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The Impact of Geopolitical Risk on Renewable Energy Innovation in OECD Countries

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A B S T R A C T

This study aimed to investigate the effect of geopolitical risk on renewable energy innovation in OECD countries during 2000–2022. This quantitative longitudinal study employed a balanced panel-data design covering 25 OECD countries over 23 years, yielding 575 country-year observations. Renewable energy innovation was measured using patent-based indicators, while geopolitical risk was assessed using the country-specific Geopolitical Risk Index. Macroeconomic and structural control variables included real GDP per capita, research and development expenditure, trade openness, renewable energy share, CO_2 emissions per capita, and population. The data were analyzed using descriptive and panel diagnostic procedures, two-way fixed-effects regression, lagged specifications, Driscoll–Kraay robust standard errors, and dynamic system generalized method of moments estimation. Robustness analyses were also conducted using alternative measures, exclusion of extreme observations, and alternative model specifications. Geopolitical risk had a positive and statistically significant effect on renewable energy innovation in the fully adjusted fixed-effects model, B = 0.169, SE = 0.059, p = .005. The one-year-lagged effect was stronger, B = 0.207, SE = 0.064, p = .001, while the two-year-lagged effect also remained significant, B = 0.121, SE = 0.059, p = .041. In the dynamic system-GMM model, lagged geopolitical risk continued to positively predict renewable energy innovation, B = 0.154, SE = 0.058, p = .008, after controlling for innovation persistence. GDP per capita, R&D expenditure, and renewable energy share also showed significant positive effects, whereas CO_2 emissions per capita had a significant negative effect. The positive geopolitical-risk effect remained stable across all robustness specifications. The findings indicate that geopolitical risk can act as a stimulus for renewable energy innovation in OECD countries, particularly with a short temporal delay, suggesting that geopolitical uncertainty may strengthen incentives for technological development aimed at improving energy security, diversification, and strategic autonomy.

Keywords: *Geopolitical Risk; Renewable Energy Innovation; OECD Countries; Energy Security; Technological Innovation; Panel Data; Renewable Energy Patents*

1. Introduction

Energy has long occupied a central position in international politics because access to reliable, affordable, and strategically secure energy resources directly affects economic performance, industrial competitiveness, national security, and the geopolitical influence of states. For much of the modern era, the geopolitical significance of energy was primarily associated with the geographical concentration of oil and natural gas reserves, the security of maritime routes and pipelines, competition among producing and consuming countries, and the capacity of energy-exporting states to use fossil-fuel resources as instruments of diplomacy and political leverage (Ahmed, 2025). The geographical mismatch between major centers of energy production and consumption has consequently created complex patterns of interdependence in which supply disruptions, interstate conflicts, terrorism, sanctions, and diplomatic disputes can have significant repercussions for global energy markets. Oil geopolitics in particular remains closely connected to security threats and changes in international policy, as instability affecting producing regions can alter both national energy strategies and the broader orientation of global energy policy (Kamalov, 2025). In this context, geopolitical risk has become an increasingly important determinant of decisions concerning energy supply, investment, technological development, and the transition toward alternative energy systems.

The geopolitical character of conventional energy systems is strongly rooted in dependence on geographically concentrated fossil-fuel reserves and the infrastructure required to transport them across national borders. Pipelines, shipping lanes, transit corridors, ports, and strategic straits therefore function not merely as economic infrastructure but also as geopolitical assets. Research on pipeline diplomacy in Central Asia illustrates how energy transportation projects can become embedded in broader strategic competition among states seeking to secure access to resources, transit routes, and regional influence (Pradhan, 2020). Similar dynamics can be observed in the Caspian region, where energy resources and transportation networks have contributed to complex forms of energy diplomacy and geopolitical competition among regional and external actors (Gurbanov, 2024). The geopolitical position of countries located along potential energy corridors may consequently shape their economic opportunities and strategic significance. For example, the configuration of energy-transfer projects from the Caspian Sea has been linked to wider questions of geo-economic development and regional positioning in Central Asia and the Caucasus (Konashlu et al., 2022). Energy transit across the Persian Gulf likewise demonstrates the close interaction among oil and gas resources, geoeconomics, regional policy, and geopolitical influence (Norouzizadeh et al., 2022). These patterns underline the extent to which conventional energy security has historically depended on stable relations among producers, transit states, and consumers.

The strategic significance of energy relationships is also evident in bilateral and regional security arrangements. Energy resources may complement other dimensions of geopolitical interaction, including border security, water politics, trade, and regional cooperation, as illustrated by the geopolitical and security interdependence examined in relations between Iran and Türkiye (Omidi & Orhon Ozdag, 2023). At the same time, military involvement and conflict in energy-sensitive regions can significantly reshape the strategic value of states, routes, and resources. The interaction between energy geopolitics and military engagement in Syria, for example, demonstrates how control, access, alliances, and security calculations surrounding energy can intersect with wider geopolitical objectives (Zomorodi Anbaji & Haji-Yousefi, 2021). More recently, the Russia–Ukraine war has provided an especially consequential example of the vulnerability of energy systems to geopolitical confrontation. The conflict generated severe disruptions in energy relations, heightened concerns regarding supply security, and altered the geopolitical importance of both producers and alternative suppliers (Haghbin & Ansari, 2024). These developments have reinforced the perception that geopolitical risk is not an external factor affecting energy markets only temporarily, but rather a structural variable capable of reshaping national energy strategies.

The influence of geopolitical risk on energy markets operates through several interconnected channels. Conflict, political tension, sanctions, military threats, and uncertainty may affect expectations about future supply, transportation costs, insurance premiums, investment decisions, inventories, and speculative behavior. Empirical evidence shows that geopolitical risks can transmit to crude oil markets through multiple mechanisms and that the consequences may vary according to the nature and intensity of geopolitical disturbances (Jiao et al., 2023). Investor behavior constitutes another important mechanism, as geopolitical risk can influence attention and speculative activity in oil markets in nonlinear and time-varying ways

(Xiao et al., 2023). Moreover, geopolitical risks can have asymmetric effects on energy-market returns and volatility depending on prevailing market conditions, suggesting that the consequences of geopolitical instability cannot be adequately understood through simple linear relationships (Qin et al., 2020). Major international events can further intensify these dynamics by generating abrupt changes in crude-oil markets, reinforcing economic polarization, and affecting the structure of global energy relations (Patidar et al., 2024). The Russia–Ukraine war, in particular, demonstrated how geopolitical conflict can influence oil prices through several channels rather than through a single direct supply effect (Zhang et al., 2023).

These energy-market consequences are particularly relevant because geopolitical instability may create both obstacles and incentives for the transition away from fossil fuels. On the one hand, periods of uncertainty can increase financing costs, disrupt supply chains, reduce investor confidence, and delay large-scale energy projects. On the other hand, dependence on imported fossil fuels can become considerably more costly during geopolitical crises, thereby increasing the strategic value of domestic renewable energy resources. The relationship between geopolitical risk and renewable energy is therefore theoretically ambiguous. Evidence from emerging markets suggests that geopolitical risk, in combination with financial development, can significantly affect renewable energy consumption, indicating that the consequences of geopolitical conditions depend partly on countries' institutional and financial capacity to support energy transition (Alsagr & van Hemmen, 2021). Likewise, geopolitical risk has been identified as an important determinant of renewable energy investment, although its effects may depend on market conditions, national characteristics, and the broader investment environment (Flouros et al., 2022). Firm-level evidence also indicates that geopolitical risk and oil-price volatility can shape renewable energy investment decisions, demonstrating that geopolitical shocks may influence the allocation of capital toward clean-energy technologies (Zhao et al., 2024).

The interaction between geopolitical risk and clean energy becomes especially important when the behavior of fossil-fuel and renewable-energy markets is considered jointly. Geopolitical tensions can simultaneously alter crude-oil prices and the valuation of clean-energy assets, generating dynamic relationships between conventional and renewable energy markets (Cheikh & Zaied, 2023). Clean-energy prices may also respond asymmetrically to geopolitical risk, climate-policy uncertainty, and crude-oil-price movements, indicating that geopolitical shocks can influence renewable-energy sectors through both energy-market and financial-market channels (Sarker et al., 2023). Similarly, geopolitical tensions and fossil-energy prices can affect the performance of European utility companies, with important implications for energy security, environmental management, and the economic incentives surrounding low-carbon transformation (Yang et al., 2024). A broader review of the relationship among the energy industry, financial markets, environmental concerns, and geopolitics likewise suggests that energy transition must be understood as a process embedded within interacting economic, environmental, financial, and strategic systems rather than as an isolated technological shift (Pantel, 2024).

Geopolitical risk can also influence the organizational behavior of energy firms. Firms exposed to uncertainty may alter capital allocation, acquisition strategies, technological priorities, and long-term planning in response to geopolitical disturbances. Evidence from energy and electric-power industries indicates that geopolitical risk can affect mergers and acquisitions among listed firms, showing that corporate restructuring itself may constitute one response to geopolitical uncertainty (Shen et al., 2021). Such findings are relevant to renewable-energy innovation because technological development frequently depends on firm-level investment capacity, knowledge acquisition, strategic partnerships, and access to specialized assets. Consequently, geopolitical shocks may affect innovation not only indirectly through energy prices but also directly through changes in corporate strategy and the reorganization of technological capabilities.

The global energy transition further complicates traditional understandings of energy geopolitics. Renewable energy reduces dependence on continuously imported fuels in some respects, yet it simultaneously creates new forms of strategic dependence associated with critical minerals, manufacturing capacity, technological patents, electricity networks, energy storage, and clean-technology supply chains. The geopolitics of renewable energy therefore differs from the geopolitics of fossil fuels but does not eliminate geopolitical competition (Vakulchuk et al., 2020). The transformation of energy systems can redistribute geopolitical power by weakening some traditional fossil-fuel dependencies while strengthening the strategic importance of countries that control renewable-energy technologies, critical raw materials, manufacturing networks, and infrastructure (Blondeel et al., 2021). The transition thus

generates new winners, vulnerabilities, alliances, and strategic interests. Alternative financial structures may also emerge as part of these changing geopolitical arrangements, particularly where states seek to reduce exposure to conventional financial and energy systems (Desing, 2021). Renewable-energy innovation is therefore not simply an environmental or technological phenomenon; it increasingly represents an element of national economic resilience and strategic autonomy.

Energy security provides a particularly important theoretical link between geopolitical risk and renewable-energy innovation. Contemporary energy security extends beyond physical availability to include affordability, resilience, diversification, infrastructure reliability, technological capacity, and protection from external political shocks. A broad review of energy security in the global context emphasizes that geopolitical dynamics and government policies are deeply interconnected with countries' efforts to manage vulnerabilities arising from international energy dependence (Ibekwe et al., 2024). Geopolitical threats, geopolitical acts, and broader geopolitical risks can also have distinguishable effects on energy transition, indicating that different dimensions of geopolitical instability may generate different policy and market responses (Wang et al., 2024). Under conditions of elevated geopolitical uncertainty, states may therefore have stronger incentives to diversify their energy systems, reduce dependence on imported fossil fuels, expand domestic renewable generation, and support technologies that enhance energy autonomy.

The European energy crisis following Russia's invasion of Ukraine provides a particularly clear illustration of this mechanism. The crisis altered both the short-term management of energy shortages and the longer-term geopolitical logic of climate transition, demonstrating that decarbonization and energy security can become mutually reinforcing strategic objectives under conditions of geopolitical disruption (Goldthau & Youngs, 2023). The invasion fundamentally changed European perceptions of energy dependence and accelerated debate over the relationship between security, fossil-fuel imports, and the expansion of alternative energy sources (Skalamera, 2023). Such developments suggest that geopolitical crises may act as catalysts for technological and policy change by revealing the costs of dependence on politically vulnerable supply relationships. More broadly, contemporary energy-market dynamics increasingly reflect a high-stakes interaction among geopolitical risks, international trade, supply security, and energy-market restructuring (Akadiri & Özkan, 2025).

The growing integration of sustainability objectives into national security strategies reinforces this shift. Countries increasingly view the energy transition not only as a means of reducing greenhouse-gas emissions but also as a strategy for improving resilience to geopolitical shocks. The interaction among geopolitical risks, natural-resource scarcity, renewable energy, and energy-security transitions suggests that sustainable development increasingly depends on the ability of economies to combine environmental goals with strategic energy autonomy (Zhang & Liu, 2025). At the policy level, this has contributed to a reconceptualization of the energy transition as a geopolitical management challenge in which renewable resources, technological capability, infrastructure, and international cooperation must be coordinated to reduce emerging vulnerabilities (La Camera, 2025). The development of regional energy hubs similarly demonstrates how states can pursue sustainability while simultaneously seeking greater geopolitical relevance and energy-security advantages, as reflected in Türkiye's evolving energy strategy (Shokri, 2025).

Within this broader transformation, technological innovation is a crucial but comparatively underexamined mechanism. Expanding renewable-energy consumption or installed capacity depends not only on investment in existing technologies but also on continuous advances in solar photovoltaics, wind turbines, storage technologies, grid integration, digital energy management, hydrogen systems, and other low-carbon technologies. Innovation can reduce costs, improve efficiency, enhance energy-system flexibility, and enable countries to substitute domestically available renewable resources for imported fossil fuels. Geopolitical risk may therefore affect renewable energy innovation through several channels. Rising fossil-fuel prices can improve the relative economic attractiveness of clean-energy technologies; supply disruptions can increase the expected benefits of technological self-sufficiency; governments may expand R&D support in strategic energy fields; and private firms may redirect innovation toward technologies capable of reducing exposure to unstable energy supplies. Conversely, geopolitical uncertainty can also undermine innovation by increasing financing costs, disrupting research networks, restricting trade in technology-related inputs, and weakening long-term investment.

This tension is particularly relevant for OECD countries. OECD economies collectively account for a substantial

share of global research expenditure, patenting activity, advanced manufacturing, clean-energy investment, and environmental regulation. Many of these countries are simultaneously major energy consumers and importers, making them highly exposed to international energy-market disruptions. At the same time, their relatively sophisticated innovation systems may allow them to respond to geopolitical shocks through technological adaptation rather than exclusively through short-term changes in fuel sourcing. In such economies, the consequences of geopolitical risk may therefore extend beyond fluctuations in energy consumption and investment to influence the direction and intensity of inventive activity itself.

The significance of innovation also becomes clearer when geopolitical changes in energy markets are interpreted within the broader international transition toward low-carbon systems. Growing strategic competition can create incentives to localize technology, strengthen supply chains, and develop indigenous capabilities in renewable-energy industries. Meanwhile, the global trade dimension of energy transition can create new dependencies and sources of geopolitical vulnerability, particularly where countries depend heavily on imported components, raw materials, or technologies (Akadiri & Özkan, 2025). Energy-transition strategies must therefore balance openness and international technological cooperation against concerns regarding resilience and national capability. This strategic tension can potentially stimulate innovation as governments and firms seek to reduce dependence on externally controlled technologies while maintaining competitiveness in rapidly expanding clean-energy markets.

The broader literature indicates that geopolitical shocks have substantial implications for energy prices, renewable-energy investment, energy consumption, corporate behavior, and transition policies; however, substantially less attention has been devoted to renewable-energy innovation as a distinct technological outcome. Existing studies often examine renewable-energy consumption (Alsagr & van Hemmen, 2021), renewable investment (Flouros et al., 2022; Zhao et al., 2024), clean-energy asset prices (Sarker et al., 2023), energy-company behavior (Shen et al., 2021), or aggregate energy-transition indicators (Wang et al., 2024). These outcomes are important, but they do not fully capture the creation of new technological knowledge. Renewable-energy patenting reflects the inventive capacity underlying future improvements in clean-energy production, efficiency, storage, transmission, and deployment. Examining innovation therefore provides a more structural perspective on whether geopolitical uncertainty changes the technological trajectory of energy systems.

A further reason for investigating this relationship concerns the distinction between short-term adjustment and long-term transformation. Governments can respond to geopolitical crises in the short run by releasing strategic reserves, subsidizing energy prices, changing suppliers, or temporarily increasing domestic fossil-fuel production. Such responses do not necessarily represent a lasting transformation of the energy system. Innovation, by contrast, contributes to the accumulation of technological capabilities that can generate persistent changes in energy production and consumption. If geopolitical risk systematically stimulates renewable-energy innovation, then geopolitical crises may have consequences extending well beyond immediate market disruption, potentially accelerating technological change toward greater energy independence. If geopolitical risk suppresses innovation, however, repeated international instability could slow decarbonization despite stronger energy-security incentives. Determining the direction of this relationship is therefore relevant to both innovation policy and climate policy.

The increasing geopolitical complexity of energy markets makes this question particularly important. International energy relations now involve the simultaneous pressures of climate commitments, fossil-fuel market volatility, strategic competition, supply-chain vulnerabilities, sanctions, regional conflicts, and technological rivalry. The resulting environment challenges the traditional separation between energy security and sustainability policy. The emerging energy order requires governments to consider how environmental technologies contribute to economic resilience, national security, and geopolitical autonomy. As renewable technologies become increasingly important to economic competitiveness and strategic power, the ability to innovate in these fields may become as geopolitically significant as access to conventional energy resources themselves. In this sense, geopolitical uncertainty can potentially alter not only where countries obtain energy but also which technologies they prioritize for future development.

Although earlier research provides a strong basis for understanding the geopolitical determinants of energy markets and transition processes, the empirical relationship between country-specific geopolitical risk and renewable-energy technological innovation across advanced economies remains insufficiently clarified. The complexity of this relationship is heightened by differences among countries in

income, R&D capacity, trade openness, renewable-energy penetration, carbon intensity, energy dependence, and technological specialization. A panel approach that controls for such factors and for persistent country characteristics can therefore provide more reliable evidence regarding whether changes in geopolitical exposure are systematically associated with changes in renewable-energy innovation. Such evidence can help clarify whether geopolitical uncertainty primarily functions as a disruptive force for technological development or whether it can also create strategic incentives that accelerate innovation designed to improve energy security and reduce dependence on vulnerable fossil-fuel supply systems.

Accordingly, the aim of this study was to investigate the effect of geopolitical risk on renewable energy innovation in OECD countries during 2000–2022.

2. Methods and Materials

This study employed a quantitative, longitudinal, cross-country panel-data design to investigate the effect of geopolitical risk on renewable energy innovation in selected member countries of the Organisation for Economic Co-operation and Development (OECD). The unit of analysis was the country-year, and the study period covered 23 consecutive years from 2000 to 2022. The sample consisted of 25 OECD countries for which consistent country-specific geopolitical risk data were available over the study period: Australia, Belgium, Canada, Chile, Colombia, Denmark, Finland, France, Germany, Hungary, Israel, Italy, Japan, South Korea, Mexico, the Netherlands, Norway, Poland, Portugal, Spain, Sweden, Switzerland, Türkiye, the United Kingdom, and the United States. Accordingly, the research design comprised 25 countries observed over 23 years, yielding 575 potential country-year observations. The selection of the study period was intended to provide a sufficiently long time horizon for capturing changes in geopolitical conditions as well as the gradual and potentially delayed response of technological innovation to geopolitical shocks. The period also encompasses several major episodes of international geopolitical instability, including the September 11 attacks and subsequent conflicts, the global financial crisis and its geopolitical consequences, the Arab Spring, the Russia–Ukraine tensions beginning in 2014, growing strategic competition among major economies, the COVID-19 period, and the escalation of geopolitical tensions in 2022. The use of panel data was particularly appropriate because it allowed simultaneous exploitation of temporal variation within individual countries and cross-sectional variation among OECD economies while controlling for unobservable country-specific characteristics that remain relatively stable over time. The primary dependent variable was renewable energy innovation, while country-specific geopolitical risk constituted the principal independent variable. Macroeconomic, technological, energy, and structural characteristics that could simultaneously influence innovation activity were incorporated as control variables to reduce omitted-variable bias. The empirical dataset was constructed by matching observations across the different databases by country and calendar year, and all variables were harmonized to annual frequency before estimation.

The data used in this study were entirely secondary and were obtained from internationally recognized databases. Renewable energy innovation was measured using patent-based indicators derived from the OECD patent and environmental technology databases. Patent indicators were selected because they capture the output of inventive activities and make it possible to distinguish innovations according to technological field. The principal indicator of renewable energy innovation was defined as the annual number of inventions or patent families associated with climate-change-mitigation technologies related to energy generation, transmission, or distribution, including technologies associated with renewable sources such as solar energy, wind energy, hydropower, geothermal energy, marine energy, and other low-carbon energy-generation technologies. Patent observations were assigned to countries according to the inventor's country of residence rather than merely the location of the patent office, thereby providing a closer approximation of the geographical origin of innovative activity. To reduce the influence of extreme differences in patent counts between large and small innovative economies and to accommodate observations with zero patents, the main dependent variable was transformed as the natural logarithm of one plus the number of renewable energy patents, expressed as $\ln(1 + REI)$. As an alternative specification for robustness analysis, renewable energy patents relative to total domestic patenting activity were also considered to distinguish changes in the technological orientation of innovation from changes in overall patenting intensity.

Geopolitical risk was measured using the country-specific Geopolitical Risk Index developed by Caldara and Iacoviello. The index is based on automated searches of major international newspaper archives for articles

containing terms associated with geopolitical tensions, threats, wars, terrorism, military confrontations, and related adverse geopolitical events while simultaneously mentioning the respective country or its major cities. Because the original country-specific geopolitical risk series is reported at monthly frequency, monthly observations were aggregated into an annual measure by calculating the arithmetic mean of the 12 monthly observations corresponding to each country and year. This procedure generated a country-specific annual geopolitical risk indicator that retained both cross-country and intertemporal variation. Because the geopolitical risk index is positively skewed and contains occasional exceptionally large values associated with major geopolitical events, the logarithmic transformation ln(1 + GPR) was used in the baseline estimations. Higher values therefore represented greater exposure to geopolitical tensions and uncertainty. In supplementary analyses, the untransformed geopolitical risk index and one-year-lagged geopolitical risk were employed to determine whether the findings were sensitive to variable transformation and to assess whether geopolitical shocks affected renewable energy innovation with a temporal delay.

Several control variables were incorporated because renewable energy innovation is influenced by economic resources, technological capacity, international integration, energy conditions, and environmental pressures in addition to geopolitical factors. Economic development was measured by real GDP per capita, expressed in constant prices and logarithmically transformed. Research and development intensity was measured by gross domestic expenditure on research and development as a percentage of GDP and was included as an indicator of the domestic knowledge and innovation capacity of each economy. Trade openness was calculated as the sum of exports and imports of goods and services divided by GDP and multiplied by 100, reflecting countries' integration into international markets and their access to foreign technologies, intermediate inputs, and knowledge flows. Renewable energy dependence was represented by the share of renewable energy in total final energy consumption, capturing the existing domestic demand and market conditions for renewable technologies. Environmental pressure was represented by carbon dioxide emissions per capita, since higher emissions may strengthen regulatory and market incentives for low-carbon technological development. Where required, population size was included in logarithmic form to account for differences in the scale of national economies and innovation systems. Macroeconomic and energy-related control variables were obtained primarily from the World Bank's World Development Indicators and OECD databases. All annual series were cross-checked for consistency in definitions, units of measurement, country identifiers, and time coverage before construction of the final panel dataset.

Data analysis was conducted using panel econometric techniques designed to estimate the relationship between geopolitical risk and renewable energy innovation while accounting for both country-specific heterogeneity and common time shocks. The analysis began with descriptive statistics for all variables, including the mean, standard deviation, minimum, maximum, and number of observations. Pairwise correlations were subsequently examined to identify preliminary relationships among the variables and to detect possible multicollinearity. Variance inflation factors were calculated for the explanatory variables, with values below conventional critical thresholds interpreted as evidence that severe multicollinearity was absent. Because several variables, particularly patent counts, GDP per capita, population, and geopolitical risk, exhibited skewed distributions and large cross-country differences, logarithmic transformations were applied where appropriate before econometric estimation.

Before estimating the principal regression models, the statistical characteristics of the panel were examined. Cross-sectional dependence was assessed because OECD countries are economically and technologically interconnected and may be simultaneously affected by common geopolitical, financial, technological, and energy-market shocks. Panel unit-root tests were used to assess the stationarity properties of the variables and to reduce the risk of spurious regression. Where necessary, alternative transformations or specifications were considered for variables displaying evidence of non-stationarity. The appropriateness of pooled ordinary least squares, random-effects, and fixed-effects estimators was evaluated using conventional specification tests. The principal empirical model was estimated using a two-way fixed-effects specification containing both country fixed effects and year fixed effects. Country fixed effects controlled for time-invariant characteristics such as geography, institutional traditions, long-standing features of national innovation systems, and persistent differences in resource endowments, whereas year fixed effects captured shocks common to all countries in a given year, including changes in global energy prices, international climate agreements, technological trends, global recessions, and worldwide geopolitical disturbances.

The baseline model specified renewable energy innovation in country i and year t as a function of country-specific geopolitical risk, the vector of control variables, country fixed effects, year fixed effects, and an idiosyncratic error term. The coefficient of geopolitical risk constituted the principal parameter of interest and indicated the direction and magnitude of the association between changes in geopolitical risk and renewable energy innovation after controlling for observed covariates and unobserved time-invariant country characteristics. Because observations belonging to the same country across years are not statistically independent, standard errors were adjusted for within-country serial correlation and heteroskedasticity by clustering them at the country level. In additional estimations, Driscoll–Kraay standard errors were employed to provide robustness against heteroskedasticity, serial correlation, and cross-sectional dependence.

To examine whether geopolitical risk affected technological innovation immediately or with a delay, the analysis additionally estimated models in which geopolitical risk was lagged by one and two years. This specification was theoretically relevant because the transformation of geopolitical pressures into research investment, technological development, patent applications, and eventually recorded inventions generally requires time. A dynamic specification containing the lagged dependent variable was also examined to account for persistence in national renewable energy innovation. Where dynamic-panel estimation was required, a system generalized method of moments estimator was used as a robustness procedure, with appropriate lagged values of endogenous variables employed as internal instruments and diagnostic tests applied to assess serial correlation and instrument validity. The number of instruments was restricted to avoid instrument proliferation.

Several robustness analyses were conducted to determine whether the estimated geopolitical-risk effect depended on the operationalization of renewable energy innovation or the econometric specification. The models were re-estimated using the share of renewable-energy inventions in total patenting as an alternative dependent variable, using the geopolitical risk index in levels rather than logarithmic form, and applying lagged geopolitical risk indicators. Sensitivity analyses also examined the results after excluding exceptionally high geopolitical-risk observations and highly innovative large economies to determine whether the estimated relationship was driven disproportionately by extreme events or individual countries. Where appropriate, continuous variables were winsorized at the first and ninety-ninth percentiles as an additional check against the influence of extreme observations.

The statistical significance of estimated coefficients was evaluated using two-tailed tests at the 5% significance level, while coefficients significant at the 1% and 10% levels were also reported to provide a more complete assessment of statistical evidence. The magnitude and sign of the geopolitical risk coefficient were interpreted together with its confidence interval rather than solely on the basis of statistical significance. Model diagnostics, specification tests, and robustness estimations were considered jointly when evaluating the stability of the results. The final analytical procedure therefore combined descriptive analysis, panel diagnostics, two-way fixed-effects regression, lagged specifications, robust standard-error estimation, and dynamic-panel and alternative-measure robustness tests to provide a comprehensive assessment of the effect of geopolitical risks on renewable energy innovation across OECD countries during 2000–2022.

3. Findings and Results

The final dataset used for the empirical analysis consisted of a balanced panel of 25 OECD countries observed annually over the 23-year period from 2000 to 2022. Accordingly, the analytical sample contained 575 country-year observations, with 23 annual observations available for each country. The countries included in the study were Australia, Belgium, Canada, Chile, Colombia, Denmark, Finland, France, Germany, Hungary, Israel, Italy, Japan, South Korea, Mexico, the Netherlands, Norway, Poland, Portugal, Spain, Sweden, Switzerland, Türkiye, the United Kingdom, and the United States. The composition of the sample provided substantial heterogeneity in economic size, technological capacity, research and development intensity, energy structure, exposure to geopolitical disturbances, and the maturity of renewable energy innovation systems. Large advanced economies such as the United States, Germany, Japan, France, and the United Kingdom were represented alongside comparatively smaller OECD economies such as Finland, Denmark, Portugal, Hungary, and Chile. Similarly, the panel included economies characterized by relatively high renewable energy penetration as well as countries with historically greater dependence on fossil fuels. This heterogeneity was advantageous for the analysis because it provided sufficient cross-sectional and temporal variation to assess whether changes in geopolitical risk were

systematically associated with changes in renewable energy innovation after accounting for observable macroeconomic and technological characteristics and unobservable country-specific factors. No country was excluded from the analytical sample after construction of the final balanced panel, and all 575 potential country-year observations were retained in the baseline models.

Table 1 presents the descriptive statistics for the dependent variable, the principal independent variable, and the control variables included in the empirical models.

Table 1

Descriptive Statistics of the Study Variables

Variable	N	Mean	SD	Minimum	Maximum
Renewable energy innovation, ln(1 + REI)	575	4.18	1.47	0.69	7.36
Geopolitical risk, ln(1 + GPR)	575	4.61	0.49	3.54	6.08
Real GDP per capita, ln	575	10.54	0.46	9.23	11.44
R&D expenditure (% of GDP)	575	2.08	0.91	0.19	4.93
Trade openness (% of GDP)	575	82.73	48.61	20.72	326.18
Renewable energy share (%)	575	18.91	14.72	0.43	76.18
CO_2 emissions per capita	575	7.81	3.61	1.47	20.18
Population, ln	575	16.78	1.39	14.51	19.58

As shown in Table 1, the logarithm of renewable energy innovation had a mean of 4.18 and a standard deviation of 1.47, with values ranging from 0.69 to 7.36. The comparatively large dispersion of this variable indicates considerable heterogeneity in renewable energy inventive activity among the OECD economies included in the panel. Such variation was expected because the sample incorporated both globally important innovation-intensive economies and smaller countries with substantially lower absolute patenting activity. The logarithmically transformed geopolitical risk index had a mean of 4.61 and a standard deviation of 0.49, with a minimum of 3.54 and a maximum of 6.08. Although the dispersion of the transformed geopolitical risk measure was lower than that of renewable energy innovation, its observed range indicates meaningful variation across countries and years, reflecting the uneven geographical and temporal distribution of geopolitical tensions. Real GDP per capita had a mean logarithmic value of 10.54, confirming that the sample primarily consisted of relatively high-income economies while still retaining meaningful differences in economic development. R&D expenditure averaged 2.08% of GDP, with observed values varying from 0.19% to 4.93%, indicating substantial differences in national commitments to knowledge creation and technological development. Trade openness showed particularly pronounced dispersion, averaging 82.73% of GDP with a standard deviation of 48.61, which was consistent with the inclusion of both large economies with sizable domestic markets and smaller, highly trade-dependent OECD economies. Renewable energy accounted, on average, for 18.91% of final energy consumption, although values ranged from only 0.43% to 76.18%, demonstrating considerable diversity in national energy structures. Average CO_2 emissions amounted to 7.81 units per capita, with a standard deviation of 3.61, while the logarithm of population averaged 16.78. Collectively, the descriptive findings demonstrate that the sample contained sufficient variation in geopolitical exposure, innovation performance, economic development, research capacity, international integration, energy composition, environmental pressure, and national scale to support the subsequent panel econometric analysis.

Before estimating the regression models, the statistical properties of the panel data were examined. Cross-sectional dependence, serial correlation, heteroskedasticity, stationarity, and the relative appropriateness of fixed-effects and random-effects estimation were assessed. The results of these diagnostic procedures are presented in Table 2.

Table 2

Panel Diagnostic Tests and Model Specification Results

Diagnostic test	Test statistic	p	Decision
Pesaran cross-sectional dependence test	12.74	< .001	Cross-sectional dependence present
Wooldridge serial correlation test	19.86	< .001	First-order serial correlation present
Modified Wald heteroskedasticity test	168.42	< .001	Groupwise heteroskedasticity present
Hausman specification test	36.91	< .001	Fixed-effects model preferred
CIPS test: Renewable energy innovation	-2.91	.002	Stationary
CIPS test: Geopolitical risk	-3.18	< .001	Stationary
CIPS test: GDP per capita	-2.63	.008	Stationary
CIPS test: R&D expenditure	-2.79	.004	Stationary
CIPS test: Trade openness	-3.07	< .001	Stationary
CIPS test: Renewable energy share	-2.68	.006	Stationary
CIPS test: CO_2 emissions	-2.74	.004	Stationary
Maximum variance inflation factor	2.31	—	No severe multicollinearity
Mean variance inflation factor	1.67	—	No severe multicollinearity

The diagnostic findings reported in Table 2 provided important guidance regarding the appropriate estimation strategy. The Pesaran cross-sectional dependence statistic was 12.74 and statistically significant at $p < .001$, demonstrating that disturbances affecting one OECD country were not independent of developments occurring in other countries. This finding was theoretically plausible given the substantial economic, technological, financial, and energy-market interdependence among OECD economies. Geopolitical disturbances, international energy-price movements, global technological changes, climate agreements, and major financial events can simultaneously influence several countries, making cross-sectional independence an unrealistic assumption. The Wooldridge test was also statistically significant, $F = 19.86$, $p < .001$, indicating the presence of first-order serial correlation within individual country panels. In addition, the modified Wald test yielded a statistic of 168.42, $p < .001$, confirming groupwise heteroskedasticity. Taken together, these findings justified the use of robust standard-error procedures rather than conventional fixed-effects standard errors.

The Hausman specification test was statistically significant, $\chi^2 = 36.91$, $p < .001$, indicating that the individual-country effects were systematically correlated with the explanatory variables and that the fixed-effects estimator was therefore preferable to the random-effects estimator. Consequently, two-way fixed-effects models incorporating both country and year fixed effects constituted the principal estimation strategy. The cross-sectionally augmented IPS tests also indicated that the principal variables were stationary at the levels or transformations used in the models. The test statistics ranged from -2.63 for real GDP per capita to -3.18 for geopolitical risk, and all corresponding tests were statistically significant at $p < .01$. These findings reduced concerns that the estimated relationships could be attributable to common stochastic trends rather than meaningful economic relationships. Multicollinearity was likewise not identified as a serious problem. The maximum variance inflation factor was 2.31 and the mean VIF was 1.67, both substantially below conventional thresholds indicating problematic collinearity. Consequently, none of the explanatory variables was removed on multicollinearity grounds. Given the simultaneous presence of heteroskedasticity, serial correlation, and cross-sectional dependence, the principal two-way fixed-effects models were estimated using robust inference, with Driscoll–Kraay standard errors additionally used to verify the stability of statistical significance.

Table 3 reports the principal two-way fixed-effects regression results. Four models were estimated sequentially. Model 1 contained geopolitical risk without additional control variables but included country and year fixed effects. Model 2 added GDP per capita and R&D expenditure. Model 3 additionally controlled for trade openness and the renewable energy share, while Model 4 represented the fully adjusted specification containing all explanatory variables, including CO_2 emissions and population.

Table 3

Two-Way Fixed-Effects Estimates of the Effect of Geopolitical Risk on Renewable Energy Innovation

Variable	Model 1 B (SE)	Model 2 B (SE)	Model 3 B (SE)	Model 4 B (SE)
Geopolitical risk, ln	0.241*** (0.071)	0.205*** (0.065)	0.183*** (0.061)	0.169*** (0.059)
GDP per capita, ln	—	0.742*** (0.211)	0.667*** (0.201)	0.614*** (0.194)
R&D expenditure (% GDP)	—	0.281*** (0.063)	0.247*** (0.060)	0.231*** (0.058)
Trade openness (% GDP)	—	—	0.002* (0.001)	0.002* (0.001)
Renewable energy share (%)	—	—	0.011*** (0.003)	0.010*** (0.003)
CO_2 emissions per capita	—	—	—	-0.039** (0.018)
Population, ln	—	—	—	0.174 (0.142)
Country fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
Observations	575	575	575	575
Countries	25	25	25	25
Within R^2	.42	.53	.59	.62
Overall model p	< .001	< .001	< .001	< .001

The results presented in Table 3 demonstrate a consistently positive and statistically significant relationship between geopolitical risk and renewable energy innovation. In the initial specification containing only geopolitical risk together with country and year fixed effects, the coefficient of geopolitical risk was positive and statistically significant, B = 0.241, SE = 0.071, p < .01. The coefficient declined moderately following the inclusion of economic and technological controls but remained statistically significant in every specification. After GDP per capita and R&D expenditure were incorporated in Model 2, the geopolitical risk coefficient remained positive, B = 0.205, SE = 0.065, p < .01. In Model 3, after further adjustment for trade openness and the renewable energy share, the coefficient was 0.183, SE = 0.061, p < .01. Most importantly, in the fully adjusted Model 4, geopolitical risk remained positively associated with renewable energy innovation, B = 0.169, SE = 0.059, p < .01. Because both geopolitical risk and renewable energy innovation were expressed logarithmically, the estimated coefficient can be interpreted approximately as an elasticity. Holding other factors constant, a 1% increase in geopolitical risk was associated with approximately a 0.17% increase in renewable energy innovation. Thus, the results suggest that elevated geopolitical uncertainty was followed by greater inventive activity in renewable energy technologies rather than by a contraction in such innovation.

Several control variables were also significantly associated with renewable energy innovation. GDP per capita showed a positive coefficient in the fully adjusted model, B = 0.614, SE = 0.194, p < .01, indicating that improvements in economic development were associated with greater renewable energy inventive activity within countries over time. R&D expenditure was similarly positive and highly significant, B = 0.231, SE = 0.058, p < .01, confirming the importance of national research capacity in supporting technological innovation. Trade openness demonstrated a comparatively small but positive association, B = 0.002, SE = 0.001, p < .10, suggesting that greater integration into international markets may facilitate knowledge diffusion, access to technological inputs, and exposure to international competitive pressures. The renewable energy share was positively associated with innovation, B = 0.010, SE = 0.003, p < .01, implying that countries with expanding renewable energy sectors also experienced greater innovation in renewable technologies. CO_2 emissions per capita showed a negative coefficient, B = -0.039, SE = 0.018, p < .05, after all other factors were controlled, which may indicate that economies characterized by persistent carbon intensity were comparatively slower in redirecting technological activity toward renewable energy. Population was positive but statistically non-significant, B = 0.174, SE = 0.142, suggesting that changes in national scale did not independently explain renewable energy innovation after country fixed effects and the other covariates were incorporated. The within-country explanatory power increased from R^2 = .42 in Model 1 to R^2 = .62 in Model 4, indicating that the fully adjusted specification accounted for approximately 62% of the within-country temporal variation in renewable energy innovation.

Because innovation processes frequently require several years to translate changing economic incentives and geopolitical conditions into research projects, inventions, and patents, additional models were estimated to determine whether the effect of geopolitical risk occurred contemporaneously or with a temporal lag. Table 4 presents models containing contemporaneous geopolitical risk, one-year-lagged geopolitical risk, two-year-lagged geopolitical risk, and a distributed-lag specification in which current and lagged values were estimated simultaneously.

Table 4

Lagged Effects of Geopolitical Risk on Renewable Energy Innovation

Geopolitical risk variable	B	SE	t	p
Current geopolitical risk	0.142	0.061	2.33	.020
Geopolitical risk, t - 1	0.207	0.064	3.23	.001
Geopolitical risk, t - 2	0.121	0.059	2.05	.041
Current GPR in distributed-lag model	0.113	0.058	1.95	.052
GPR, t - 1 in distributed-lag model	0.181	0.062	2.92	.004
GPR, t - 2 in distributed-lag model	0.096	0.055	1.75	.081
Sum of distributed-lag coefficients	0.390	0.127	3.07	.002

The results in Table 4 provide evidence that the relationship between geopolitical risk and renewable energy innovation was not restricted to the year in which geopolitical disturbances occurred. The contemporaneous geopolitical risk coefficient remained positive and statistically significant, B = 0.142, SE = 0.061, p = .020, indicating an immediate response of renewable energy innovation to increases in geopolitical uncertainty. However, the magnitude of the association was strongest when geopolitical risk was lagged by one year. Specifically, the one-year-lagged coefficient was B = 0.207, SE = 0.064, p = .001, showing that geopolitical risk in the preceding year was associated with a comparatively larger increase in renewable energy innovation in the current year. The two-year-lagged geopolitical risk coefficient also remained positive and statistically significant, B = 0.121, SE = 0.059, p = .041, although its magnitude was smaller than the one-year effect. The pattern therefore suggests that the innovation response to geopolitical disturbances was distributed over time and reached its greatest magnitude approximately one year after the increase in geopolitical risk.

The distributed-lag model provided further support for this interpretation. When current, one-year-lagged, and two-year-lagged geopolitical risk were entered simultaneously, the contemporaneous coefficient was 0.113 and approached conventional statistical significance, p = .052, while the one-year-lagged coefficient remained clearly significant, B = 0.181, SE = 0.062, p = .004. The two-year-lagged coefficient was smaller, B = 0.096, SE = 0.055, p = .081. Importantly, the sum of the three coefficients was 0.390 and was statistically significant, SE = 0.127, p = .002. This cumulative effect indicates that a sustained increase in geopolitical risk was associated with a materially larger medium-term increase in renewable energy innovation than suggested by the contemporaneous coefficient alone. The temporal structure of the results is consistent with the expectation that geopolitical shocks initially alter perceptions of energy security and vulnerability, after which governments and firms adjust investment priorities, research programs, and technological development strategies. Because the generation and registration of patentable inventions require time, the stronger one-year-lagged coefficient provides a plausible indication that the technological response to geopolitical uncertainty is not instantaneous.

An additional dynamic panel model was estimated to account for persistence in renewable energy innovation and to reduce concerns regarding simultaneity and potential endogeneity. Renewable energy innovation tends to be path dependent because countries possessing accumulated technological capabilities, specialized human capital, research infrastructure, and established innovative firms are more likely to continue producing new renewable energy inventions. Consequently, the lagged dependent variable was introduced, and the model was estimated using system generalized method of moments. The results are presented in Table 5.

Table 5

Dynamic Panel System-GMM Estimates of Renewable Energy Innovation

Variable	B	SE	z	p
Renewable energy innovation, t - 1	0.671	0.079	8.49	< .001
Geopolitical risk, t - 1	0.154	0.058	2.66	.008
GDP per capita, ln	0.403	0.183	2.20	.028
R&D expenditure (% GDP)	0.167	0.055	3.04	.002

Trade openness (% GDP)	0.001	0.001	1.71	.087
Renewable energy share (%)	0.007	0.003	2.53	.011
CO_2 emissions per capita	-0.028	0.014	-2.00	.046
Population, ln	0.108	0.097	1.11	.267
Number of observations	550			
Number of countries	25			
Number of instruments	23			
AR(1) test, p	.003			
AR(2) test, p	.381			
Hansen test, p	.427			

The dynamic-panel estimates reported in Table 5 reinforce the principal fixed-effects findings. The lagged dependent variable was strongly positive and statistically significant, B = 0.671, SE = 0.079, p < .001, providing clear evidence of persistence and path dependence in national renewable energy innovation. In practical terms, countries with comparatively high levels of renewable energy inventive activity in one year tended to maintain higher levels of innovation in the subsequent year. After this persistence was explicitly controlled, one-year-lagged geopolitical risk continued to exert a positive and statistically significant effect, B = 0.154, SE = 0.058, p = .008. The persistence of the geopolitical risk coefficient in the dynamic specification is important because it reduces the likelihood that the positive relationship identified in the fixed-effects analysis merely reflected the continuation of previous innovation trends.

The control variables generally retained the direction observed in the baseline models. GDP per capita remained positively associated with renewable energy innovation, B = 0.403, SE = 0.183, p = .028, while R&D expenditure continued to exhibit a strong positive effect, B = 0.167, SE = 0.055, p = .002. The renewable energy share was also positive and significant, B = 0.007, SE = 0.003, p = .011. Trade openness remained positive but was significant only at the 10% level, B = 0.001, SE = 0.001, p = .087. CO_2 emissions per capita remained negatively associated with innovation, B = -0.028, SE = 0.014, p = .046, whereas population was not statistically significant, p = .267. The diagnostic statistics supported the adequacy of the system-GMM specification. As expected in first-differenced residuals, the AR(1) test was statistically significant, p = .003, whereas the AR(2) test was not significant, p = .381, indicating no evidence of problematic second-order serial correlation. The Hansen test of overidentifying restrictions was also non-significant, p = .427, suggesting that the instrument set could not be rejected as invalid. The number of instruments was limited to 23, remaining below the number of cross-sectional units and thereby reducing concerns regarding excessive instrument proliferation. Overall, the dynamic estimates confirmed that the positive association between geopolitical risk and renewable energy innovation remained evident after accounting for innovation persistence and potential endogeneity.

A final set of robustness analyses was conducted to determine whether the principal finding depended on the particular measurement of renewable energy innovation, transformation of geopolitical risk, treatment of extreme observations, or presence of highly innovative economies. These results are presented in Table 6.

Table 6

Robustness and Sensitivity Tests for the Effect of Geopolitical Risk

Robustness specification	GPR coefficient	SE	p	Conclusion
Baseline two-way fixed effects	0.169	0.059	.005	Positive and significant
Driscoll–Kraay standard errors	0.169	0.064	.010	Positive and significant
Renewable patents as share of total patents	0.126	0.051	.014	Positive and significant
Untransformed GPR index	0.003	0.001	.006	Positive and significant
Variables winsorized at 1st and 99th percentiles	0.158	0.056	.006	Positive and significant
Excluding the United States	0.161	0.060	.008	Positive and significant
Excluding the United States, Japan, and Germany	0.148	0.063	.020	Positive and significant
Excluding observations above 99th percentile of GPR	0.153	0.058	.009	Positive and significant
Country-specific linear time trends included	0.137	0.061	.026	Positive and significant
One-year-lagged GPR	0.207	0.064	.001	Positive and significant

As shown in Table 6, the positive effect of geopolitical risk on renewable energy innovation was robust across a broad range of alternative specifications. The baseline two-way fixed-effects coefficient was 0.169, SE = 0.059, p = .005. When Driscoll–Kraay standard errors were used to address cross-sectional dependence, serial correlation, and heteroskedasticity simultaneously, the point estimate remained unchanged and continued to be statistically significant, SE = 0.064, p = .010. This result indicates that the principal inference was not attributable to an overly restrictive conventional error structure. When the dependent variable was redefined as renewable energy patents relative to total domestic patenting activity, geopolitical risk remained positive and significant, B = 0.126, SE = 0.051, p = .014. This finding is particularly relevant because it indicates that rising geopolitical risk was associated not merely with an expansion in overall patenting but also with a relative reorientation of innovative activity toward renewable energy technologies.

The results were also insensitive to the functional form of the geopolitical risk measure. When the original, untransformed geopolitical risk index was used, its coefficient remained positive and statistically significant, B = 0.003, SE = 0.001, p = .006. Winsorizing continuous variables at the first and ninety-ninth percentiles produced a coefficient of 0.158, SE = 0.056, p = .006, demonstrating that the baseline relationship was not driven by a limited number of extreme observations. Similarly, removing the United States, which accounted for a substantial proportion of renewable energy patenting in the sample, yielded a coefficient of 0.161, SE = 0.060, p = .008. The result also remained statistically significant after simultaneously excluding three of the largest innovation-producing economies—the United States, Japan, and Germany—with B = 0.148, SE = 0.063, p = .020. Thus, the observed relationship did not appear to be driven disproportionately by a small number of technologically dominant OECD countries.

Excluding observations above the ninety-ninth percentile of the geopolitical risk distribution produced a positive coefficient of 0.153, SE = 0.058, p = .009, suggesting that exceptional geopolitical crises were not solely responsible for the estimated effect. Furthermore, when country-specific linear time trends were added to control for heterogeneous long-term innovation trajectories across countries, geopolitical risk continued to exhibit a positive association with renewable energy innovation, B = 0.137, SE = 0.061, p = .026. Finally, the one-year-lagged geopolitical risk specification generated the largest estimated coefficient among the principal robustness models, B = 0.207, SE = 0.064, p = .001, further supporting the temporal pattern identified in the lag analysis.

Taken together, the empirical findings provide consistent evidence of a positive relationship between geopolitical risk and renewable energy innovation in the selected OECD countries during 2000–2022. The association remained statistically significant after controlling for economic development, national R&D intensity, trade openness, renewable energy penetration, carbon emissions, population, country-specific fixed characteristics, and common annual shocks. The results were also robust to alternative standard-error estimators, alternative measurements of innovation and geopolitical risk, lagged specifications, the treatment of extreme observations, the exclusion of major innovative economies, country-specific trends, and dynamic-panel estimation. The one-year-lagged effect was consistently stronger than the contemporaneous association, indicating that the technological response to geopolitical disturbances developed progressively rather than occurring entirely within the same year. Overall, the findings suggest that increased geopolitical risk may operate as an external stimulus for renewable energy innovation in OECD economies by increasing the strategic value of energy independence, highlighting vulnerabilities associated with imported fossil fuels, and strengthening incentives to develop domestic and diversified low-carbon energy technologies.

4. Discussion and Conclusion

The present study investigated the effect of geopolitical risk on renewable energy innovation across 25 OECD countries during 2000–2022 using a longitudinal panel-data framework. The findings showed that geopolitical risk had a positive and statistically significant effect on renewable energy innovation, and this relationship remained stable after controlling for economic development, research and development expenditure, trade openness, renewable energy penetration, carbon emissions, population size, country-specific fixed effects, and common annual shocks. The baseline two-way fixed-effects model indicated that higher geopolitical risk was associated with greater renewable energy inventive activity, while the lagged models revealed that the effect was strongest after a one-year delay. The dynamic system-GMM estimates further confirmed that geopolitical risk retained a positive effect even after

controlling for the strong persistence of renewable energy innovation. In addition, the robustness tests showed that the result was not driven by the transformation of the geopolitical risk index, exceptionally high-risk observations, the presence of large innovative economies, or the specific operationalization of renewable energy innovation. Taken together, these findings suggest that geopolitical disturbances may function not only as sources of economic and energy-market uncertainty but also as catalysts for technological responses aimed at increasing energy independence, diversification, and resilience.

The positive relationship between geopolitical risk and renewable energy innovation is consistent with the broader argument that geopolitical instability can increase the strategic value of energy diversification. Conventional energy systems are highly exposed to geopolitical disruptions because oil and natural gas production, transportation routes, and transit infrastructure are concentrated geographically and frequently depend on politically sensitive international relationships. Energy has historically functioned as an instrument of strategic leverage, and disruptions in oil and gas supply can rapidly affect international diplomacy and national security priorities (Ahmed, 2025). The positive innovation response found in the present study can therefore be interpreted as a strategic adaptation mechanism through which countries seek to reduce dependence on vulnerable fossil-fuel imports. This interpretation is also compatible with studies emphasizing that geopolitical instability can alter national energy policy by increasing concerns over supply security and strengthening incentives to diversify the energy mix (Kamalov, 2025). In OECD economies, where technological and financial capacities are generally more advanced, such diversification may take the form not only of greater deployment of existing renewable technologies but also of intensified innovation aimed at developing more efficient and domestically controllable energy solutions.

The results are also aligned with evidence that geopolitical risk can stimulate renewable energy investment. Flouros and colleagues identified geopolitical risk as an important determinant of investment in renewable energy, showing that geopolitical conditions influence the allocation of capital toward alternative energy systems (Flouros et al., 2022). Similarly, firm-level evidence indicates that geopolitical risk and oil-price volatility can affect renewable energy investment behavior, implying that geopolitical disturbances may alter the relative attractiveness of clean-energy assets (Zhao et al., 2024). The current findings extend this line of research from investment behavior to inventive activity. Investment and innovation are closely linked, because higher expected demand for renewable technologies can raise expected returns to research and development, thereby encouraging firms and governments to increase technological effort. When geopolitical instability increases the perceived long-term cost of fossil-fuel dependence, resources may be redirected toward the development of renewable technologies with greater strategic value. The positive effect observed in this study therefore suggests that one response to geopolitical uncertainty is not merely portfolio substitution toward existing renewable assets but also greater creation of new energy-related technological knowledge.

The findings can further be explained through the interaction between geopolitical risk and fossil-energy markets. Previous research has shown that geopolitical shocks affect crude-oil markets through several transmission mechanisms, including supply expectations, financial speculation, transport disruption, and changing risk perceptions (Jiao et al., 2023). Geopolitical risk can also influence investor attention and speculative behavior in oil markets in nonlinear and time-varying ways (Xiao et al., 2023), while the effects on energy returns and volatility may differ according to market conditions (Qin et al., 2020). These dynamics create economic incentives for substitution away from fossil fuels when geopolitical tensions increase the volatility or expected cost of conventional energy. The Russia–Ukraine war, for example, demonstrated that geopolitical conflict can rapidly alter oil-price dynamics through multiple channels (Zhang et al., 2023). Against this background, the positive relationship between geopolitical risk and renewable energy innovation found in the present study can be interpreted partly as a technological response to increases in fossil-fuel uncertainty. When conventional energy becomes less predictable, innovation in renewable technologies may become more valuable because it improves the feasibility of reducing exposure to external price and supply shocks.

The findings also support the growing literature on the geopolitical consequences of the energy transition. The shift toward renewable energy does not eliminate geopolitical competition but changes its structure. Renewable technologies reduce dependence on imported fuels in some respects, while creating new strategic dependencies associated with technology, critical materials, manufacturing capacity, and infrastructure (Vakulchuk et al., 2020). The energy transition can therefore redistribute

geopolitical power by altering which resources, technologies, and industrial capabilities are strategically important (Blondeel et al., 2021). The present findings indicate that geopolitical instability itself may accelerate this redistribution by stimulating technological innovation in renewable energy. In other words, geopolitical risk may create stronger incentives for states and firms to acquire technological capabilities that reduce dependence on traditional energy systems. This is particularly important for OECD countries, which possess substantial research infrastructure and are therefore better positioned to convert geopolitical pressure into technological adaptation.

The stronger one-year-lagged effect found in this study is theoretically meaningful. Renewable energy innovation is unlikely to respond immediately to geopolitical shocks because research projects, funding decisions, experimental development, patent preparation, and organizational restructuring require time. The finding that geopolitical risk in the preceding year had a larger effect than contemporaneous geopolitical risk suggests that technological responses develop gradually following changes in the strategic energy environment. This pattern is consistent with evidence that geopolitical disturbances influence corporate strategy and restructuring decisions in energy industries. Geopolitical risk has been shown to affect mergers and acquisitions among energy and electric-power firms, indicating that firms adjust organizational and investment strategies in response to geopolitical uncertainty (Shen et al., 2021). Such adjustments may subsequently support technological development through access to knowledge, capabilities, and new investment opportunities. The delayed effect observed in the present study may therefore reflect the time required for geopolitical concerns to be translated into concrete R&D and innovation decisions.

The positive association between geopolitical risk and renewable energy innovation is also consistent with the idea that energy security and climate policy increasingly reinforce each other. A comprehensive review of global energy security shows that geopolitical dynamics are deeply connected to national policies concerning resilience, diversification, and the reliability of energy supply (Ibekwe et al., 2024). Different dimensions of geopolitical instability, including geopolitical threats and geopolitical acts, can influence the pace and direction of energy transition (Wang et al., 2024). The present findings suggest that technological innovation is one of the channels through which this relationship operates. As geopolitical risk rises, the strategic value of domestic clean-energy capabilities may increase, encouraging governments and firms to support renewable energy research as part of broader energy-security strategies. This mechanism is particularly plausible in economies that are heavily dependent on internationally traded fossil fuels, because innovation can reduce long-term exposure to external suppliers and volatile markets.

The European energy crisis following the Russian invasion of Ukraine provides a clear illustration of this mechanism. The crisis fundamentally altered the political meaning of decarbonization by linking climate transition more directly to strategic autonomy and security of supply (Goldthau & Youngs, 2023). The invasion also transformed the geopolitics of European energy by increasing the urgency of reducing dependence on Russian fossil fuels and diversifying energy sources (Skalamera, 2023). The present results are compatible with this experience: geopolitical disruption can generate incentives for accelerating technological development in renewable energy because clean-energy innovation becomes relevant not only for emissions reduction but also for national security. The consequence is that the energy transition may be accelerated under geopolitical pressure when countries possess sufficient financial, institutional, and technological capacity to respond.

The positive coefficient of GDP per capita is also consistent with theoretical expectations. Renewable energy innovation requires substantial financial resources, research infrastructure, skilled human capital, and sophisticated markets, all of which are more available in higher-income economies. Economic development therefore provides the resource base necessary to transform geopolitical incentives into technological outcomes. The findings also showed a strong positive effect of R&D expenditure, supporting the view that domestic research capacity is central to renewable energy innovation. Geopolitical risk alone does not automatically produce innovation; countries must possess scientific and technological capabilities that allow them to respond effectively. This interpretation helps explain why OECD countries are an appropriate context for identifying a positive innovation response. Their comparatively developed national innovation systems enable them to translate energy-security concerns into research, patenting, and technological development.

The positive relationship between the renewable energy share and innovation further supports the existence of feedback between market development and technological change. Countries with larger renewable energy sectors create stronger markets for clean-energy technologies,

which can increase the expected returns to innovation. At the same time, technological development can improve renewable energy performance and reduce costs, thereby facilitating further deployment. This mutually reinforcing relationship may become more pronounced during geopolitical crises because energy security strengthens demand for renewable alternatives. The broader literature similarly shows that geopolitical risk can affect renewable energy consumption in interaction with financial development and institutional conditions (Alsagr & van Hemmen, 2021). The present findings suggest that the same broad process may apply to innovation: stronger renewable markets can create an environment in which geopolitical pressures are more readily translated into technological development.

The positive but relatively modest effect of trade openness also deserves attention. International trade can promote renewable energy innovation by facilitating access to advanced technologies, specialized components, research networks, and foreign knowledge. At the same time, geopolitical tension can disrupt precisely these channels. Contemporary energy markets are increasingly characterized by interaction among geopolitical risks, international trade, and energy security (Akadiri & Özkan, 2025). The fact that trade openness remained positively associated with innovation suggests that access to international markets continues to support technological development despite geopolitical uncertainty. However, the comparatively small magnitude of the coefficient may also reflect the increasing tension between efficiency through global integration and resilience through technological localization. Geopolitical risk may therefore encourage OECD countries to maintain the benefits of international technological exchange while simultaneously strengthening domestic innovation capacity.

The negative association between CO_2 emissions per capita and renewable energy innovation, after controlling for other factors, may indicate that economies with persistently carbon-intensive energy structures face structural barriers to technological transition. High carbon intensity can reflect entrenched fossil-fuel infrastructure, established industrial interests, and path dependence that slow the reorientation of innovation toward renewable technologies. This interpretation is consistent with the broader literature showing that the energy transition is not merely a technological process but a geopolitical and institutional transformation (Blondeel et al., 2021). The result suggests that geopolitical risk does not affect all economies uniformly; its capacity to stimulate innovation may depend on whether existing energy systems allow technological resources to be redirected toward renewable alternatives.

The robustness findings strengthen confidence in the main conclusion. The positive geopolitical-risk effect remained significant when Driscoll–Kraay standard errors were employed, when renewable energy innovation was measured relative to total patenting activity, when geopolitical risk was entered in untransformed form, when extreme observations were winsorized, and when major innovative economies were excluded. The relationship also persisted after country-specific linear trends were incorporated. This consistency is important because geopolitical risk and renewable energy innovation are both highly heterogeneous across countries. The robustness results indicate that the main finding cannot be attributed solely to a small number of major crises or highly innovative countries.

The dynamic system-GMM results provide additional support for the interpretation of geopolitical risk as an innovation stimulus. Renewable energy innovation exhibited strong persistence, which was expected because technological development depends on accumulated capabilities and knowledge. Even after this persistence was controlled, lagged geopolitical risk remained positive and significant. This finding implies that the geopolitical-risk effect was not merely capturing the continuation of existing innovation trajectories. Instead, increases in geopolitical risk appear to have contributed additional explanatory power beyond prior innovation performance. The validity of this result was further supported by the absence of significant second-order serial correlation and the acceptable Hansen test.

The findings can also be interpreted within the broader transformation of global energy diplomacy. Energy transition is increasingly being managed as a geopolitical process rather than solely as an environmental program (La Camera, 2025). Countries are seeking to strengthen energy autonomy while simultaneously positioning themselves within emerging clean-energy markets. Türkiye's aspiration to become an energy hub, for example, illustrates how sustainability and geopolitical strategy are becoming increasingly interconnected (Shokri, 2025). Similar dynamics can be observed in regions where energy infrastructure, transit routes, and geopolitical positioning remain central to national strategy (Gurbanov, 2024; Konashlu et al., 2022; Norouzizadeh et al., 2022). As energy systems diversify, technological innovation becomes an

additional source of geopolitical capability alongside control over conventional resources and transit routes.

The results are also compatible with evidence that modern energy systems increasingly connect environmental, financial, and geopolitical dimensions. Reviews of the energy sector have emphasized the interdependence among financial markets, environmental concerns, energy industries, and geopolitical forces (Pantel, 2024). Likewise, clean-energy prices have been shown to respond asymmetrically to geopolitical risk, climate-policy uncertainty, and crude-oil prices (Sarker et al., 2023). European utility-company performance is also shaped by geopolitical risk and fossil-energy-price changes, highlighting the financial consequences of geopolitical instability for energy-transition actors (Yang et al., 2024). These findings provide an important context for the current study: renewable energy innovation is embedded in a wider system in which geopolitical shocks alter prices, expectations, financing conditions, and strategic priorities. The positive innovation effect may therefore represent the cumulative outcome of several reinforcing channels rather than a single causal mechanism.

Finally, the study's results support the broader proposition that geopolitical instability may accelerate some components of sustainable energy transition, even though it remains economically and socially costly overall. Sustainable development increasingly lies at the intersection of geopolitical risk, natural-resource constraints, renewable energy, and energy security (Zhang & Liu, 2025). Geopolitical crises may raise the immediate costs of energy provision, but they can also reveal vulnerabilities in existing systems and create stronger incentives for technological diversification. The findings of the present study suggest that, within OECD countries, renewable energy innovation is one area in which such adaptive responses are visible. This does not imply that geopolitical conflict is beneficial or desirable. Rather, it indicates that countries with sufficiently developed innovation systems may respond to geopolitical pressure by accelerating technological efforts intended to reduce future vulnerability.

This study has several limitations that should be considered when interpreting the findings. First, the analysis was restricted to 25 OECD countries for which consistent country-specific geopolitical risk data were available, and the results therefore cannot automatically be generalized to all OECD members or to developing and emerging economies. Second, renewable energy innovation was measured using patent-based indicators. Although patent data provide a widely used proxy for inventive output, not all innovations are patented, patent quality varies substantially, and patent counts do not directly measure commercialization or technological diffusion. Third, the annual geopolitical risk index may conceal shorter-term fluctuations and heterogeneous responses to different categories of geopolitical events. Fourth, despite the use of fixed effects, lagged specifications, robust standard errors, and system-GMM estimation, the possibility of residual endogeneity cannot be entirely eliminated. Fifth, national-level analysis may mask important variation across firms, industries, renewable-energy technologies, and regions within countries. Finally, the study did not explicitly distinguish geopolitical threats, actual geopolitical events, sanctions, wars, terrorism, and diplomatic disputes, although these different forms of geopolitical risk may influence innovation through distinct mechanisms.

Future studies should extend the analysis in several directions. Researchers could examine larger samples that include emerging and developing economies in order to determine whether the positive relationship observed in OECD countries depends on institutional quality, financial development, research capacity, or income level. Future research could also disaggregate renewable energy innovation into solar, wind, hydrogen, storage, geothermal, hydropower, smart-grid, and other technological categories because geopolitical shocks may affect individual technologies differently. Firm-level and sector-level studies would be particularly useful for identifying the microeconomic mechanisms linking geopolitical uncertainty to R&D expenditure, patenting behavior, strategic alliances, and investment decisions. Future studies could also distinguish between geopolitical threats and realized geopolitical events and examine nonlinear or threshold effects to determine whether moderate and extreme geopolitical risks generate different innovation responses. Spatial panel models could be employed to capture innovation spillovers across neighboring or economically integrated countries. In addition, the interaction of geopolitical risk with fossil-fuel import dependence, critical-mineral dependence, financial development, environmental regulation, government R&D subsidies, and climate-policy stringency should be investigated as potential moderators. High-frequency or event-study designs may also help identify the short-run effects of major geopolitical crises before they are translated into longer-term patenting outcomes.

The findings have several practical implications for policymakers, energy regulators, and innovation managers. Governments should treat renewable energy innovation as part of national energy-security strategy rather than only as an environmental-policy instrument. Public R&D support, innovation tax incentives, research grants, demonstration programs, and public-private partnerships should be designed to strengthen technological capacity in areas that reduce exposure to imported fossil fuels and geopolitical disruption. Policymakers should also diversify clean-energy supply chains and invest in domestic capabilities related to energy storage, grid modernization, advanced renewable manufacturing, and critical energy technologies. Because the strongest geopolitical-risk effect appeared with a time lag, governments should avoid purely reactive short-term responses and instead establish permanent innovation mechanisms that can rapidly scale when geopolitical conditions deteriorate. Energy firms should incorporate geopolitical scenarios into long-term R&D and technology planning and assess whether their innovation portfolios reduce dependence on vulnerable suppliers or transport routes. International cooperation among OECD countries should also be maintained in areas such as joint research, technology standards, critical-material recycling, and knowledge exchange so that greater energy resilience does not lead to unnecessary technological fragmentation. Overall, the most effective policy response is to convert geopolitical vulnerability into sustained investment in technological capability, diversification, and renewable-energy resilience.

Authors' Contributions

Authors contributed equally to this article.

Declaration

In order to correct and improve the academic writing of our paper, we have used the language model ChatGPT.

Transparency Statement

Data are available for research purposes upon reasonable request to the corresponding author.

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Ethics Considerations

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