologies and energy-efficient behaviors. While these effects may be indirect and gradual, they are important in reducing long-term energy vulnerability and supporting more resilient energy systems (Blanka, Bardhan, & Haquec, 2019; Fordham, 2011; Jessel, Sawyer, & Hernandez, 2019).

To assess the presence of heteroskedasticity, the Breusch–Pagan–Godfrey test was conducted, as can be seen at Table 6. The results indicate that the null hypothesis of homoskedasticity cannot be rejected, as the associated probability values exceed the 5% significance level. This suggests that the variance of the residuals remains constant, indicating no evidence of heteroskedasticity in the model. As a robustness check, the White test was also employed. Consistent with the previous findings, the results show that the null hypothesis of homoskedasticity cannot be rejected. Taken together, these results provide strong evidence that the model does not suffer from heteroskedasticity and that the estimated coefficients can be considered reliable. This confirms that the variance of the residuals is constant and that the model does not suffer from heteroskedasticity.

The stability of the estimated ARDL model was assessed using both the CUSUM and CUSUM of Squares (CUSUMSQ) tests and the results were presented in Figure2. The graphical results indicate that the recursive residuals remain within the 5% critical bounds throughout the entire sample period. This suggests that there are no significant structural instabilities or systematic parameter shifts in the model. In particular, the CUSUM test confirms the stability of the model's coefficients over time, while the CUSUMSQ test provides additional evidence regarding the stability of the variance of the residuals. The consistency of both tests strengthens the reliability of the estimated results. Although minor fluctuations can be observed in certain sub-periods, these deviations remain well within the critical limits and do not indicate any structural breakdown. Overall, the findings support the conclusion that the estimated ARDL model is stable and robust, and that the empirical results can be considered reliable for inference.

To further investigate potential structural changes in the model, the Quandt–Andrews unknown breakpoint test was applied. The results in Table 7 provides clear evidence of a statistically significant breakpoint around 2012, as indicated by the maximum LR F-statistic (8.1407, $p < 0.01$). The exponential and average test statistics consistently support this finding, reinforcing the presence of a structural shift in the sample period. However, when these results are considered alongside the CUSUM and CUSUMSQ stability diagnostics, a more nuanced picture emerges. Both stability tests show that the recursive residuals remain within the 5% critical bounds, suggesting that the overall model structure is stable over time. Taken together, these findings indicate that while a structural change occurred around 2012, it does not undermine the stability of the estimated long-run relationship. Instead, the breakpoint appears to reflect a gradual structural transition rather than a fundamental instability in the model.

CONCLUSION

This study examines the relationship between gender equality and energy security risk in the United States within an ARDL-ECM framework, allowing for a distinction between short-run dynamics and long-run structural effects. The empirical findings highlight that gender-related factors play a meaningful role in shaping energy security outcomes, particularly in the long run.

First, the results indicate that higher levels of gender inequality (GII) are associated with increased energy security risk (ESRI). Importantly, this effect is not observed in the short run but emerges over time, suggesting that gender inequality operates through gradual and structural channels. This finding underscores the idea that reducing gender disparities may improve the efficiency, inclusiveness, and resilience of energy systems in the long term.

Second, income per capita (GDPPC) and urbanization (URB) are found to be positively associated with energy security risk. This reflects the growing energy demand driven by economic development and urban expansion, which may place additional pressure on energy systems and increase vulnerability to disruptions. These findings highlight the importance of managing economic growth and urbanization in a sustainable manner.

Third, an increase in the share of women investors (WINV) is associated with a reduction in energy security risk. This suggests that greater female participation in investment processes may contribute to more balanced decision-making, diversified perspectives, and more sustainable energy practices. In this sense, women's involvement in energy-related investments appears to play a constructive role in enhancing energy security.

Overall, the findings point to the importance of adopting a more inclusive approach to energy policy. Gender equality should not be seen merely as a social objective, but also as a structural component of effective and resilient energy systems. Policies that promote women's participation in education, labor markets, and decision-making processes, particularly in energy-related sectors, are likely to generate long-term benefits for energy security.

From a policy perspective, integrating gender considerations into energy governance frameworks may help to improve both efficiency and equity in energy systems. Tools such as gender-responsive budgeting and gender impact assessments can support policymakers in designing more inclusive and adaptive energy policies. In line with feminist security perspectives (Musango, et al., 2020), energy security should be understood as a context-dependent and socially embedded concept, shaped by differences in access, power, and representation.

Finally, this study suggests several directions for future research. Further work could explore the causal mechanisms linking gender equality and energy security through case-based or micro-level analyses. Comparative studies across countries with different socio-economic and institutional structures may also provide deeper insights into how gender dynamics influence energy systems under varying conditions.

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APPENDIX

Table 1. Descriptive Statistics

	LESRI	LGDPPC	LURB	LGII	LWINV
Mean	1.917256	4.695062	-0.595250	8.365224	1.031993
Median	1.905217	4.713827	-0.586700	8.370814	1.056619
Highest	2.003820	4.783174	-0.533132	8.432549	1.119756
Lowest	1.845981	4.588157	-0.716699	8.274080	0.879012
Std. Deviation	0.043138	0.058580	0.053580	0.047550	0.068597
Dist. Asymmetry	0.541134	-0.481649	-0.776252	-0.343210	-0.987968
Kurtosis	2.095362	2.010984	2.640297	1.959460	2.744704
JB Normality	2.487092	2.382623	3.174569	1.942368	4.961878
Significance Level	0.288360	0.303823	0.204480	0.378635	0.083665

Table 2. Summary of Unit Root Test Results

UNIT ROOT TABLE (PP)	**At Level**					
		LESRI	LGDPPC	LURB	LGII	LWINV
With Constant	t-Statistic	-1.0054	-0.7253	-11.5979	7.8055	-3.0251
	Prob.	0.7384	0.8253	0.0000***	1.0000	0.0439**
With Constant & Trend	t-Statistic	-0.3857	-1.3615	-1.0606	-0.6723	-1.4883
	Prob.	0.9835	0.8517	0.9193	0.9659	0.8112
	At First Difference					
		d(LESRI)	d(LGDPPC)	d(LURB)	d(LGII)	d(LWINV)
With Constant	t-Statistic	-4.3827	-3.5336	-0.3062	-5.4621	-2.1410
	Prob.	0.0018***	0.0141**	0.9123	0.0001***	0.2310
With Constant & Trend	t-Statistic	-4.5677	-3.4305	-4.1661	-7.1233	-2.6359
	Prob.	0.0055***	0.0668*	0.0139**	0.0000***	0.2684
UNIT ROOT TABLE (ADF)	**At Level**					
		LESRI	LGDPPC	LURB	LGII	LWINV
With Constant	t-Statistic	-0.8311	-0.8856	-2.8269	3.0447	-2.0410
	Prob.	0.7956	0.7783	0.0678*	1.0000	0.2687
With Constant & Trend	t-Statistic	-0.3857	-1.7856	-1.4545	0.1857	-1.5619
	Prob.	0.9835	0.6856	0.8202	0.9966	0.7832
	At First Difference					
		d(LESRI)	d(LGDPPC)	d(LURB)	d(LGII)	d(LWINV)
With Constant	t-Statistic	-4.3740	-3.5694	-0.8985	-5.4589	-2.0168
	Prob.	0.0018***	0.0130**	0.7717	0.0001***	0.2784
With Constant & Trend	t-Statistic	-4.6117	-3.5461	-2.2434	-7.0652	-2.4773
	Prob.	0.0049***	0.0530*	0.4478	0.0000***	0.3359

Notes: Asterisks indicate significance levels: (*) at 10%, (**) at 5%, and (***) at 1%.
One-sided p-values provided by MacKinnon (1996)

Table 3. ARDL Bound Test Result (Null Hypothesis: No levels relationship)

Test Statistic	Value	k	Significance	I(0)	I(1)
F-statistic	4.980	4	10%	2.525	3.560
			5%	3.058	4.223
			1%	4.280	5.840

Table 4. ARDL Estimation Result

Dependent Variable: LESRI

Maximum dependent lags: 2 (Automatic selection)

Model selection method: Akaike info criterion (AIC)

Dynamic regressors (2 lags, automatic): LGDPPC LURB LGII LWINV

Selected Model: ARDL(1, 0, 0, 2, 0)

Variable	Coefficient	Std. Error	t-Statistic	Prob.*
LESRI(-1)	0.415008	0.159874	2.595841	0.0173
LGDPPC	1.434496	0.381366	3.761468	0.0012
LURB	0.703758	0.608331	1.156867	0.2610
LGII	0.288794	0.462100	0.624959	0.5391
LGII(-1)	0.691627	0.483048	1.431799	0.1676
LGII(-2)	0.600897	0.483867	1.241864	0.2287
LWINV	-0.582248	0.210433	-2.766909	0.0119
C	-9.972348	4.380626	-2.276467	0.0340
R-squared	0.906624	Mean dependent var		1.919190
Adjusted R-squared	0.873942	S.D. dependent var		0.044017
S.E. of regression	0.015628	Akaike info criterion		-5.244531
Sum squared resid	0.004885	Schwarz criterion		-4.863901
Log likelihood	81.42344	Hannan-Quinn criter.		-5.128169
F-statistic	27.74108	Durbin-Watson stat		1.762341
Prob(F-statistic)	0.000000			

Table 5. Error Correction Model (ECM) Results

Dependent Variable: D(LESRI)

Selected Model: ARDL(1, 0, 0, 2, 0)

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	-9.972348	4.380626	-2.276467	0.0340
LESRI(-1)	-0.584992	0.159874	-3.659075	0.0016
LGDPPC	1.434496	0.381366	3.761468	0.0012
LURB	0.703758	0.608331	1.156867	0.2610
LGII(-1)	1.581318	0.384940	4.107963	0.0005
LWINV	-0.582248	0.210433	-2.766909	0.0119
D(LGII)	0.288794	0.462100	0.624959	0.5391
D(LGII(-1))	-0.600897	0.483867	-1.241864	0.2287

Table 6. Heteroskedasticity Test Results

Test	Statistic	Prob.	Result
Breusch-Pagan-Godfrey	1.2720	0.3130	No heteroskedasticity
White Test	1.2226	0.3362	No heteroskedasticity

Table 7. Quandt-Andrews Unknown Breakpoint Test

Statistic	Value	Prob.
Maximum LR F-statistic (2012)	8.140700	0.0000
Maximum Wald F-statistic (2012)	40.70350	0.0000
Exp LR F-statistic	2.547201	0.0001
Exp Wald F-statistic	17.49759	0.0000
Ave LR F-statistic	4.313735	0.0000
Ave Wald F-statistic	21.56867	0.0000

Note: Probabilities are computed using Hansen’s (1997) method. The breakpoint is identified at 2012.

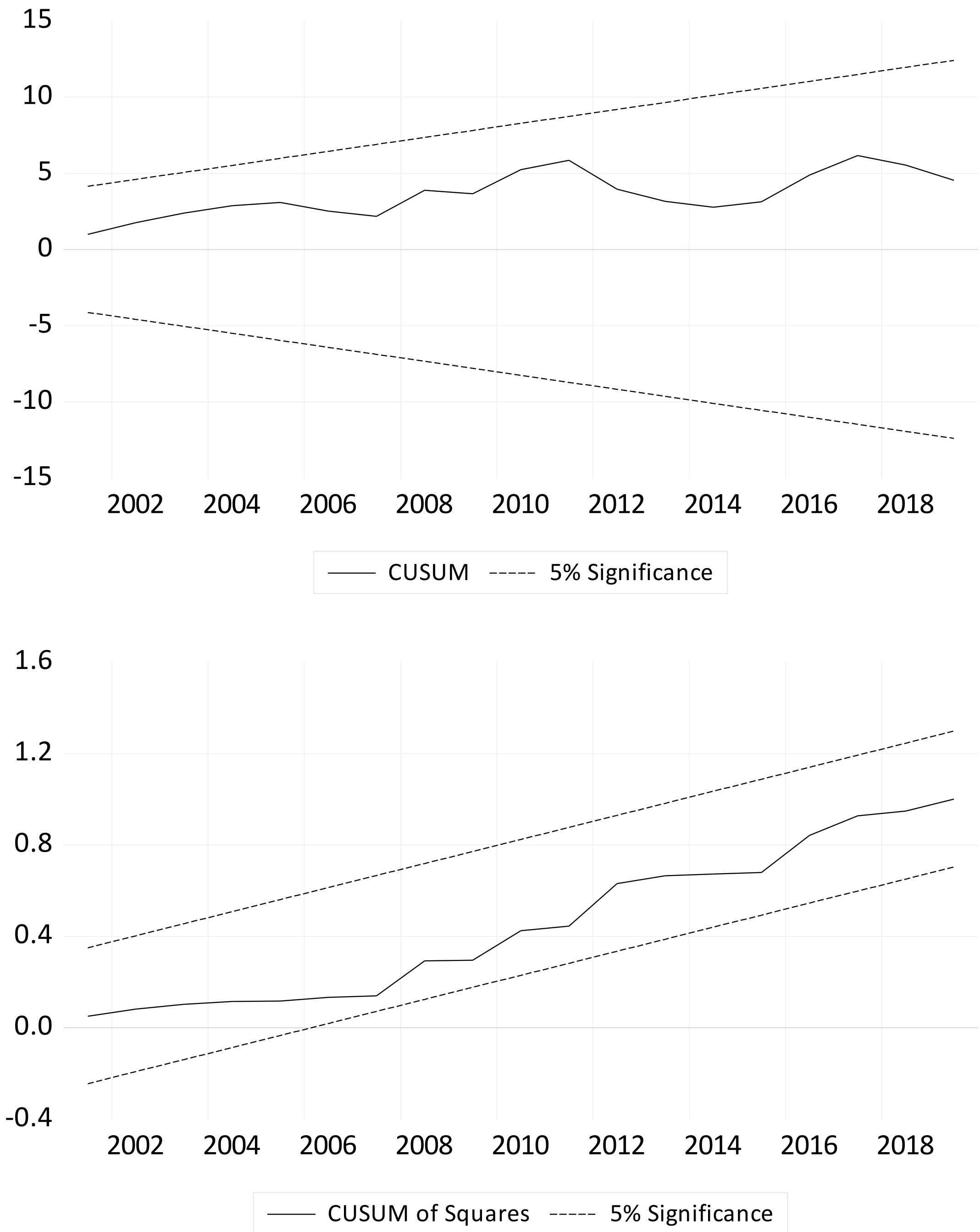

Figure 2. Stability Diagnostics: CUSUM and CUSUM of Squares Tests