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Energy Sources Diversification Towards Achieving Energy Independence

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ABSTRACT

This study, for the 1st time, reviews the cause of energy sources diversification on energy independence risk. To achieve this objective, the dataset across 64 countries spanning the time in the middle of 2000 and 2018 is used. For empirical analysis, method of moments quantile regression (MMQR) to cope with heteroscedasticity, partially linear functional-coefficient (PLFC) model to run nonlinear analysis, also difference-in-differences (DID) method to deal with endogeneity of Chinese energy investment are employed. The MMQR findings show that energy sources diversification has an adverse cause to energy independence risk across all the quantiles, 10-90%, and the development stage of the nations. Moreover, PLFC estimations also reveal that nonlinear relation is significant and depends on stage of economic development. Further, our findings obtained by DID method represent that Chinese energy investment is beneficial to cope with energy independence risk.

Keywords: Energy Independence Risk, Energy Sources Diversification, Method of Moments Quantile Regression
JEL Classifications: Q4, Q42, C23

1. INTRODUCTION

The diversification of energy sources is transitioning from conventional sources, primarily non-renewable energy sources, into renewable energy sources (Shahbaz, 2024; Gozgor and Paramati, 2022). The United Nations (UN, 2025) promotes diversifying energy sources to include more renewable energy, such as wind, solar, and hydropower. Ensuring energy diversification is also a core strategy of the International Energy Agency (IEA, 2020), enhancing energy security, reducing dependence on a particular energy source, and enhancing the world transition toward sustainable and resilient energy systems. Moreover, the World Bank (2024) actively promotes energy diversification as a key strategy for improving energy security, lowering dependence on fossil energies, and supporting economic development. The United Nations (UN, 2024) promotes energy independence as a critical factor for economic stability, sustainable development and national security. By reducing dependence on external energy sources, countries can increase their resilience to geopolitical risks, market fluctuations and supply chain disruptions. The International Monetary Fund (IMF, 2024) supports energy independence as a way to enhance economic stability, fiscal resilience and national security.

Energy sources diversification in context of various factors is gaining interest of both scholars and practitioners. Given the rapid changes in the energy sector, business models need to be able to adapt. Strategic diversification of energy sources also helps companies, including multinational or supranational companies, to manage geopolitical challenges by minimising the risks associated with regional instability and supply disruptions. A number of companies are planning to launch investment projects or increase the level of investment in environmentally friendly and energy efficient solutions. Of course, diversification of energy sources can be viewed from different perspectives. The drivers of diversification policies can be addressed (Hoang et al., 2025; Jewell et al., 2016) or the manifestations of diversification in the context of other factors such as environmental degradation (Yilanci et al., 2025; Hoang et al., 2025), the intensity and nature of investment (Sun et al., 2024; Wen et al., 2024), including foreign direct investment (Wen et al., 2024), and the promotion of investment efforts (Yilanci et al., 2025; Sun et al., 2024). Attention has also been paid to the impacts of energy diversification and the degree of diversification on individual firms (Gozgor et al., 2024) or entire national economies (Chen et al., 2024; Gozgor and Paramati, 2022). It is also interesting to explore different concepts of diversification (Caceres-Najarro et al., 2024; Triguero-Ruiz et al., 2023; Puy-Alquiza et al., 2022). The behaviour of business actors and the effects on their efforts to diversify energy sources or save energy have also been the subject of research (Zou et al., 2025). A relatively more recent issue is the question of energy security (Dolge and Blumberga, 2022). The focus has also been on the link between energy security and diversification of oil import sources (Vivoda, 2009). We did not find a study assessing the cause of energy sources diversification on energy independence risk.

Although substantial investigation has been explored on energy source diversification and energy independence, the energy diversification's direct cause to energy independence risk remains insufficiently explored. Whereas a theoretical relationship between the two concepts has been established, this exploration tends to address the impcat of energy sources diversification on energy independence risk, this filling the gap in the literature. For ensuring the reliability of the outcome, the research employs Difference-In-Difference Regressions, a partially linear functional-coefficient model, and lastly the Method of Moments Quantile Regression. These approaches effectively address challenges such as nonlinearity and endogeneity. The results confirm the theoretical and economic connection of energy independence risk and energy source diversification, offering valuable outcomes to the current literature. This study aims to fill the gap in the field by examining the relationship in the middle of energy diversification also independence, concepts that have been extensively examined separately in existing literature. The research employs a comprehensive methodological framework to address key gaps identified in prior studies. The analysis utilizes applying the method of moments quantile regression in order to identify heterogeneous effects through various energy quantile levels independence risk and development stages. Additionally, Partially Linear Functional-Coefficient modeling elucidates the nonlinear dynamics between diversification strategies and economic growth trajectories. The study employs Difference-in-Differences regressions to isolate the causal impact of Chinese energy investments, an important but underexamined geopolitical factor, on risk mitigation. Furthermore, this article employs a global panel of 64 countries from 2000 to 2018, controlling for institutional and macroeconomic factors. It provides empirical evidence supporting the theorized inverse relationship between diversification and energy risk, while also offering insights into the mediating effects of policy environments and foreign investments on this relationship. The findings validate the economic rationale for diversification and provide actionable policy implications for developing context-specific energy security frameworks in various development levels.

The rest of the article is organized as follows: Section-II reviews the literature with a special focus on energy diversification and independence risks. Section-III describes the datas and methodology employed. Section-IV presents empirical findings, and Section-V concludes with policy implications of the empirical findings.

2. LITERATURE REVIEW

2.1. The Influence of Energy Sources Diversification on Energy Independence Risk

Energy independence has become a critical goal for nations seeking to secure their economic stability and national security in an increasingly volatile global landscape. One key strategy emerging in this pursuit is the diversifying energy sources, which involves expanding the various types of energy sources such as renewable, fossil, and alternative energy options to reduce the dependence on the only supply. This approach is gaining traction as a means to mitigate risks associated with geopolitical tensions, price fluctuations, and environmental concerns. By spreading energy production across a broader spectrum of sources—such as nuclear, wind, natural gas, and solar—countries can buffer themselves against supply disruptions and enhance their resilience. This introduction explores how diversifying energy sources is increasingly recognized as a pivotal factor in reducing risk and bolstering energy independence, reshaping the way nations power their futures.

Interest in examining the energy source diversification's cause on risks related to energy independence is growing in literature. Dagar et al. (2024) analyze a dataset from 1995 to 2023 which include 26 nations and 3 continents, to evaluate energy security. Findings indicate that increased economic policy uncertainty correlates with a contraction in energy sources, adversely affecting energy security. Kim et al. (2024) examined impact variables of energy supply security, and analyzed the green transition's influence on energy security. Their findings indicate that the diversity of energy trading partners significantly influences the dynamics of energy security. Chiwaridzo (2023) examined the link among energy independence, green tourism supply chain management and renewable energy technologies in Zimbabwe's tourism sector. The findings reveal a significant relationship between RET, green tourism SCM, and four dependent variables: energy grid resilience, energy self-sufficiency, energy capacity, and energy access and efficiency. Laimon and Yusaf (2024) introduced the integrated renewable energy-driven hydrogen system as a practical approach to achieving energy independence and self-sufficiency. Their study provides a significant contribution to the current debate about renewable energy integration, highlighting the system's potential as a feasible tool to achieve energy independence. Similarly, Fan et al. (2024) examined the effect of energy diversity on the risks associated with energy security. Their findings reveal a clear association between diversified energy portfolios and reduced susceptibility to energy security shocks, with the results suggesting that expanding fossil energy diversification is more effective for mitigating risks than transitioning to a clean energy portfolio. Kosai and Unesaki (2020) defined fuel diversity for electricity generation as a preliminary step in their study of its short- and long-term implications. This analysis concludes that a reevaluation of the electricity supply system's design policy is necessary, focusing on the assessment of fuel diversity for electricity. Ahmed et al. (2022) explored energy diversity-economic growth nexus in Nordic countries. Their findings show that energy diversification has a positive cause to economic growth. However, additional inquiry is needed to determine the impact of energy diversification on economic growth in developing countries. Abhyankar et al. (2023) proposed a strategy for India to meet its growing energy demand and achieve near-total energy independence by 2047. Their research focused on the power, transport, and industrial sectors, which together account for over 80% of the country's energy consumption and CO_2 emissions. They noted that India could significantly reduce fossil fuel imports, and thus achieve energy independence. Caldera et al. (2023) analyzed how Sri Lanka could utilize indigenous renewable energy sources to meet its energy needs for electricity, heating, transportation, and desalination by 2050. Their findings suggest that Sri Lanka's growing energy demand can be fully addressed by promoting electricity generated by renewables and various supporting technologies. Francesco (2025) investigated strategies to secure energy supplies at affordable costs while safeguarding the common market, focusing on the EU-Russia gas interdependence. Their study highlighted the implications of power dynamics in the EU's gas independence process with Russia. Lastly, Rivera Rodríguez et al. (2025) examined the connections among energy independence, mental health, structural and natural disasters in Puerto Rico. Their research revealed that individuals with access to solar panels expressed positive perceptions of their mental well-being and overall quality of life. Viviescas et al. (2019) assessed the short- and long-term contributions of renewable energy to energy security in Latin America. Their results indicate that Brazil is well-positioned to integrate renewable energy sources in Latin America. This assertion is based on the observation that Brazil has the strongest capacity among Latin American countries to complement and be complemented by other regional entities. Kuziboev et al. (2025) evaluate the oil dependence's impact on energy risk across 84 countries using annual data in the middle of 2000 and 2021. This study finds that dependence on oil resources correlates with increased global energy risk, especially in developing countries. This analysis indicates that oil dependence is not a contributing factor to energy risk in developed countries.

Despite literature indicating the impact of energy source diversification on energy independence risk, no study has specifically examined this relationship. This study empirically explores the influence of energy source diversification on energy independence risk, contributing to the literature that supports the previously posited negative theoretical linkage.

2.2. The Effect of Economic Development, Government Effectiveness and Government Expenditure on Energy Independence Risk

Previous studies examine the effect of economic development on energy independence risk. Wen et al. (2024) investigated the relationship between Chinese investment and various factors in Africa, including economic development, growth, population dynamics, gross domestic savings, domestic credit, energy consumption, and energy independence. Their results indicated that a GDP decrease negatively affects energy independence. Atalla and Bean (2017) examined the factors influencing energy productivity changes in 39 countries from 1995 to 2009. They confirm the economic hypothesis that higher income per capita correlates with increased energy prices and greater energy productivity. A higher output proportion from the industrial sector indicates lower energy productivity levels. Chu et al. (2023) examined the link between economic growth and a nation's energy needs for industrialization and infrastructure development. Their findings indicated that increased economic growth may require greater reliance on energy imports, reducing energy independence. They further noted that economic development significantly negatively impacts renewable energy at low quantiles. Bakhsh et al. (2024) examined the outcomes of environmental governance, energy transition, geopolitical risk, green innovation, economic growth, and economic complexity on energy transition in twenty OECD countries from 1990 to 2021. Their results indicate the cross-sectional interdependencies in economic growth, highlighting a prevalent economic singularity that influences energy transitions. Radovanović et al. (2017) examined the interplay among environmental degradation, economic growth and energy security across 28 EU countries during the period from 1990 to 2012. Employing principal component analysis, the study identified GDP per capita, energy intensity, and carbon intensity as the key variables driving variations in a multidimensional measure of energy security.

The literature explores the influence of government effectiveness on energy independence risk. For example, Dong et al. (2024) investigated the connection in the middle of natural resource rents and renewable energy consumption, highlighting the importance of government capacity—specifically regulatory quality and government effectiveness—in strengthening this connection. Their analysis revealed a nonlinear association between natural resource rents and renewable energy consumption. Ngoma et al. (2024) studied the interplay among economic development, biomass energy utilization, legal frameworks, and government efficiency in the Republic of Congo from 1990 to 2020, offering valuable insights for policymakers striving to balance economic growth with climate stability. Tang et al. (2025) analyzed how digital government initiatives impact corporate energy efficiency in resource-based cities in China. Using a detailed dataset from listed companies, their findings demonstrated that digital government development significantly improves corporate energy efficiency. Wang et al. (2022) observed that improved institutional quality and higher per capita income positively influenced renewable energy consumption in 32 OECD countries between 1997 and 2019. Azimi et al. (2025) concluded that timely policy interventions are crucial for addressing energy security and institutional quality challenges, which are vital for achieving sustainable economic growth. Lastly, Hwang et al. (2025) found that, across 85 countries from 2003 to 2021, the impact of institutional quality on renewable energy deployment remained ambiguous, while the influence of the digital economy was consistently positive and significant.

Liu et al. (2024) investigated the effects of exogenous shocks from vertical government control reforms on urban energy efficiency during the audit reform process, suggesting that improved audit efficiency, green technology innovation, and energy structure optimization have positive impacts. Taghizadeh-Hesary and Rasoulinezhad (2025) analyzed the link between energy transition and government debt in 15 developing nations. Their analysis suggest that an increase in government spending has a notable impact on the accumulation of public debt. Xu (2025) explored the implications of government outlays on energy poverty, initiating the research by computing an energy poverty index for 30 Chinese provinces. The research delved into how government expenditure could mitigate energy poverty. The results highlighted that government spending inversely correlates with energy poverty across all quantile provinces, implying a reduction in energy poverty. Bousnina and Gabsi (2023) validated the association in the middle of energy poverty and public expenditures in 20 sub-Saharan countries over the period from 2006 to 2020, pinpointing a critical threshold at roughly 17.65% of GDP. They suggested a reciprocal causal relationship in the middle of CO_2 emissions and energy poverty in countries experiencing high levels of energy poverty. Oh (2023) investigated the impact of local government spending on air quality on CO_2 emissions, employing a two-stage dynamic panel model. His empirical study revealed that local government investment in air quality positively influences per-capita GDP.

3. DATA AND METHODOLOGY

3.1. Data

In this paper, we worked with annual data from a panel of 64 countries from 2000 to 2018 to examine the effect of energy independence risk (EIR) on energy diversification. The length and range of the period under study is due to the availability of the data for energy sources diversification. The dependent variable, energy sources diversification (ENDIV), serves as an index reflecting the extent of diversification in energy sources, where a higher index signifies a greater degree of diversification. The primary independent variable is energy independence risk (EIR). EIR is assessed on a scale ranging from 0 to 100, with a higher score reflecting an enhanced level of environmental performance. The control variables encompass economic development, represented by gross domestic product per capita in current US dollars, Chinese energy investment measured in million USD, and government effectiveness, indicated by total government expenditure on final consumption as a percentage of GDP. The data regarding the diversification of energy sources is derived from the research conducted by Gozgor and Paramati (2022). Data on GDP per capita and Chinese energy investments has been sourced by the World Bank Open Data (https://data.worldbank.org).

The logarithmic transformation is utilized to analyze the data concerning energy independence risk, diversification of energy sources, per capita GDP, and investments in energy within China. Government expenditure and government effectiveness cannot be converted into a natural logarithm because the former is presented in percentage form, while the latter includes negative values. The linear panel specification of the model is formulated as follows:

$$LOGEIR_{it} = a_0 + a_1\ LOGENDIV_{it} + a_2\ LOGPGDP_{it} + a_3\ GEF_{it} + a_4\ GEX_{it} + \epsilon_{it} \quad (1)$$

Where, a_0 is an intercept, a_1, a_2, a_3, a_4 are parameters associated with the variables, ϵ_{it} is the error term, i represents the cross-section dimension, and t denotes the time series dimension. Based on the theoretical predictions, it is anticipated that a_1 is expected to have a negative sign. This is due to the fact that increased energy diversification might reduce vulnerabilities associated with independence. The value of a_2 is hypothesized to be negative due to the fact that increased economic development makes it possible to improve energy infrastructure and technological capabilities. If foreign investments are made to improve energy infrastructure and facilitate technology transfer, then it is anticipated that a_3 is expected to have a negative sign. As stronger institutions improve the investment climate and enhance the implementation of energy policies, it is anticipated that a_4 is expected to have a negative sign.

3.2. Methodology

3.2.1. MMQR

The research utilizes MMQR for the assessment of the energy independence risk-energy diversity nexus over 64 countries. The MMQR model presents more benefits than conventional linearity-based panel methods, as demonstrated in equation-1. It captures heterogeneous effects potentially overlooked by linear models by estimating the causes of covariates at various quantiles of the regressand. The MMQR effectively utilizes outlying observations, unlike OLS-based estimation methods, due to its quantile-based approach to dependent variable estimation. MMQR does not assume a normal distribution for error terms, unlike OLS regression. It permits greater flexibility in managing various data distributions (Galvao, 2011; Machado and Silva, 2019).

Various geopolitical factors, for instance, economic crises and pandemics, also wars, play a crucial role in causing significant fluctuations in energy markets. Almeida et al. (2025) identify which the COVID-19 pandemic also global political tensions influence the patterns of energy market behavior. Ahmed et al. (2025) conducted an investigation into the interconnectedness and spillover effects among geopolitical events, geopolitical threats, and the markets for both clean and dirty energy commodities. The study also focused on periods characterized by significant geopolitical shocks, including the Russia-Ukraine conflict. The determinative effects of energy uncertainty, global supply chain pressures, and oil supply and demand shocks on economic stability were analyzed by Yang and Fu (2025). Cincinelli and Pellini (2025) examined electricity markets and analyze how geopolitical and climate risks contribute to extreme price volatility. To account for the variability introduced by geopolitical fluctuations, quantile regression methods are often used to explore the relationships among energy-related variables. Javed et al. (2025) specifically applied the MMQR technique to examine the interplay between the shift to green energy, financial development, and green technological innovation. Kuziboev et al (2025) adopted a similar approach to assess the impact of oil dependence on energy risk, introducing a previously unexplored variable. Sharipov et al. (2025) also utilize this methodology to investigate the linkage between institutional quality, renewable energy, energy policy risk, economic development, and ESG performance across 137 countries from 2000 to 2022. Yang and Zhan (2024) employ panel quantile regression to explore the diverse effects of solar, hydro, and wind energy on energy security. Ren et al. (2025) use Quantile-on-Quantile regression to study the time-frequency effects of climate risks and oil shocks on energy futures under different market conditions and investment horizons.

According to Machado and Silva (2019), the initial step in estimating the MMQR involves transforming the linearity-based panel technique in the following manner:

$$LOGEIR_{it} = \alpha_i + X_{it}^{'}\beta + (?_i + Z_{it}^{'}\gamma)U_{it} \quad (2)$$

β signifies the vector including the parameters of the regessors, i.e. $X_{it}^{'} = [\text{LOGENDIV}_{it}\ LOGPGDP_{it}\ \text{GEF}_{it}\ \text{GEX}_{it}]$. α_i denotes the fixed effects, and δ_i denotes the quantile fixed effect. Z_{it} denotes a vector of differentiable transformations of regressors that fulfill the condition $P\left\{\delta_i + Z_{it}^{'}\gamma > 0\right\} = 1$. U_{it} is an unobservable random variable that is uncorrelated with explanatory variables and normalized to meet the moment conditions as follows: $E(U_{it}) = 0$ and $E(|U_{it}|) = 1$.

The numerical values defining the equation −3, i.e. α_i, β', δ_i, γ' also $q(\tau)'$, are determined based on the first moment conditions, considering the regressors' exogeneity as described by Machado and Silva (2019). The the model can be rewritten in terms of quantiles as follows:

$$Q_{EIR_{it}}\left(\tau \middle| X_{it}\right) = \left(\alpha_i + \delta_i q\left(\tau\right)\right) + X_{it}^{'}\beta + Z_{it}^{'}\gamma q(\tau) \quad (3)$$

The equation-3 facilitates the estimation of conditional quantiles for the response variable based on the explanatory variables. The fixed effect for individual i at quantile τ, representing the distributional cause in τ, is expressed with the scalar parameter $i(\tau) \equiv (\alpha_i + \delta_i\, q(\tau))$. The one-step version of GMM (Hansen, 1982), is utilized in the estimation[1].

3.2.2. PLFC model

The volatility of energy markets indicates a nonlinear nature, as corroborated by various scholarly studies (e.g. Bouteska et al., 2023; Xu and Zhang, 2023; Huang et al., 2022). Cooray et al. (2025) utilize the PLFC model to evaluate the correlation between risks associated with energy and the diversity of energy. This study conducts a nonlinear analysis of the relationship between energy independence risk and the diversification of energy sources, building on prior research. The PLFC model is utilized for this purpose. The PLFC model provides an alternative specification by incorporating a wider array of nonlinearities through the gradual adjustment of parameters according to particular variables. This methodology offers a cohesive and adaptable framework for comprehending the interconnections between factors (Huang et al., 2021).

The linearity-based model presented in equation-1 has been restructured as the PLFC model, as demonstrated below (Zhang and Zhou, 2021):

$$LOGEIR_{it} = h(LOGPGDP_{it})LOGENDIV_{it} + X_{it}^{'}\beta + \gamma_i + u_{it} \quad (4)$$

In equation-4, $h(LOGPGDP_{it})$ is a functional coefficient, unknown, that measures the energy independence risk`s marginal cause. Similarly to Liu et al. (2022), the study hypothesizes, the functional coefficient, $h(LOGPGDP_{it})$, is caused with $LOGPGDP_{it}$ to examine the nonlinearity of energy independence risk. Unlike the MMQR model, the PLFC model defines $X_{it}^{'}$ as the explanatory variables excluding energy sources diversification, specifically $X_{it}^{'} = [LOGPGDP_{it}\ \text{GEF}_{it}\ \text{GEX}_{it}]$. The variables in $X_{it}^{'}$ are presuöed to have a linear effect on energy independence risk. The error term is denoted as u_{it}, while γ_i represents unobserved heterogeneity.

The estimation process for the PLFC model requires determining the unknown functional coefficient $h(LOGPGDP_{it})$. The regression's non-linear component is modeled through the sieve basis functions' combinations based on linearity. The sieve technique was selected for its computational efficiency, allowing for the approximation of functional coefficients with basis functions' versatile set which might grow with the surge of the sample size (Du et al., 2020). The given PFLC model in equation (4) is estimated with two-stage estimation procedure, incorporating the sieve method for the approximation of the components which are nonparametric (Baltagi and Li, 2002; Chen, 2007). Initially, an equation expressed in its reduced form for the endogenous regressors is estimated through the application of sieve approximation. There are several sieve approaches for estimating unknown functions, and in our analysis, we prefer B-splines because they are commonly utilized by researchers for this purpose. In the second stage, equation-4 is estimated using OLS, employing the approximations of the networks obtained from the first stage (Du et al., 2020; Libois and Verardi, 2013).

3.2.3. Difference in differences (DID) method

Additionally, the objective of this research is to investigate the potential endogeneity of Chinese energy investment in relation to energy independence risk. Recent research has demonstrated that Chinese investment is important in the attainment of energy independence. To be more specific, Wen et al. (2024) investigate the influence of Chinese investment on energy independence in Africa, and their findings indicate that Chinese investment has a beneficial effect on energy independence. Chinese investments promote the diversification of a nation's energy mix (Fung et al., 2004; Kang, et al., 2018). The difference-in-differences approach is employed to investigate the impact of Chinese energy investment on the energy independence risk of host countries. Following

1 Refer to Machado and Silva (2019) for details on the model's estimation steps.

the Belt and Road Initiative's introduction by China in 2013, the experimental period was selected to span 2014-2019 (Massimiliano et al. 2024). This initiative is designed to stimulate infrastructure investment worldwide. The dual temporal and regional distinction in our study is predicated on this condition. In order to evaluate the risk of energy independence from Chinese FDI outflows, we implemented a difference-in-differences (DID) test (Blundell and Dias, 2009; Meyer et al., 1995). The model is illustrated below:

$$LOGEIR_{it} = \beta_0 + \beta_1 DY_{it} + \beta_2 LOGPGDP_{it} + \beta_3 GEF_{it} + \beta_4 GEX_{it} + \varepsilon_{it} \quad (5)$$

Where, DY_{it} can be expressed as $DY_{it} * YEAR_{it}$; $YEAR_{it}$ is employed to assess whether the BRI was implemented in that year *t*. Throughout the years 2007-2013, the variable is assigned a value of 0; in the remaining years, it takes the value of 1. Furthermore, the DID method is applied incorporating one-way fixed effects.

4. EMPIRICAL RESULTS

This section initially investigates the cross-sectional dependency within the model's residuals through several tests for cross-sectional dependence. Table 1 presents the Pesaran scaled LM, Breusch-Pagan LM, and Pesaran CD tests. The findings indicate a marked cross-sectional association among the panel units, as evidenced by the statistically significant test results of all three tests performed at a 1% significance level. This suggests which the residuals within various cross-sections are interrelated, a common characteristic in panel data encompassing multiple countries or regions.

Following the confirmation of interdependence across cross-sections, unit root also study of cointegrated series are performed to assess the long-term connection in the middle of the variables. Table 2 presents the outcomes of the CIPS unit root test. Table 2 includes findings for the variables in both their original levels and after first differencing. The findings reveal which all variables exhibit non-stationarity at the initial levels but become stationary upon first differencing, as evidenced by the statistically significant test results for the first differences. This implies that the variables are integrated at the first order, I(1).

The Westerlund (2005) cointegration test is applied as aresult of the variables having similar integration order. Table 3 reveals the presence of cointegration among the variables, evidenced by a variance ratio statistic that is significant at the 1% level. This supports the existence of a long-run equilibrium connection in the middle of renewable energy and the explanatory variables, which include energy independence risk, diversification of energy sources, GDP per capita, government expenditures, and government effectiveness.

According to the results given in Table 4, diversity of energy sources significantly and negatively impacts on energy independence risk (LOGEIR) across all the quantiles, from 10% to 90% quantiles. This means the energy source diversification decreases that risk. This fact has been demonstrated in the case of Japanese politics in the last decades of the 20th century (Lesbirel,

Table 1: Cross-sectional dependence analysis

Variable	Statistic	Probability
Pesaran scaled LM	206.298	0.000
Breusch-Pagan LM	14909.27	0.000
Pesaran CD	51.066	0.000

Table 2: CIPS unit root analysis

Variable	Level	First difference
LOGEIR	−1.204	−2.322**
LOGENDIV	−2.140*	−4.112***
LOGPGDP	−2.078	−3.045***
GEF	−1.766	−4.094***
GEX	−1.448	−3.238***

***, **, and * signify statistical significance at the 1%, 5%, and 10% levels, accordingly

Table 3: Westerlund cointegration analysis

Variable	Statistic	P-value
Variance ratio	15.9221	0.000

*** denote statistical significance at 1% level. Trend is included

2004). However, it depends on the degree of energy diversification and, in particular, on the structure of the diversified resources, be it the nature of the resources (fossil resources, renewables) or the country of origin (De Rosa et al., 2022). Furthermore, economic development (LOGPGDP) positively and significantly impacts energy independence risk (LOGEIR) in lower and middle quantiles between 10% and 50% quantiles, which is in line with Odhiambo's (2014) conclusion that in lower-middle-income countries, it is economic growth that drives energy consumption. In contrast, in upper-middle-income countries, the energy consumption causes economic growth. This ambiguous result may have many other causes. For example, the dependency of many countries on imports of vital energy sources like oil and gas from even one country (Ćirović et al., 2015; Bluszcz, 2017; Yalta and Yalta, 2017). High economic development causes higher energy consumption that can lead to a higher need for imports and an increase in the independence risk (Stern, 2011). It is, for example, the case of the European Union (Boneva, 2018). On the other hand, countries of higher GDP tend to make greater adoption of renewable energy sources and thus increase their energy independence (Ntanos et al., 2018). Moreover, government effectiveness has a negative and significant cause to energy independence risk (LOGEIR) only in 50%, 75% and 90% quantiles. The decrease of the energy independence risk due to the increase of the government effectiveness was expected following, e.g. Naimoğlu et al. (2023). However, greater government efficiency often leads to a reduction in energy intensity (Chang et al., 2018), which decreases energy dependence. This finding can explain and confirm our result. Lastly, government expenditure (GGEX) significantly and negatively impacts energy independence risk (LOGEIR), from 25% to 90% quantiles. This result is not fully in accordance with Ijaz and Sumayya (2022), who found that government expenditure is a factor in increasing energy use, which can lead to an increase of energy dependence. Higher government expenditure can decrease the energy dependence risk in cases where a significant part of it is directed towards the promotion of renewable energy sources (Caruso et al., 2020). An interesting finding to consider is also the inverse relationship - higher energy dependence can lead to a higher growth of government expenditures destined especially for the renewable energy R&D (Grafström et al., 2023).

According to Table 5, in developed countries, energy diversity (LOGENDIV) negatively impacts the risks associated with energy independence (LOGEIR) across all the quantiles, 10-90%. This situation can be related to the fact that developed countries activate the resources of their own territory in developing renewable energy production at the expense of importing non-renewable resources from abroad (Leal-Arcas et al., 2023; Liutak et al., 2021). This may not always be true, however, as the path to energy independence may also include technological advances that enable the extraction of non-renewable resources on our own territory that were previously impossible or uneconomical (Moretto, 2013). In such case, of course, there is no diversification of energy sources. Furthermore, economic development (LOGPGDP) has a statistically crucial and beneficial impact of energy independence risk (LOGEIR) in lower and middle quantiles from 10% to 50%. This is not consistent with the finding that developed countries with high GDP per capita face a higher energy independence risk and require a significantly higher share of renewable energy to increase their level of energy independence compared to countries with lower GDP per capita (Kukharets et al., 2023). Furthermore, government effectiveness (GEF) negatively impacts energy independence risk (LOGEIR) across all the quantiles. This is in line with our results on all the set of countries and the above-cited studies as well. The fact the effect of the government effectiveness is higher in developed countries might be due to the simple fact this effectiveness is higher in developed countries than in developing countries because of various factors (Wandaogo, 2022; Garcia-Sanchez et al., 2013; Lee and Whitford, 2009). Lastly, government expenditure (GEX) negatively and significantly affects energy independence risk (LOGEIR) in all the quantiles, 10-90%. This effect is partially attributable to the fact that government expenditures encourage the adoption of renewable energy technologies (Gorji and Martek, 2023).

The results in Table 6 show that in developing economies, the diversity of energy (LOGENDIV) negatively causes to the risks related to energy independence (LOGEIR) across all the quantiles, 10-90%. This result only confirms the previous results of the analysis for the whole set of countries studied and separately for developed countries. Energy diversification should be supported as it has been also proved to be a significant stimulator of economic growth in developing countries (Solarin et al., 2025). Economic development (LOGPGDP) has no impact on energy independence risk (LOGEIR) at any quantiles. Yet, Chu et al. (2023) assume that the economic development of developing countries is more likely to increase energy independence risk. Government effectiveness (GEF) impacts energy independence risk (LOGEIR) only in the quantile of 10%. This result can be related to the above-cited overall situation of the government effectiveness level in developing countries caused by the lack of tools and measures (Lee and Whitford, 2009) or guidelines (Gisselquist and Resnick, 2014) increasing that effectiveness and the factors of increasing the effectiveness differ from developed countries (Wandaogo, 2022). Government expenditures (GEX) negatively and significantly affect energy independence risk (LOGEIR) in the quantiles from

Table 4: MMQR analysis (whole sample)

Variable	10%	25%	50%	75%	90%
Dependent variable: LOGEIR					
LOGENDIV	−1.511***	−1.520***	−1.533***	−1.545***	−1.554***
LOGPGDP	0.049***	0.043***	0.034**	0.027*	0.021
GEF	−0.061	−0.073	−0.090**	−0.105***	−0.117***
GEX	−0.013*	−0.016***	−0.21***	−0.025***	−0.028***
Constant	4.072***	4.281***	4.59***	4.862***	5.063***

***, **, and * signify statistical significance at the 1%, 5%, and 10% levels, accordingly

Table 5: MMQR analysis (developed economies)

Variable	10%	25%	50%	75%	90%
Dependent variable: LOGEIR					
LOGENDIV	−1.337***	−1.316***	−1.292***	−1.263***	−1.246***
LOGPGDP	0.087***	0.076***	0.064**	0.049	0.040
GEF	−0.236***	−0.225***	−0.213***	−0.199***	−0.190***
GEX	−0.007	−0.012*	−0.017**	−0.024**	−0.028**
Constant	3.332***	3.584***	3.875***	4.224***	4.438***

***, **, and * signify statistical significance at the 1%, 5%, and 10% levels, accordingly

Table 6: MMQR analysis (developing economies)

Variable	10%	25%	50%	75%	90%
Dependent variable: LOGEIR					
LOGENDIV	−1.199***	−1.973***	−1.953***	−1.939***	−1.927***
LOGPGDP	−0.004	−0.001	0.001	0.004	0.006
GEF	0.207**	0.125*	0.040	−0.018	−0.069
GEX	−0.016	−0.020**	−0.024***	−0.028***	−0.030***
Constant	5.490***	5.618***	5.750***	5.842***	5.921***

***, **, and * signify statistical significance at the 1%, 5%, and 10% levels, accordingly

25% to 90%. We have already discussed the role of GEX in promoting renewable energy technologies. It has been confirmed, for instance, in Zambia (Bowa et al., 2019). The impact of GEX is, in this case, stronger than in the case of developed countries (Gorji and Martek, 2023).

In the next phase, we employed the PLFC model to explore the non-linear impact of energy diversification on the risk of energy independence. Figure 1 visually represents these findings. Figure 1 displays estimates of the functional coefficients of energy diversification (LOGENDIV) that affect the risk of energy independence. These coefficients exhibit non-linear variations as LOGPGDP values increase. The results suggest that the impact of energy diversification on the risk of energy independence depends on economic development. The non-linear nexus is demonstrated with the argument that the coefficient based on functionality fluctuates at various stages of economic prosperity. The obtained assessments reveal, energy diversity has a significant marginal cause to the risk of energy independence. This effect is adverse and lessens as GDP per capita growths. When assessing the benefits of energy diversification, the economic situation must be considered, as shown by the changes in the functional coefficients. The adverse cause of energy diversity to the risk of energy independence is not severe for nations with lower GDP per capita, while an increase in energy diversification has a more pronounced effect in more developed economies. This observation can be ascribed to the fact that many developed countries with high GDP per capita are energy-intensive and rely on imports (Yildirim and Yasa, 2014). The MMQR estimates support the finding of a significant negative effect of energy diversity to the risks associated with energy independence. The outcome aligns with expectations, as a diversified energy source structure is considered a primary factor in achieving energy independence (Yasnolob et al., 2019; Redko et al., 2022; Ikevuje et al., 2024), and several countries are pursuing energy diversification as a strategy for energy independence (Pelton, 2023; Chu, 2023). Addressing climate change is a crucial energy priority, involving the enhancement of energy efficiency and the promotion of renewable energy technology development and implementation (Jewell et al., 2016).

Table 7 presents the findings on how Chinese energy investments affect the risk of energy independence. The estimations indicate that Chinese energy investment (DY) significantly and negatively influences energy independence risk (LOGEIR) in both fixed effects DID regressions, with and without control variables. This aligns with Wen et al. (2024) who noted the positive and significant relationship between Chinese investment and energy independence in 28 African countries. These investments encompassed projects in hydro, wind, and solar energy. However, neither our analysis nor Wen et al. (2024) specifically explored the impact on the development of fossil fuel and renewable energy generation. Another study suggests that foreign direct investment (FDI) encourages the transition to renewable energy sources (Doytch and Narayan, 2016). It is likely that this effect is driven by direct investments into energy production. Historically, FDI has been slightly negatively correlated with the share of renewable energy in energy consumption and has often led to increased pollution (Sarkodie et al., 2020; Marton and Hagert, 2017).

Figure 1: Energy sources diversification' marginal cause to energy independence risk

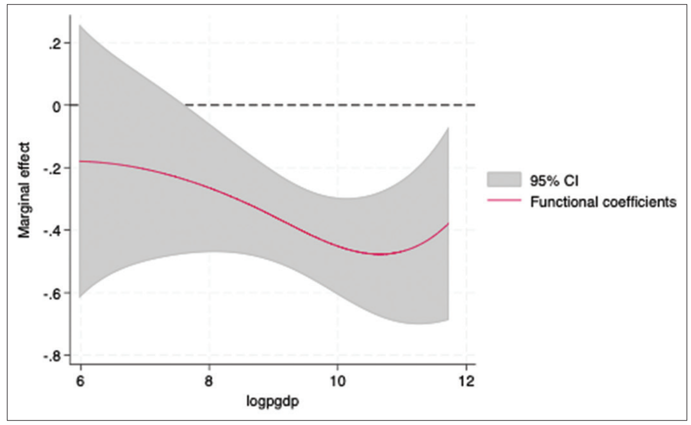

Table 7: DID regression results

Variable	Dependent variable: LOGEIR Fixed effects DID regression without controls Model 1	Fixed effects DID regression with controls Model 2
DY	−0.114***	−0.088***
TIME	0.196***	0.165***
TREATED	-	-
LOGPGDP	-	0.057***
GEF	-	−0.092**
GEX	-	−0.020***
Constant	2.751***	2.626***
P-value of F-statistic	0.000	0.000

***, **, and * signify statistical significance at the 1%, 5%, and 10% levels, accordingly

5. CONCLUSION, POLICY IMPLICATIONS AND LIMITATIONS

This research led the way in examining how the diversification of energy sources impacts the risk of energy independence. Covering the period from 2000 to 2018, the dataset includes data from 64 countries. Our empirical findings are derived for heteroscedasticity considerations and non-linear analyses, employing MMQR and PLFC models, and the Difference-In-Differences Regression to assess endogeneity due to Chinese energy investments. The results corroborate the theoretical proposition that the diversification of energy sources significantly also negatively affects the risk of energy independence. Specifically, the MMQR results show that diversification of energy sources decreases the risk of energy independence across quantiles ranging from 10% to 90%. Furthermore, the PLFC estimates reveal, the potential adverse effect of energy diversity on the risks related to energy independence becomes more evident with the more developed economy. The DID approach's endogeneity checks also indicate that Chinese energy investments contribute to reducing the risk of energy independence in recipient countries.

Admittedly, energy sources diversification is an important policy tool to decrease risks associated with energy independence. The negative effect is robust even under heterogeneity. Moreover, the sub-sample analysis across economic development stage shows that the impcat of energy sources diversification on energy independence risk remains significant and negative, validating the significance of diversifying energy sources. With energy sources diversification, energy independence can be achieved effectively. Therefore, policymakers should focus on energy sources diversification, especially renewable and other forms of low-carbon energy. Non-linear results reveal that the energy diversity's adverse cause to energy independence risk depends on economic development level. The economic development stage determines the investment and expenditures in the energy sector. Consequently, as a result of high economic development, spendings on the energy sector for energy sources diversification play a crucial role to develop renewable energy, and thus achieving energy independence. Follow-up research needs to address the impact of the myriad and structure of diversification on reducing the risk of energy independence. There is also a need to focus specifically on the overall importance of renewables in the structure of diversification. In countries with high GDP, in addition to the efficiency of government and its effect on energy diversification and thus on reducing the risk of energy independence, the impact of business behaviour, especially of large and multinational ones, needs to be investigated. It is also necessary to take into consideration the ability of companies to purchase energy or its sources from abroad independently of the government of the country where the companies are located and its energy policy. The connection in the middle of energy diversification and economic growth necessitates further investigation in the context of developing countries.

Moreover, attracting foreign investment is also beneficial in reducing energy independence risk. The flow of Chinese energy investment is leading to a fall in energy independence risk in the host countries. This gives an assumption that nations should foster attracting foreign investments on energy sector, further improving the investment climate and giving preferences. The link between the origin of investment and energy diversification also needs to be analysed, and the question needs to be asked whether building independence from energy sources increases dependence on foreign investment. The study also has some limitations. More precisely, to conduct the estimations at disaggregated levels of energy sources diversification might represent robust results. There is an interest in checking the effect of each energy source data on energy independence risk. However, due to the availability of the data, this drawback cannot be addressed. Instead, this limitation serves as future work in the field.

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