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Climate Change and Energy Security Risk: Do Green Patents, Institutional Quality, and Human Capital Make a Difference?

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ABSTRACT

Climate change poses a significant threat to global energy security, yet the mechanisms through which this relationship unfolds—and the factors that buffer their adverse impacts—remain underexplored. This study examines the link between climate change, proxied by CO_2 emissions, and energy security risk (ESR), with a particular focus on the mediating roles of green patent, institutional quality, and human capital. Utilizing a newly compiled historical dataset encompassing ESR and climate indicators, and applying a suite of robust empirical strategies—including sensitivity tests, alternative variable specifications, and instrumental variable techniques—we provide compelling evidence that rising CO_2 emissions substantially elevate ESR across GCC countries between 1990 and 2023. Importantly, we find that the interaction between climate change and the tripartite mediating factors reduces ESR significantly. Additionally, the study establishes threshold levels for these mitigating factors, beyond which they effectively transform energy insecurity into energy security. Moreover, the efficacy of these mitigating effects appears to be conditioned by macroeconomic and demographic factors, manifesting more strongly in contexts characterized by higher levels of economic development and stable population dynamics. To enhance the buffering capacity of these factors, policy efforts should prioritize the development of resilient energy systems, demographic sustainability, and stringent environmental governance. These findings offer timely and actionable insights for GCC countries and other fossil fuel-dependent economies striving to align energy security objectives with long-term climate resilience.

1 | Introduction

In recent decades, the critical importance of understanding the direct impact of climate change on energy security risk (ESR) has come to the fore amid growing public policy concerns (Bashir et al. 2025; Bergougui et al. 2025; Rahman et al. 2025). The rapid escalation of climate-related disasters—including extreme temperature variations, severe precipitation events, intense wind gusts, and prolonged droughts—has not only led to tragic losses of life and widespread social disruption but has also inflicted substantial damage on energy infrastructure worldwide (Al-Maadid, Ben Ali, and Younis 2025; Ben Ali and Al-Maadid 2025). Such events challenge the reliability of energy systems, which are fundamental to economic activities, emphasizing the significance of integrating climate resilience into energy security planning. Energy is a cornerstone of modern economies, driving nearly every facet of societal function from industrial production to personal well-being (Mininni et al. 2024; Zhang et al. 2023). When climate change-related disasters disrupt energy systems—through direct physical damages to infrastructure or by destabilizing market conditions—the resultant energy insecurity can ripple through

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economies, exacerbating social inequalities and impairing growth (Salisu et al. 2025). Notably, the recent geopolitical crises such as the Russia–Ukraine war and COVID-19 epidemic have further underscored the fragility of global energy supplies, with household energy costs nearly doubling in some regions (Kim et al. 2025). This heightened uncertainty spotlights the urgent need for countries to focus on sustainable alternatives and robust policy mechanisms that mitigate these vulnerabilities.

Historically, climate change has been intricately linked with a range of adverse outcomes: from economic disruptions and reduced labor productivity to environmental degradation and conflicts over natural resources. Scholarly work over the past decades—from studies by Crowley (2000) and Tol (2002) to more recent analyses by Hegerl et al. (2019), Loucks (2021), and Neale et al. (2025)—has delineated how carbon emissions, which underlie climate change, accelerate the deterioration of the ozone la1yer and trigger extreme weather events. These phenomena, in turn, disrupt energy supply chains and jeopardize the affordability and accessibility of energy. Moreover, research has pointed to the critical roles of green energy and energy storage innovations in curbing carbon emissions and ensuring a more resilient energy supply in the face of disruptive climate events (Mideksa and Kallbekken 2010).

Despite growing consensus on the dangers posed by climate change, there is a notable gap in our empirical understanding of how climate change directly influences overall ESR. While previous studies have examined specific components—such as the impact on electricity production or energy expenditures (Bui et al. 2024; Campagnolo and De Cian 2022)—a holistic analysis that encompasses both the direct and indirect effects of climate-induced disasters on energy systems has been elusive. Furthermore, the policy response, largely focused on adjusting energy portfolios by balancing fossil fuels with alternative energy sources, often overlooks the potent role of institutional frameworks, green patents, and human capital in mediating these risks.

Current literature tends to explore the trade-offs between renewable and non-renewable energy policies without fully addressing how innovations in green technology, supported by robust institutions and skilled human capital, might attenuate the adverse impacts of climate change on energy security. Although exploratory studies (Bazilian et al. 2011; Ha 2025; King and Gulledge 2014; Vrochidis and Chalaris 2023) have shed light on certain facets of the climate–energy nexus, the empirical evidence remains fragmented. There is a clear need for rigorous, comprehensive research that not only quantifies direct relationships but also elucidates how targeted policy interventions can reduce ESR through enhanced technological and institutional capacities.

A growing body of research underscores the link between climate change and ESR. For example, extreme weather events driven by climate change have been linked to significant interruptions in energy production and distribution (Kahn et al. 2021; X. Wang et al. 2012). Policy studies have also demonstrated that investments in green energy, such as green patents and sustainable infrastructure, can mitigate some of these impacts by reducing carbon emissions and diversifying energy sources (X. Chen et al. 2021; Lim and Kim 2012). Conversely, reliance on dirty energy sources not only perpetuates vulnerability but also accelerates the rate of global climatic shifts, thereby creating a vicious cycle of increasing energy insecurity (Gentile and Gupta 2025; Mares and Moffett 2016).

Within the Gulf Cooperation Council (GCC) region, the stakes are particularly high. The economies of these countries are deeply intertwined with energy production and exportation, making them exceptionally susceptible to the risks associated with climate change. Recent policy interventions have aimed to accelerate the shift toward cleaner energy—Europe alone has committed more than $763 billion to support the transition—yet fossil fuel dependencies persist.[1] However, the GCC region faces unique challenges due to its heavy reliance on fossil fuels, limited diversification in its energy mix, and the pressing need to balance short-term energy security with long-term sustainability goals. Effective policy interventions in the region must therefore draw on both global best practices and localized strategies, integrating advanced green patents, strong institutional support, and the development of human capital to build a more resilient energy infrastructure.

This study is designed with several key objectives in mind:

- To quantify the direct impact of climate change on overall ESR by analyzing CO_2 emissions and extreme weather events.
- To examine the mitigating role of green patents, institutional quality, and human capital in reducing ESR.
- To compare the efficacy of these mitigating factors in GCC economies of varying sizes, particularly contrasting the experiences of higher GDP countries with those in the lower half.
- To provide tailored policy recommendations that address both global trends and regional specifics, with a special focus on the GCC region.

The primary aim of this research is to bridge the empirical gap in understanding the direct nexus between climate change and ESR. Through developing a robust theoretical framework and employing comprehensive empirical analyses, this study demonstrates that while climate change exacerbates energy insecurity—particularly in lower GDP economies—strategic enhancement of clean innovation, coupled with strong institutional support and human capital development, can significantly counterbalance these adverse effects. Our work contributes both to the broader scholarly discourse on climate change impacts and offers practical policy guidance for fostering sustainable and resilient energy systems at global and regional scales.

Our study makes four distinct contributions to the literature:

- Comprehensive ESR measurement framework: Our analysis uses annual data from multiple integrated databases. Core energy security data comes from the Global Energy Institute's comprehensive international risk index, which assesses energy security across four key dimensions: economic stability, geopolitical issues, environmental impact, and system reliability. These components include 29 different metrics covering power generation capacity, supply chain resilience, operational efficiency, consumption patterns, and emission levels.

- Holistic climate impact assessment: We create a comprehensive climate metric including: CO_2 emissions (million tonnes), extreme temperature events, extreme precipitation patterns, extreme wind conditions, and prolonged drought periods. This multidimensional approach captures the full range of climate-related threats to energy security.
- Mechanistic pathway analysis: Beyond establishing empirical links between climate change and ESR, we identify and examine three main transmission channels: green patent innovation, institutional quality, and human capital development. This mechanistic approach offers insights into specific policy intervention points.
- Contextual heterogeneity analysis: We investigate systematic differences by income level (high-income versus lower-income economies) and population size (large versus small populations), providing a detailed understanding of how climate-energy security relationships differ across varied economic and demographic settings.

The structure of the paper is organized as follows: In Section 2, the theoretical foundation is introduced along with the formulation of research hypotheses. Section 3 focuses on the dataset and establishes a simplified model that connects climate change, moderating factors, and energy security. Section 4 showcases the findings and delves into their interpretation, while Section 5 offers additional examination. Finally, Section 6 wraps up with a summary of policy insights drawn from the research outcomes.

2 | Theoretical Mechanism and Research Hypotheses

2.1 | Climate Change and Energy Security: Theoretical Foundations

The climate change–energy security risks nexus is intricate and multifaceted, with green patents, institutional quality, and human capital emerging as pivotal mechanisms to mitigate these risks. The environmental economics literature has extensively examined the complex relationships between climate variables, technological innovation, and energy systems, providing crucial insights into how environmental degradation and energy security intersect (Caglar et al. 2023; Pata, Kartal, et al. 2023). Studies have demonstrated that information and communication technologies (ICT) can effectively mitigate environmental degradation across technologically advanced nations, while the role of renewable energy technologies in emissions reduction remains contested (U. K. Pata and Yurtkuran 2022). Furthermore, research on environmental regulations reveals their critical importance in promoting sustainability, though their effectiveness varies significantly across different economic contexts and policy frameworks (Caglar et al. 2023). Energy security—defined as affordable, uninterrupted access to reliable to energy—is increasingly jeopardized by the impacts of climate change. Rising global temperatures have intensified cooling demands in residential, commercial, and industrial sectors, placing unprecedented strain on energy grids during peak periods (Mideksa and Kallbekken 2010). This heightened demand has already led to grid failures in regions experiencing extreme heatwaves, with cascading effects on critical services and economic activity. Additionally, the growing frequency and severity of extreme weather events—such as floods, hurricanes, droughts, and wildfires—pose direct threats to energy infrastructure, including transmission lines, power plants, and distribution networks, resulting in prolonged supply disruptions that can last for weeks or months (Ramião et al. 2023). The environmental economics literature further emphasizes that the effectiveness of different energy sources in achieving carbon neutrality varies considerably across countries and contexts. Research on major nuclear power nations reveals that while nuclear energy can reduce carbon emissions in some countries like Russia, renewable sources such as solar and wind power show differential impacts depending on national circumstances and implementation strategies (Kartal et al. 2023). These findings underscore the complexity of energy transition policies and highlight the need for country-specific approaches to achieving both energy security and environmental sustainability (Ugur Korkut Pata and Hizarci 2022; U. K. Pata et al. 2025).

Hypothesis 1. *Climate change positively affects energy security risks.*

Compounding these challenges, climate change has accelerated the global transition from fossil fuels to cleaner energy sources (Hrnčić et al. 2021). While this shift is essential for long-term sustainability, it introduces new vulnerabilities, such as the high upfront costs of renewable technologies, intermittency issues with wind and solar generation, and reliability concerns during the early adoption phases (Ciarreta et al. 2014). Recent geopolitical events, such as the Russia-Ukraine war, have further exposed vulnerabilities in global energy markets, underscoring the urgent need for resilient and diversified energy systems (Z. Liu et al. 2025).

2.2 | Moderating Mechanisms in the Climate–ESR Nexus

Building on the resource-based view and institutional theory, we propose that the relationship between climate change (measured by CO_2 emissions) and ESR is contingent upon three critical moderating factors: green patents, institutional quality, and human capital. These variables do not operate in isolation but form an interconnected system of capabilities and governance structures that collectively determine a nation's resilience to climate-energy challenges. The theoretical foundation rests on the premise that climate change creates external pressures on energy systems, but the magnitude of resulting energy security risks depends on internal adaptive capacities. Green patents represent technological capabilities, institutional quality reflects governance capabilities, and human capital embodies knowledge capabilities. These three dimensions work synergistically: technological solutions require institutional support for deployment and skilled human resources for development and implementation, while strong institutions facilitate both innovation and human capital development.

2.2.1 | Green Patents as Technological Moderator

Green patents play a pivotal role in alleviating the link between carbon dioxide emissions and energy security concerns through technological pathway moderation. They foster technological advancements designed to tackle the fundamental causes of climate change while improving the resilience and sustainability of energy systems (Abbas et al. 2024). Green patents operate through two complementary channels.

- First, they enable emission-reduction pathways by fostering the improvement of low-carbon technologies—such as wind turbines, energy-efficient appliances, energy storage systems, and solar panels—that directly reduce CO_2 emissions. By transitioning away from fossil fuels, these innovations decelerate climate change, reducing the intensity of severe weather phenomena that pose risks to energy systems (Acemoglu et al. 2016; Bergougui 2024b).
- Second, they enhance system resilience by contributing to building resilient energy systems capable of withstanding climate-related stresses. For example, patented advancements in flood-resistant power grid designs, hurricane-resistant wind turbines, and smart grid technologies enhance system flexibility and responsiveness, reducing vulnerability to extreme weather events. Innovations in energy storage address intermittency issues associated with renewable energy sources, improving reliability and addressing key energy security concerns during the transition phase (Iyke 2024).

The effectiveness of green patents in moderating the climate–ESR nexus depends on their interaction with institutional and human capital factors, as patents require supportive policy environments and skilled implementation.

Hypothesis 2. *Green patents significantly moderate the positive climate change–energy security risk nexus.*

2.2.2 | Institutional Quality as Governance Moderator

Institutional quality plays a pivotal role in shaping the relationship between CO_2 emissions and ESR through governance pathway moderation, establishing the frameworks, regulatory stability, and policy environments essential for effective climate action and energy system adaptation (Nilsson 2011). Strong institutions operate through three interconnected channels.

- First, emission governance reduces CO_2 emissions through the implementation of robust policies, enforcement of higher environmental standards, and promotion of clean energy investments. Studies demonstrate that improvements in institutional quality lead to measurable reductions in emissions across various economies, particularly those reliant on fossil fuel exports (Albahouth and Tahir 2025; Cai et al. 2025).
- Second, risk management governance directly addresses ESR by implementing disaster preparedness measures, enforcing stricter standards for infrastructure resilience, and developing comprehensive emergency response capabilities. Better-governed countries maintain energy security during extreme weather events due to their ability to anticipate disruptions and respond effectively (OECD 2019).
- Third, investment governance fosters predictable environments that attract long-term investments in renewable energy infrastructure and grid modernization. By creating stable regulatory frameworks and transparent processes, strong institutions reduce uncertainties for investors, enabling the deployment of innovative solutions that enhance energy security (Giganti et al. 2025).

Institutional quality amplifies the effectiveness of both green patents and human capital by providing the governance infrastructure necessary for their optimal utilization.

Hypothesis 3. *Higher institutional quality weakens the positive climate change–energy security risk nexus.*

2.3 | Human Capital as Knowledge Moderator

Human capital—the collective knowledge, skills, and adaptive capabilities of individuals—plays a central role in addressing the interlinked challenges through knowledge pathway moderation (Lenihan et al. 2019). Human capital operates through three complementary mechanisms.

- First, technological implementation capacity ensures that skilled workforces can advance technological innovation, deploy green energy solutions, and adapt to climate-driven disruptions (Arcelay et al. 2021). Professionals such as engineers, scientists, and technicians are critical for designing, operating, and maintaining renewable energy infrastructure and smart grids that can withstand climate stresses (International Renewable Energy Agency 2022).
- Second, adaptive capacity enhancement enables societies to respond dynamically to climate-related disruptions. Workers with problem-solving abilities can devise emergency protocols, optimize resource allocation during crises, and manage renewable energy variability (Worku 2022).
- Third, governance capacity building strengthens policymaking and advocacy efforts. Knowledgeable policymakers and informed publics drive forward-looking energy policies and ensure transitions align with resilience goals (Dehghan Shabani 2024; Yao et al. 2020).

Human capital effectiveness is enhanced when combined with green technological solutions and strong institutional frameworks, creating synergistic effects.

Hypothesis 4. *Higher levels of human capital reduce the positive climate change–energy security risk nexus.*

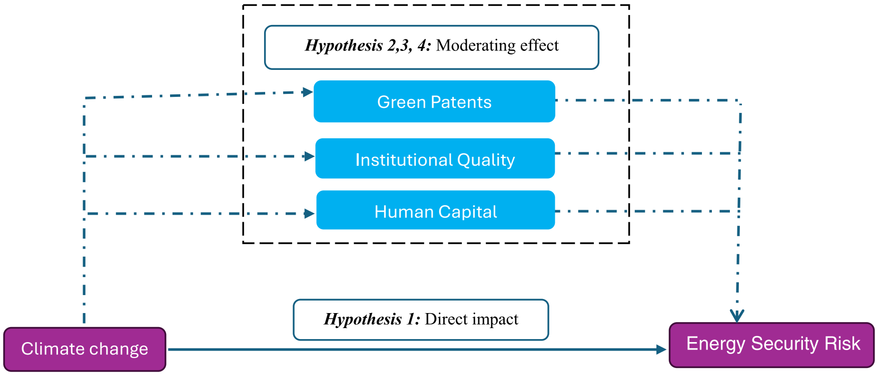

FIGURE 1 | Analytical framework.

Incorporating these mechanism analyses, Figure 1 illustrates this comprehensive framework of transmission channels linking climate change (measured by CO_2 emissions) to ESR. It highlights how green patents, institutional quality, and human capital serve as critical intervention points, transforming climate challenges into opportunities for enhanced energy resilience. By strengthening these mechanisms, societies can navigate the interplay between climate change and ESR, ensuring reliable, affordable, and sustainable energy access in a rapidly changing world.

3 | Data and Econometric Strategy

3.1 | Data

Our analysis employs yearly measurements drawn from multiple databases. The core energy security data come from the Global Energy Institute, which maintains a comprehensive international risk index. This index evaluates energy security through four critical dimensions: economic stability, geopolitical factors, environmental impact, and system reliability. These components integrate 29 distinct metrics, encompassing aspects like power generation capacity, supply chains, operational efficiency, consumption patterns, and emission levels. To facilitate meaningful cross-country comparisons, the institute standardized all 29 metrics by setting 1980 as the baseline year with a value of 1000. Subsequent years' measurements are calibrated proportionally against this reference point. A higher index score indicates elevated ESR and reduced overall security.

For compatibility with our climate analysis, we transformed the annual energy security data into monthly intervals.[2] The climate dataset incorporates various indicators discussed in academic research (Ben Ali et al. 2025; Chen et al. 2021; Gortan et al. 2024) such as carbon dioxide output and extreme climate events (Al-Maadid, Ben Ali, and Si Mohammed 2025; Iyke 2024). This climate information covers six GCC countries from 1990 through 2023. We enriched this combined dataset with contextual economic indicators that prior research has linked to energy security concerns. These include measures of economic development, foreign direct investment flows, international trade, and natural resource revenues. These factors provide crucial context about energy accessibility, cost dynamics, usage patterns, and potential vulnerabilities (Ahmadov and van der Borg 2019; Morikawa 2012; Sadorsky 2011). Table 1 presents descriptive statistics for the variables in the study. The average ESR is 1356, with a maximum value of 1858, reflecting severe energy insecurity in nations such as Qatar, Kuwait, and Saudi Arabia. These elevated ESR values indicate systemic vulnerabilities in energy systems across the sample. Meanwhile, CO2 emissions average 11.5 million metric tons (Mt), with peaks reaching 62.3 million Mt. Such high emission levels risk accelerating climate change, which could further destabilize energy security by intensifying resource scarcity and infrastructure disruptions. To address these intertwined challenges, our empirical analysis evaluates the effect of climate change on energy security and highlights the critical role of green patents, strong institutions, and human capital as effective policy tools.

To facilitate interpretation and meet modeling assumptions, all variables are log-linearized so coefficients can be read as elasticities. Variables that include zero values are transformed using $\log(x+1)$, ensuring that observations with zero values remain in the sample without producing undefined log terms.

3.2 | Model

We propose a practical framework to study how climate change and other factors influence ESR over time. The model is structured as:

$$\begin{aligned} ln\ \mathrm{ESR}_{it} = \beta_0 + \beta_1 ln\ \mathrm{CC}_{it} + \beta_2 ln\ \mathrm{GDP}_{it} + \beta_3 ln\ \mathrm{TNRR}_{it} \\ + \beta_4 ln\ \mathrm{TO}_{it} + \beta_5 ln\ \mathrm{RE}_{it} + \beta_6 ln\ \mathrm{INDS}_{it} \\ + \beta_6 ln\ \mathrm{POP}_{it} + \delta_i + \gamma_t + \varepsilon_{it} \end{aligned} \tag{1}$$

In this model, ESR denotes the energy security risk for country i at time t. The coefficients β_1 *to* β_6 capture the elasticity of ESR with respect to each independent variable; for example, β_1 quantifies the percentage change in ESR resulting from a 1% increase in CC. This specification allows for an accurate evaluation of the impact of CC on ESR while holding other factors constant. Additionally, δ_i and γ_t account for unobserved heterogeneity specific to each country and time period, respectively, and ε represents the stochastic error term.

In our analysis, we primarily assess climate change through the lens of CO_2 emissions, selected for their direct association with the core mechanisms driving climate change, their reflection of anthropogenic activity, their measurable and comparable nature across temporal and spatial dimensions, and their

TABLE 1 | Summary statistics.

Variable	Definition	Source	Mean	Std. dev.	Min	Max
Dependent variable						
ESR	Energy Security Risk	GEI (2025)	1356.403	196.2002	755.0384	1858.118
Climate variables						
CO_2	CO_2 emissions (million tons)	WDI (2025)	1.15E+07	1.40E+07	866838.6	6.23E+07
TEM	Extreme Temperatures	Gortan et al. (2024)	4.032	2.206	0.000	8.552
PRE	Extreme Perception	Gortan et al. (2024)	442.919	233.595	0.000	1094.130
GUST	Extreme Wind Gust	Gortan et al. (2024)	13.901	9.526	0.000	35.400
SPEI	Extreme Droughts	Gortan et al. (2024)	3.230	1.582	0.000	7.058
Moderating variables						
GP	Green patents	OCDE (2025)	1.760	0.934	0.243	6.250
IQ	Institutional quality	WGI (2025)	0.189	0.292	−0.466	0.844
HC	Human capital	UNDP (2025)	0.809	0.053	0.687	1.026
Control variables						
GDP	Gross Domestic Product	WDI (2025)	2855.253	1356.842	1234.410	6800.714
TNRR	Total Natural Resource Rents	WDI (2025)	2.584	0.930	0.689	4.922
TO	Trade Openness	WDI (2025)	8.501	2.761	4.143	17.884
RE	Renewable Energy	WDI (2025)	0.130	0.929	−0.056	11.921
INDS	Industrialization	WDI (2025)	4.398	0.691	3.184	6.234
POP	Population	WDI (2025)	7.307	0.749	5.509	8.333

Abbreviations: GEI, Global Energy Institute; OECD, Organization for Economic Co-operation and Development; UNDP, United Nations Development Program; WDI, World Development Indicators; WGI, Worldwide Governance Indicators.

interconnectedness with broader climate impacts. Additionally, we incorporate supplementary indicators of climate change, such as extreme weather events. Beyond climate-related variables, our model includes a suite of conditioning factors influencing energy security risk, such as GDP, TNRR, TO, POP, INDS, and REN. These predictors are integrated to address potential omitted variable bias, ensuring a robust empirical framework.

To explore how green patents, institutional quality, and human capital might influence the link between climate change and energy security risk, we construct interaction terms that combine each of these potential moderators with a proxy for climate change—namely, CO_2 emissions. This approach follows the moderation framework proposed by Baron and Kenny (1986). We then assess these interaction effects across three distinct models, which are outlined as follows:

$$ln\ \mathrm{ESR}_{it} = \beta_0 + \beta_1\ ln\ \mathrm{CC}_{it} + \beta_2 ln\ \mathrm{GP}_{it} + \beta_3\left(ln\ \mathrm{CC}_{it} * ln\ \mathrm{GP}_{it}\right) + \beta_4 CV_{it} + \delta_i + \gamma_t + \varepsilon_{it} \quad (2)$$

$$ln\ \mathrm{ESR}_{it} = \beta_0 + \beta_1\ ln\ \mathrm{CC}_{it} + \beta_2 ln\ \mathrm{IQ}_{it} + \beta_3\left(ln\ \mathrm{CC}_{it} * ln\ \mathrm{IQ}_{it}\right) + \beta_4 CV_{it} + \delta_i + \gamma_t + \varepsilon_{it} \quad (3)$$

$$ln\ \mathrm{ESR}_{it} = \beta_0 + \beta_1\ ln\ \mathrm{CC}_{it} + \beta_2 ln\ \mathrm{HC}_{it} + \beta_3\left(ln\ \mathrm{CC}_{it} * ln\ \mathrm{HC}_{it}\right) + \beta_4 CV_{it} + \delta_i + \gamma_t + \varepsilon_{it} \quad (4)$$

In these models, β_3 quantifies the moderating effect, while CV_{it} refers to control variables. The analytical process involves two stages:

- Baseline regression: Estimate the model without interaction terms (Equation 1) and record the significance of the coefficients.
- Extended regression: Introduce interaction terms into the model. A statistically significant interaction term confirms moderation; nonsignificant results imply no moderating effect.

We employ a fixed effects estimator to estimate both models, which effectively controls unobserved heterogeneity across countries and over time that could otherwise bias the parameter estimates if unaddressed. This approach is particularly well suited to our analysis, as it enables us to focus on within-country variations over time by estimating individual country intercepts, without requiring assumptions about the stationarity of the variables. This choice is further justified by the structure of our data, where the number of time periods (T) substantially exceeds the number of countries (N). To ensure robustness, we also used an alternative estimator tailored for scenarios where $T > N$, in order to confirm that our findings remain consistent across estimation methods.[3]

TABLE 2 | Baseline direct effects of climate change on ESR.

	(1)	(2)	(3)	(4)	(5)
Variables	**CO_2**	**Extreme Temp**	**Extreme Precip**	**Extreme Wind**	**Extreme SPEI**
CO_2	0.038***				
	(0.012)				
GDP	−0.244***	−0.259***	−0.258***	−0.277***	−0.256***
	(0.023)	(0.018)	(0.019)	(0.019)	(0.019)
TNRR	−0.033*	−0.048***	−0.037*	−0.027	−0.043**
	(0.019)	(0.018)	(0.019)	(0.019)	(0.019)
TO	−0.060***	−0.035**	−0.049***	−0.041***	−0.048***
	(0.018)	(0.016)	(0.017)	(0.016)	(0.018)
REN	−0.081***	−0.095***	−0.094***	−0.095***	−0.089***
	(0.007)	(0.007)	(0.007)	(0.007)	(0.007)
INDS	0.185***	0.207***	0.198***	0.201***	0.200***
	(0.024)	(0.024)	(0.024)	(0.025)	(0.024)
POP	2.475***	2.372***	2.581***	1.803***	2.486***
	(0.143)	(0.102)	(0.100)	(0.115)	(0.101)
TEM		0.317***			
		(0.039)			
PRE			0.005***		
			(0.001)		
GUST				0.088***	
				(0.007)	
SPEI					0.018***
					(0.003)
R^2	0.569	0.579	0.569	0.594	0.570

Note: Column (1) uses CO_2 emissions as the climate change measure, while Columns (2) to (5) use extreme temperature (TEMP), extreme precipitation (PRE), extreme wind gust (GUST), and extreme drought (SPEI), respectively. Coefficients (S.E. in parentheses) are reported, with *, **, and *** indicating significance at 10%, 5%, and 1%.

4 | Empirical Results and Discussion

4.1 | Baseline Result

This section explores how climate change impacts ESR by estimating Equation (1) using a fixed effects approach, with the results summarized in Table 2. Prior studies (Luft et al. 2010) have suggested that the nexus between climate change and ESR may be constrained by a trade-off between cutting CO_2 emissions and maintaining ESR. Accordingly, we use CO_2 emissions as our primary climate change indicator, with Column (1) of Table 2 presenting the corresponding estimates. For robustness, Columns (2) through (5) offer alternative measures—including extreme temperature, precipitation, wind gusts, and drought events—which consistently confirm that a 1% rise in CO_2 emissions is associated with a 0.038% increase in ESR. This relationship is driven by several mechanisms. First, CO_2 emissions can lead to extreme weather events that damage energy infrastructure and disrupt supply chains (Zhang et al. 2023). Second, high emissions often signal heavy reliance on fossil fuels, thereby exposing nations to geopolitical risks—as demonstrated by the global energy market disruptions following the Russia-Ukraine conflict (Hille and Angerpointner 2025). Third, dependence on environmentally harmful energy sources increases vulnerability during unexpected events, as witnessed during the COVID-19 pandemic (Ezeaku et al. 2021). Lastly, rising emissions heighten public demand for stricter emission standards, prompting energy system transformations that require significant investments and may increase operational costs for traditional producers, potentially affecting supply reliability and market stability (Battisti 2023; IRENA 2019; Panos et al. 2023).

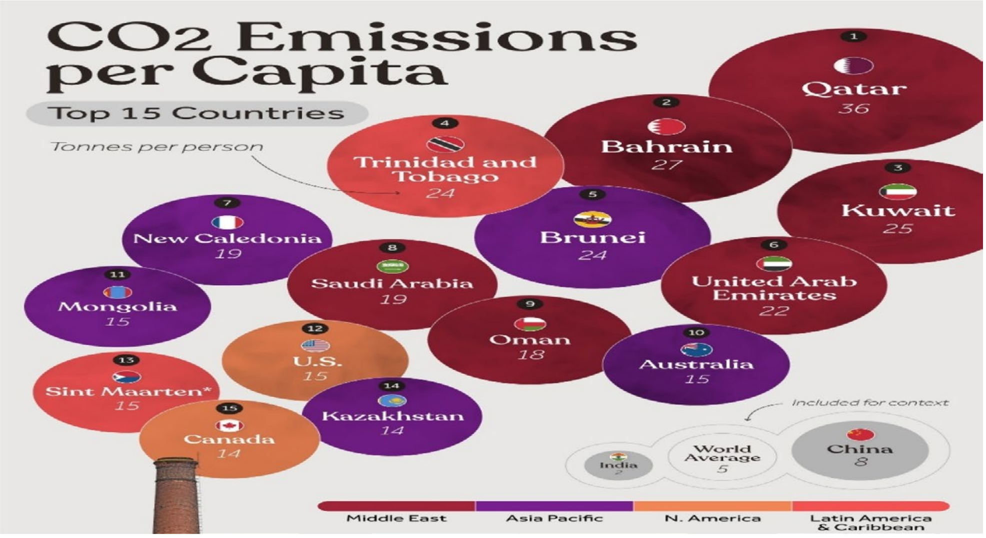

FIGURE 2 | Carbon Emissions per Capita in 15 Countries. *Source:* Our World in Data (2023).

In the GCC region, these dynamics have unique characteristics. The region ranks among the world's top 10 highest per capita CO_2 emitters, with Qatar leading in 2023 at 36.5 tons per capita. This high emission rate is driven by energy-intensive desalination processes, extensive air conditioning in extreme desert climates, and fossil fuel-dependent industrial sectors (Dawoud 2005; Moossa et al. 2022; WB 2013) (Figure 2).

Despite being major oil and gas exporters, GCC nations are increasingly aware of the ESR posed by climate change. For instance, the UAE's Energy Strategy 2050 aims for a 50% clean energy mix, while Saudi Arabia's Vision 2030 plans to develop 60 GW of renewable energy capacity (Al-Mekaimi 2025). Moreover, rising sea levels threaten critical coastal infrastructure such as Qatar's Ras Laffan LNG terminal and the UAE's Fujairah oil export hub (IRENA 2023). Initiatives like Saudi Arabia's circular carbon economy framework, along with significant investments in solar projects (e.g., Abu Dhabi's 2 GW Al Dhafra plant and Saudi Arabia's green hydrogen efforts at the NEOM project), exemplify the region's strategic efforts to balance hydrocarbon production with emission reduction (IRENA 2023).

Turning to controlling factors, our analysis reveals that larger GDP correlates with enhanced energy security, as wealthier nations have the financial capacity to invest in diverse and resilient energy infrastructures. The International Monetary Fund (IMF) has noted that a robust economy facilitates the green transition by reducing reliance on fossil fuels (Kim 2024; Tansel Tugcu and Menegaki 2024). In contrast, higher levels of industrialization tend to increase ESR. Industrial growth—especially in energy-intensive sectors such as manufacturing and mining—escalates energy demand, potentially straining supplies and infrastructure. For example, research on Turkey's energy security indicates that unchecked industrial expansion can exacerbate long-term energy vulnerabilities (Karasoy 2023). Additionally, population growth intensifies energy consumption patterns and can further stress energy systems, contributing to higher vulnerability indices (Morikawa 2012).

Furthermore, the abundant natural resources in the GCC significantly bolster energy security by generating substantial hydrocarbon revenues. These funds are reinvested in diversifying energy sources and upgrading infrastructure; for instance, Saudi Arabia's Vision 2030 aims to develop 60 GW of renewable energy, while the UAE's Energy Strategy 2050 targets a 50% clean energy share (Al-Mekaimi 2025). However, this resource wealth also poses challenges, such as overreliance on hydrocarbons and potential environmental degradation. Initiatives like Kuwait's Vision 2035 seek to address these challenges by promoting economic diversification and sustainable energy investments, an approach supported by findings from Chen et al. (2024), who observed that in 27 highly energy-consuming economies, resource abundance helps mitigate ESR. Nonetheless, the relationship between natural resource endowments and energy security is complex. While resource rents can promote energy diversification and support the development of infrastructure, they can also pose risks such as the resource curse, sociopolitical unrest, and ecological harm (Ahmadov and van der Borg 2019).

Our econometric analysis indicates that renewable energy significantly reduces ESR in the GCC region; this can be explained through multiple interconnected channels, as supported by recent studies (Giuli 2022; Khan et al. 2024; Tansel Tugcu and Menegaki 2024): (1) Renewable energy decreases reliance on imported fossil fuels, mitigating risks tied to price volatility and supply disruptions. For example, countries expanding renewables like solar and wind reduce exposure to geopolitical tensions in oil and gas markets. This diversification enhances energy independence and stabilizes supply chains—as seen in Saudi Arabia's 60 GW renewable target under Vision 2030, (2) By curbing greenhouse gas emissions, renewables address climate-related risks (e.g., extreme weather damaging infrastructure) that threaten long-term energy stability. This aligns with studies showing renewables counteract energy security threats posed by climate change, and (3) Electrification and renewable adoption reduce weaponization risks associated with fossil fuels (e.g., trade embargoes). Decentralized renewable systems also limit vulnerability to centralized infrastructure attacks or market manipulation. However, for the GCC to fully reap these benefits, its transition must carefully balance its hydrocarbon-based economy with sustainable investments.

Trade integration enhances energy security in the GCC region by diversifying supply chains and attracting infrastructure investments. However, this integration also introduces vulnerabilities, such as heightened foreign energy dependency and exposure to geopolitical disruptions—evident in recent global conflicts. Additionally, trade-driven energy consumption patterns and environmental externalities, including transportation emissions and ecological risks, amplify systemic pressures on energy systems (Sadorsky 2011).

4.2 | Mechanism Results

While our baseline results establish a clear link between CO2 emissions (as a proxy for climate change drivers) and increased ESR, it is crucial to understand factors that might mitigate this adverse relationship. Climate change impacts, largely driven by fossil fuel energy systems, can theoretically be buffered by advancements in sustainable energy, effective governance, and a capable workforce. Energy generated using patented green technologies avoids GHG emissions, while strong institutional frameworks and skilled human capital can facilitate the transition to cleaner energy and enhance adaptation capabilities, thereby reducing both CO_2 emissions and the vulnerability of energy systems to climate impacts.

To investigate these potential moderating effects, we examine how green patents, institutional quality, and human capital influence the climate change–ESR nexus. We estimate Equations (2–4), which incorporate interaction terms between CO_2 emissions and each of these factors. The results are presented in Table 3.

4.2.1 | Green Patents (Model 2)

Column (1) shows that while CO_2 emissions retain their positive and significant coefficient (consistent with baseline findings), the interaction term (CO_2 * Green Patents) is negative and statistically significant (−0.065). This indicates that a higher level of green patenting activity significantly weakens the effect of CO_2 emissions on ESR. Green patents signify a nation's capacity for technological innovation in areas like renewable energy generation, energy efficiency, and carbon capture (Bergougui et al. 2024; Bergougui and Meziane 2025). Higher innovation capacity allows countries to deploy low-carbon technologies more rapidly (Bergougui 2024a; Bergougui and Aldawsari 2024). This diversification away from fossil fuels reduces exposure to both the direct physical impacts of climate change on traditional energy infrastructure

TABLE 3 | Effect of CO_2 emissions on ESR.

	Model (2)	**Model (3)**	**Model (4)**
	Green patents	**Institutional quality**	**Human capital**
CO_2	0.089***	0.092***	0.566***
	(0.015)	(0.012)	(0.041)
Green Patents	1.025***	—	—
	(0.128)	—	—
*CO_2*Green Patents*	−0.065***	—	—
	(0.008)	—	—
Institutional Quality	—	0.806***	—
	—	(0.284)	—
*CO_2*Institutional Quality*	—	−0.072***	—
	—	(0.018)	—
Human Capital	—	—	15.645***
	—	—	(1.194)
*CO_2*Human Capital*	—	—	−0.984***
	—	—	(0.074)
Controls	Yes	Yes	Yes
Fixed effect	Yes	Yes	Yes
R^2	0.732	0.784	0.752

Note: This table presents findings on the moderating effects of green patents (GP), institutional quality (IQ), and human capital (HC) on the relationship between climate change and ESR. The analysis includes separate regression models for each moderator: GP (Column 1), IQ (Column 2), and HC (Column 3). Coefficient estimates are shown outside parentheses, while standard errors appear inside parentheses. Statistical significance levels are indicated as follows: $^{*}p < 0.10$, $^{**}p < 0.05$, and $^{***}p < 0.01$.

(e.g., extreme weather damage) and the geopolitical volatility associated with fossil fuel Abbas et al. 2024; Lin et al. 2023; Q. Wang et al. 2024). Essentially, innovation provides the tools to build a more resilient and less carbon-intensive energy system, thus buffering against climate-related risks. For GCC nations, fostering and utilizing green patents is vital for translating diversification goals (like those in the UAE's Energy Strategy 2050 and Saudi Vision 2030) into tangible reductions in energy system vulnerability (Al-Sarihi and Mansouri 2022; Alqahtani 2023).

4.2.2 | Institutional Quality (Model 3)

Column (2) highlights a significant and negative interaction term (CO_2*Institutional Quality) of −0.072, underscoring the critical role of institutional quality in mitigating ESR associated with rising CO_2 emissions. This finding suggests that stronger institutions—characterized by regulatory effectiveness, rule of law, government stability, and control of corruption—play a pivotal role in buffering against the adverse impacts of climate change on energy systems (Almulhim et al. 2025).

High institutional quality fosters a stable and predictable environment that is essential for attracting long-term investments in complex energy projects, such as renewable energy infrastructure and grid modernization. These projects are foundational to building climate-resilient energy systems capable of withstanding the increasing frequency and severity of extreme weather events (Azimi et al. 2025). Moreover, robust institutions enable effective policy implementation, ensuring that climate adaptation strategies, disaster response mechanisms, and energy transition frameworks are not only designed but also executed efficiently. For instance, strong governance frameworks facilitate the integration of intermittent renewable energy sources into national grids while maintaining reliability and affordability (Azimi et al. 2025). In the context of GCC nations, the importance of institutional quality becomes even more pronounced. The GCC's ambitious energy diversification goals, such as the UAE's Energy Strategy 2050 and Saudi Vision 2030, rely heavily on institutional capacity to manage the transition away from oil dependence. Robust institutions are essential to oversee large-scale renewable energy projects like the Al Dhafra solar plant and the NEOM green hydrogen initiative, ensuring these investments are effectively implemented and aligned with long-term energy security objectives. Furthermore, strong institutions help mitigate risks associated with geopolitical uncertainties and volatile fossil fuel markets, which have been exacerbated by recent events such as the Russia–Ukraine war. Additionally, institutional quality contributes to reducing emissions by promoting cleaner energy practices and enforcing higher environmental standards. Studies indicate that improvements in institutional quality reduce CO_2 emissions across different economies, further reinforcing the link between governance and climate resilience (Stef et al. 2023). In regions like the GCC, where economic structures have traditionally relied on fossil fuel exports, strengthening institutional frameworks can help align energy policies with global sustainability goals while safeguarding domestic energy security.

4.2.3 | Human Capital (Model 4)

Column (3) confirms the moderating role of human capital. The interaction term (CO_2 * Human Capital) is strongly negative and significant (−0.984), suggesting that a more educated and skilled population substantially diminishes the negative effect of CO_2 emissions on energy security. A high level of human capital provides the skilled workforce—engineers, technicians, researchers, policymakers, and managers—required to develop, deploy, operate, and maintain advanced and resilient energy systems. It fosters innovation, enables the adoption of complex green technologies, supports effective climate risk assessment and adaptation planning within the energy sector, and facilitates public understanding and support for energy transitions. For the GCC, investing oil wealth in education and specialized training is critical to building the human capital needed to manage large-scale renewable projects, develop local green industries, and adapt existing energy infrastructure to climate challenges like extreme heat and water scarcity (Bannaga and Lezar 2024; Kheyfets et al. 2020).

4.2.4 | Threshold Effect

To gain a clearer understanding of *how* green patents, institutional quality, and human capital mediate the climate change–ESR relationship, we calculated the conditional marginal effects of CO_2 emissions on ESR at varying levels of these moderators (visualized in Figure 3, based on Table 3 estimates). These plots compellingly illustrate that the detrimental impact of rising CO_2 emissions on energy security is not uniform; it is significantly conditioned by a country's innovative capacity, governance effectiveness, and workforce skills. The analysis reveals distinct thresholds for each moderator: approximately 1.43 for green patents, 0.03 for institutional quality, and 0.58 for human capital. These thresholds represent critical junctures.

- Below the threshold: In countries where GP, IQ, or HC levels fall below these respective thresholds, the marginal effect of CO2 emissions on ESR remains positive and significant. In practical terms, this means that in environments with limited green innovation, weaker governance, or lower skill levels, the energy system is more directly vulnerable to climate change drivers—increased emissions translate more readily into heightened ESR (e.g., supply disruptions from extreme weather, instability from fossil fuel dependence).
- Above the threshold: Conversely, once a country surpasses these threshold levels, the positive marginal effect of CO2 emissions on ESR diminishes substantially, becoming statistically insignificant or potentially even negative in some ranges according to the model. This signifies that possessing sufficient innovative capacity, robust institutions, or high human capital equips a nation with the necessary tools and resilience to effectively counteract the energy security threats posed by climate change. The energy system becomes buffered, capable of adapting through technological deployment, sound policy, and skilled management, thus weakening or breaking

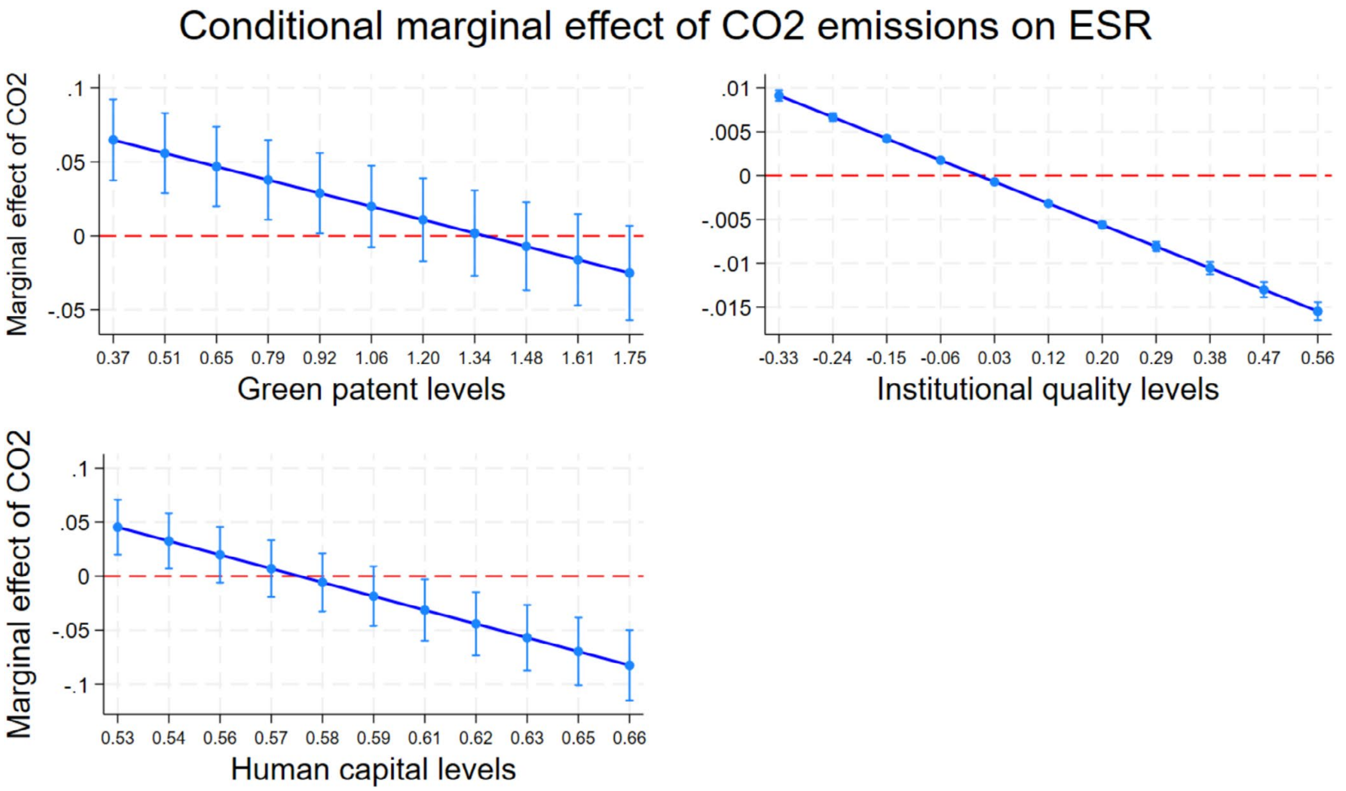

FIGURE 3 | Margins plots of the conditional effects of climate change (CO_2 emissions) on ESR. The data reflect marginal effects derived from the fixed effect regression detailed in Table 3.

the direct link between rising emissions and increased vulnerability.

In conclusion, the existence of these thresholds dramatically underscores that the impact of climate change on ESR is not predetermined. Proactive and strategic development of green innovation ecosystems, robust and adaptive institutions, and high levels of human capital can significantly mitigate associated risks. For the GCC, recognizing and strategically addressing these thresholds is paramount to successfully navigating the energy transition and building a resilient energy future in the face of climate change.

4.3 | Robustness Test

4.3.1 | Addressing Endogeneity Concerns

The nexus between ESR and climate change presents considerable econometric challenges due to inherent simultaneity bias. Energy security policy decisions influence climate outcomes through their emission implications, while climate change concurrently shapes energy security considerations through environmental and economic feedback mechanisms. This bidirectional causality manifests in complex ways: fossil fuel infrastructure investments may bolster immediate energy security but amplify long-term climate vulnerabilities through heightened emissions, whereas renewable energy investments aimed at climate mitigation can simultaneously reduce emissions and diversify energy security portfolios. Such simultaneity necessitates rigorous econometric identification strategies to establish causal relationships between climate change and ESR.

4.3.1.1 | Instrumental Variable Strategy. We address these endogeneity concerns through a multi-pronged instrumental variable approach comprising four complementary methodologies:

- IV-Lewbel: Leverages heteroskedasticity patterns for identification following Lewbel (2012), generating internal instruments when external instruments face limitations.
- IV-GMM: Employs the Generalized Method of Moments estimator to achieve efficient parameter estimation with heteroskedasticity-robust inference capabilities.
- IV-DK: Incorporates Driscoll-Kraay standard errors to simultaneously address cross-sectional dependence and serial correlation, following Hoechle (2007).
- System-GMM: Implements the Arellano-Bond System GMM estimator to tackle dynamic panel bias and potential endogeneity across all regressors using lagged levels and differences as instruments, particularly effective for panels with persistent variables and unobserved heterogeneity (Roodman 2009).

4.3.1.2 | Instrument Design and Validation. For the first three approaches, we instrument country-specific CO_2 emissions using lagged cross-sectional average emissions, exploiting multiple theoretically grounded mechanisms that establish both relevance and exogeneity conditions. This identification strategy operates through spatial spillover effects and regional atmospheric dynamics that characterize carbon emissions patterns in the environmental economics literature (Y. Liu et al. 2014). Regional CO_2 emissions exhibit strong spatial correlation due to shared atmospheric systems, prevailing wind patterns, and transboundary pollution transport mechanisms that create predictable regional emission clusters independent of local energy security considerations (Zhou et al. 2023).

The theoretical exogeneity of our instrument stems from the temporal and spatial separation embedded in its construction, combined with established regional economic integration mechanisms. By utilizing emissions data from neighboring regions with appropriate time lags, the instrument captures regional atmospheric and industrial patterns that predate current energy security concerns while remaining geographically removed from direct local energy policy influences. This spatial dependence in carbon emissions reflects fundamental physical processes of atmospheric dispersion and regional climate systems that operate according to meteorological principles rather than economic or energy security imperatives. Regional technological diffusion creates correlated emission trajectories as clean energy innovations and carbon-intensive processes spread through trade, investment, and knowledge transfer networks (Dechezleprêtre et al. 2011; Keller 2004). Additionally, international climate policy coordination generates synchronized emission patterns independent of individual country energy security decisions (Aldy and Stavins 2012). These mechanisms operate through shared industrial structures, energy systems, and regulatory environments that emerge from historical economic development patterns and inter-regional policy coordination, creating predictable relationships between regional emission patterns as documented in the spatial econometrics literature on environmental spillovers. The temporal lag structure provides additional theoretical justification by exploiting the persistence in regional emission patterns while creating temporal distance from current energy security risks. Carbon emissions exhibit strong autocorrelation due to the long-lived nature of energy infrastructure, industrial capital stocks, and institutional frameworks that determine regional carbon intensity. This persistence means that historical regional emission patterns contain predictive information about current local emissions through shared regional characteristics, while the temporal lag ensures that the instrument reflects predetermined regional conditions rather than responses to current energy security concerns.

The instrument satisfies relevance conditions through robust first-stage relationships, with F-statistics consistently exceeding 10, reflecting emission pattern persistence and gradual energy transition dynamics driven by shared technological trajectories, similar industrial development paths, and coordinated environmental policies among neighboring countries. This relevance operates through established theories of regional economic integration and industrial clustering effects, where neighboring regions develop similar industrial structures and environmental profiles due to shared factor endowments and spillover effects, as demonstrated in Porter's (1998) work on industrial clusters and Krugman's (1991) analysis of economic geography. The exclusion restriction holds because lagged regional average emissions affect individual country energy security exclusively through domestic emission channels rather than direct pathways. This theoretical foundation draws on the localized nature of energy security risks, which primarily depend on local energy infrastructure resilience, supply chain vulnerabilities, and demand–supply balances within specific geographic boundaries. While neighboring regions may share some economic characteristics, their historical emission patterns should not directly influence contemporary local energy security risks beyond their predictive relationship with current local carbon intensity. Regional emissions from previous periods cannot directly influence current energy security through cross-border supply disruptions (which operate through current conditions), regional market integration effects (captured in robustness checks), or neighboring policy spillovers (manifested through current policy variables). The theoretical framework builds on insights from industrial organization and agglomeration economics, where regional industrial clusters create predictable patterns in resource utilization and environmental outcomes. The spatial econometrics literature on environmental policy, particularly studies by Fredriksson and Millimet (2002), demonstrates how regional similarities in environmental outcomes reflect shared geographic and institutional characteristics rather than direct causal relationships to energy security. However, we acknowledge potential limitations in the exclusion restriction if regional energy markets are highly integrated or if neighboring regions face correlated energy security shocks, making the instrument validity critically dependent on regional emission patterns reflecting industrial and atmospheric characteristics rather than shared energy security vulnerabilities. For System-GMM, we employ standard instrumentation of endogenous variables with lagged levels (in first-difference equations) and lagged differences (in level equations), effectively addressing persistent time series bias and unobserved country-specific heterogeneity while maintaining the theoretical foundations established for the lagged regional averages approach.

Table 4 presents IV estimation results across all methodological approaches (Columns 1–3) alongside System-GMM estimates (Column 4) for robustness validation. The findings demonstrate remarkable consistency across specifications, with climate change maintaining statistically significant positive effects on ESR after controlling for endogeneity. This robustness across diverse IV methodologies provides compelling evidence supporting our core hypothesis that climate change causally increases energy security risks.

4.3.2 | Other Robustness Tests

To validate the reliability of our central finding—that climate change exhibits a positive association with ESR—we conducted several robustness checks.

- Specification sensitivity analysis: We systematically tested the stability of our baseline relationship by re-estimating models with CO_2 emissions (our primary climate proxy) while varying the control variable configurations. The results in Table 5 demonstrate remarkable consistency, with the CO_2 coefficient remaining positive and statistically significant across all seven alternative specifications. This robustness spans from the most parsimonious

TABLE 4 | Tackling endogeneity issues by employing instrumental variable (IV) methods.

	(1)	(2)	(3)	(4)
Variables	**IV-Lebwel**	**IV-GMM**	**IV-DK**	**System-GMM**
CO_2	0.041***	0.039***	0.039***	0.1338**
	(0.003)	(0.012)	(0.014)	(2.55)
GDP	−0.032***	−0.246***	−0.246***	0.7825***
	(0.008)	(0.023)	(0.025)	(5.01)
TNRR	−0.164***	−0.035*	−0.035*	0.6644
	(0.015)	(0.019)	(0.019)	(1.54)
TO	0.072***	−0.060***	−0.060***	−1.3676**
	(0.009)	(0.018)	(0.021)	(−2.02)
REN	−0.002	−0.080***	−0.080***	−1.6416**
	(0.007)	(0.007)	(0.009)	(−2.08)
INDS	0.210***	0.187***	0.187***	0.7297
	(0.032)	(0.024)	(0.021)	(1.15)
POP	0.722***	2.470***	2.470***	0.0000
	(0.037)	(0.144)	(0.154)	(.)
R^2	0.345	0.569	0.512	
FE	No	Yes	Yes	Yes
CD Wald F	348,758	179,243	179,243	
KP Wald F	2.353e+06	42,825	43,126	
Hansen J: *p*-value				1
AR(2): *p*-value				0.690

Note: This table presents findings from instrumental variable (IV) regressions that address endogeneity by using the lagged cross-sectional average of CO_2 emissions as an instrument for a country's CO_2 emissions. The models progress from a basic specification (IV-Lebwel) to more robust ones (IV-GMM and IV-DK). IV-Lebwel: Implements the Lewbel (2012) IV approach, which exploits heteroskedasticity for identification. IV-GMM leverages the Generalized Method of Moments (GMM) estimator, delivering efficient estimates accompanied by robust standard errors. IV-DK incorporates Driscoll-Kraay (DK) standard errors to address cross-sectional dependence and heteroskedasticity. Standard errors are presented within parentheses, while the Kleibergen-Paap (KP Wald F) and Cragg-Donald (CD Wald F) F-statistics evaluate the robustness of the instruments. Hansen overidentification *p* values greater than 0.05 for almost all of the specifications imply that we cannot reject the null hypothesis which states that the instruments used are valid. Statistical significance is represented by *, **, and *** corresponding to the 10%, 5%, and 1% thresholds, respectively.

model (Column 1, including only CO_2) to the fully saturated specification (Column 2, incorporating all control variables). The coefficient stability across different conditioning sets confirms that the climate–ESR relationship is not driven by particular variable combinations or model specifications (Table A1).

- Cross-sectional dependence correction: Given the economic integration among GCC countries, we tested for cross-sectional dependence using Pesaran's CD test, which revealed strong interdependence across the six nations (see Table A2). To address this methodological concern, we re-estimated our key models using Pesaran's (2006) Common Correlated Effects (CCE) estimator, which accounts for unobserved common factors (Pesaran 2006). The CCE results (Table 5, Column 3) not only maintain the positive and significant climate–ESR relationship but actually strengthen the coefficient magnitude, reinforcing our core findings (Table A3).
- Nonlinear specifications: We examined potential nonlinear relationships by incorporating a quadratic CO_2 term (Column 4), which reveals a significant inverted-U relationship while maintaining the positive primary effect of climate change on ESR.
- Major events: We tested model stability against significant economic disruptions, including crisis period controls for the 2009 financial crisis (Column 5), oil price shock adjustments (Column 6), and COVID-19 pandemic effects (Column 7). These controls ensure our findings are not confounded by major economic or health crises.
- Dynamic modeling: We incorporated lagged dependent variables (Column 8) to account for potential persistence effects and dynamic adjustment processes in ESR patterns.

Across all specifications, the climate change coefficient remains consistently positive and significant, with the relationship

TABLE 5 | Robustness analysis: Climate change (CO_2) effects on ESR across model specifications.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Include only CO_2	**Include all variables**	**CCE estimator**	**Nonlinear model**	**Crisis 2009**	**Oil shock**	**Covid19**	**Dynamic model**
$ESR_{(t-1)}$								1.6133***
								(39.83)
CO_2	0.0640***	0.0246*	0.1565***	1.2468***	0.1013***	0.1021***	0.1150***	0.0094**
	(3.68)	(1.72)	(2.67)	(17.00)	(10.12)	(8.84)	(9.91)	(2.15)
CO_2_square				−0.0388***				
				(−16.46)				
GDP		−0.2602***	−0.2980	−0.3374***	−0.1619***	−0.1316***	−0.1808***	0.0077
		(−12.31)	(−1.20)	(−16.93)	(−6.67)	(−5.72)	(−8.18)	(0.80)
TNRR		0.2122***	0.0303	0.2795***	0.5481***	0.4349***	0.5163***	−0.0366***
		(6.62)	(0.40)	(10.03)	(16.95)	(16.50)	(22.09)	(−3.28)
TO		−0.1252***	−0.0029	−0.1476***	0.0330	−0.1130***	−0.1777***	0.0519***
		(−7.46)	(−0.02)	(−9.82)	(1.34)	(−5.63)	(−10.88)	(3.89)
REN		−0.0396***	1.3870**	−0.0227***	1.4720	−3.1614***	−0.1218***	−0.0459***
		(−4.80)	(1.97)	(−2.92)	(0.66)	(−7.72)	(−3.50)	(−5.26)
INDS		0.3074***	0.3638	0.2950***	0.0608**	0.1414***	0.1649***	0.0052
		(13.48)	(1.57)	(14.03)	(2.23)	(6.72)	(8.81)	(0.27)
POP		2.0393***	−12.3841**	1.8902***	−1.9379***	2.7056***	2.5949***	−0.0142
		(27.38)	(−2.02)	(25.81)	(−4.43)	(15.10)	(32.84)	(−0.27)
R2	0.531	0.724		0.761	0.771	0.706	0.767	

Note: The table presents findings on the effects of climate change on ESR, using CO_2 emissions as the primary indicator of climate change. The regression analyses progress sequentially from the most basic model to the fully detailed specification.

TABLE 6 | Lagged effects of climate extremes on ESR.

	(1)	(2)	(3)	(4)	(5)
Variables	**CO_2**	**Extreme temp**	**Extreme precip**	**Extreme wind**	**Extreme SPEI**
$CO_{2\,(t-1)}$	0.0381***				
	(3.24)				
$TEM_{(t-1)}$		0.3171***			
		(8.01)			
$PRE_{(t-1)}$			0.0055***		
			(5.06)		
$GUST_{(t-1)}$				0.0889***	
				(13.32)	
$SPEI_{(t-1)}$					0.0186***
					(5.58)
GDP	−0.2402***	−0.2562***	−0.2549***	−0.2741***	−0.2536***
	(−10.16)	(−13.81)	(−13.43)	(−14.67)	(−13.35)
TNRR	−0.0319	−0.0468**	−0.0359*	−0.0260	−0.0419**
	(−1.64)	(−2.54)	(−1.85)	(−1.36)	(−2.16)
TO	−0.0550***	−0.0312*	−0.0449**	−0.0371**	−0.0445**
	(−3.00)	(−1.87)	(−2.55)	(−2.32)	(−2.48)
REN	−0.0835***	−0.0979***	−0.0966***	−0.0984***	−0.0924***
	(−11.89)	(−14.43)	(−13.94)	(−14.11)	(−13.58)
INDS	0.1778***	0.1996***	0.1909***	0.1942***	0.1928***
	(7.37)	(8.31)	(8.03)	(7.97)	(8.09)
POP	2.4745***	2.3682***	2.5777***	1.7923***	2.4783***
	(17.06)	(22.89)	(25.51)	(15.38)	(24.31)
R^2	0.566	0.576	0.566	0.592	0.567

Note: This table presents fixed-effects panel regression results examining the lagged relationships between climate variables and energy security risk (ESR). Column (1) employs lagged CO_2 emissions as the primary climate indicator, while Columns (2)–(5) utilize lagged extreme climate measures: temperature (TEM), precipitation (PRE), wind gust (GUST), and standardized precipitation evapotranspiration index (SPEI), respectively. All climate variables are lagged by one period (t−1) to capture delayed effects and address potential simultaneity bias. t-statistics are reported in parentheses. Statistical significance is denoted by *, **, and *** at the 10%, 5%, and 1% levels, respectively.

proving robust to various econometric concerns and alternative model formulations.

4.3.3 | Lagged Effects Analysis

To address potential temporal dynamics, we examine the lagged effects of climate variables on ESR by introducing one-period lagged explanatory variables. This approach is methodologically crucial for several reasons: first, it helps identify delayed impacts of climate change on energy security decisions; second, it mitigates simultaneity bias by using predetermined values of climate variables; and third, it captures the realistic time lag between climate events and policy responses in energy security planning. Table 6 presents our lagged effects estimation across five model specifications (Columns 1–5), where each climate indicator is lagged by one period to capture delayed impacts. The results provide compelling evidence of persistent climate–ESR relationships even when accounting for temporal displacement. The results highlight the persistent influence of climate change and extreme weather on energy security risk. The lagged effect of CO_2 emissions confirms that past emissions continue to have a significant positive impact on current energy security risk, underscoring the delayed and enduring nature of climate-related challenges. This persistence reflects the physical characteristics of the climate system, where the consequences of emissions unfold over extended periods. Moreover, the analysis of lagged extreme weather indicators reveals consistent and significant impacts. Past temperature extremes exert the strongest influence, substantially increasing current energy security risk. Drought conditions and extreme precipitation also contribute to heightened risk, though their effects are more moderate. Similarly, extreme wind events display notable delayed

TABLE 7 | Country-by-country fixed-effects regression outcomes.

	(1)	(2)	(3)	(4)	(5)	(6)
	Bahrain	**Kuwait**	**Oman**	**Qatar**	**Saudi Arabia**	**United Arab Emirates**
ln_CO2	0.1626***	0.9436***	1.9029***	0.1341***	0.0815**	0.0617***
	(8.03)	(8.72)	(8.14)	(3.32)	(2.30)	(3.03)
GDP	−0.3470***	0.0578**	−0.2268**	−0.0696	0.1252	−0.0209
	(−5.99)	(2.23)	(−2.19)	(−1.21)	(1.17)	(−0.24)
TNRR	−0.1162***	−0.0837***	−0.2542***	0.0377	−0.2647***	−0.0295
	(−6.10)	(−4.04)	(−7.38)	(0.79)	(−3.08)	(−0.93)
TO	0.0992***	0.1325***	−0.1788***	0.0278	−0.5480***	0.0701***
	(3.47)	(4.46)	(−3.01)	(0.43)	(−4.88)	(2.63)
REN	0.8364***	−0.6245***	−0.3345*	1.0498*	0.0899	−0.0203*
	(6.58)	(−20.97)	(−1.68)	(1.85)	(0.53)	(−1.87)
INDS	0.0198	−0.0347*	0.5620***	−0.0349	1.0027***	0.0076
	(1.19)	(−1.78)	(5.10)	(−1.48)	(3.43)	(0.09)
POP	−3.6433	−0.1210	0.2730	0.4520	−5.9747***	−0.2718
	(−1.37)	(−0.13)	(0.69)	(0.21)	(−3.66)	(−0.30)
R^2	0.941	0.994	0.998	0.978	0.970	0.988

impacts, emphasizing the importance of considering past climatic shocks in energy security planning. Together, these findings underscore the necessity of long-term strategies to address the compounding effects of climate variability on energy systems.

4.3.4 | Country-By-Country Analysis

To provide nuanced insights into the heterogeneous impacts of climate change across the GCC region, we conduct individual country-level analyses using fixed-effects regressions. This disaggregated approach is essential for understanding how structural differences, economic characteristics, and energy portfolios across GCC nations influence the climate-ESR relationship. Table 7 presents country-specific regression results, revealing substantial heterogeneity in both the magnitude and significance of climate impacts on energy security risk.

The country-specific analysis reveals striking variations in climate vulnerability across the GCC region. Oman exhibits the highest climate sensitivity, with a CO_2 coefficient of 1.903 (significant at 1%), indicating that a 1% increase in emissions corresponds to approximately a 1.9-unit increase in ESR. This exceptionally high sensitivity likely reflects Oman's relatively limited energy infrastructure diversification and greater exposure to climate-related supply disruptions compared to its regional counterparts. Kuwait demonstrates the second-highest climate vulnerability with a coefficient of 0.944, suggesting substantial energy security risks from climate change. This finding aligns with Kuwait's heavy dependence on fossil fuel infrastructure and limited renewable energy adoption, making the country particularly susceptible to climate-induced energy system stress. In contrast, Bahrain, Qatar, Saudi Arabia, and the UAE show more moderate but statistically significant climate impacts, with coefficients ranging from 0.062 to 0.163. Despite these lower magnitudes, the consistent positive and significant relationships across all six countries confirm that climate change poses universal energy security challenges throughout the GCC region, albeit with varying intensities.

4.4 | Asymmetric Effect

This research implements the method of moments quantile regression (MMQR) framework established by Machado and Santos Silva (2019) to evaluate the potentially asymmetric effects of climate change—operationalized through CO_2 emissions—on ESR across GCC countries. While our previous analyses documented linear relationships between climate change indicators and ESR, this study advances the literature by investigating non-linear patterns across the ESR distribution spectrum. Given the substantial heterogeneity in ESR profiles among GCC member states, we examine whether climate change impacts exhibit systematic variation across different ESR quantiles. The MMQR methodological approach allows us to determine if climate change exerts differential effects contingent upon underlying ESR conditions (Bergougui 2025b, 2025c). Our hypothesis of asymmetric relationships would be substantiated if the marginal impact of climate change on ESR demonstrates dependence on the position within the ESR distribution. To provide comprehensive coverage, our analytical framework encompasses the 10th through 90th percentiles of the ESR distribution. Figure 4 presents the outcomes of the panel quantile model, where the coefficients for CO_2 emissions are consistently positive across all quantiles examined. These results corroborate

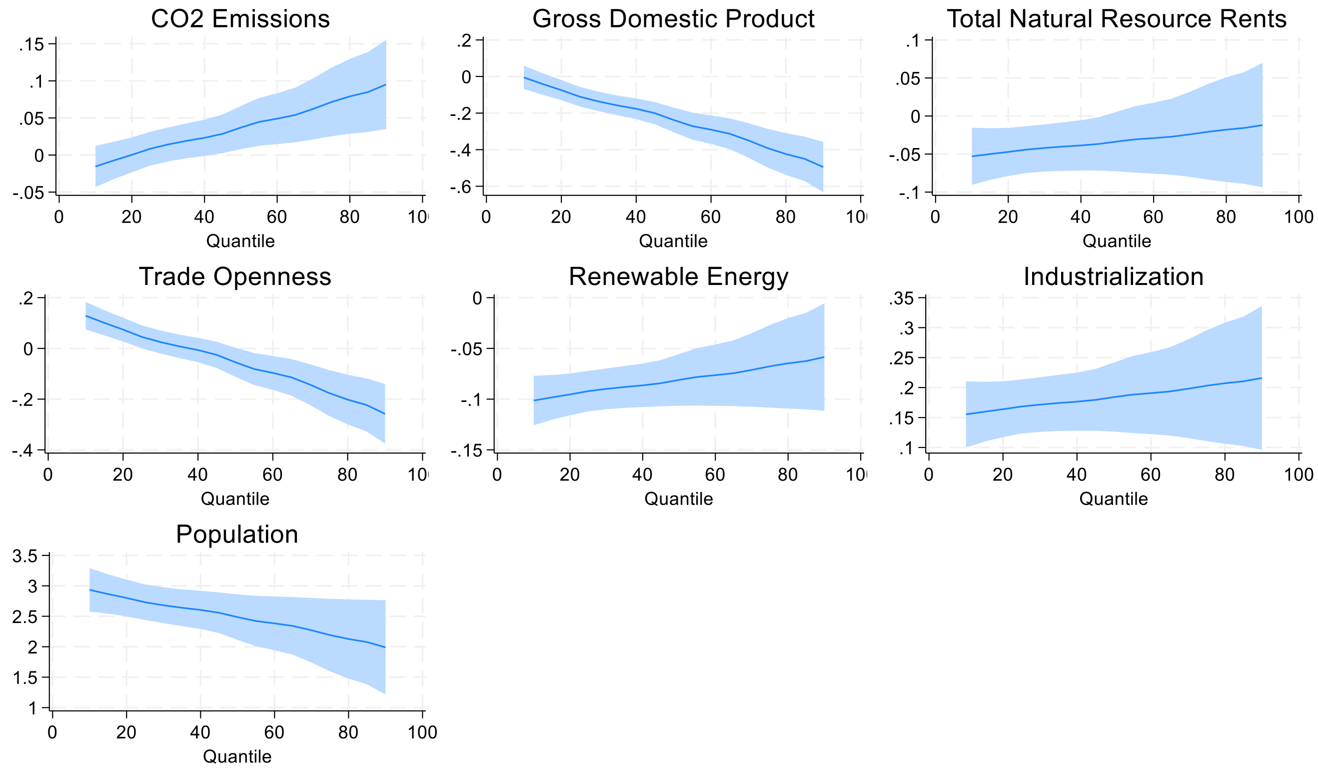

FIGURE 4 | *MMQR* results.

our baseline regression findings and indicate an intensification of the marginal suppressive effect as one moves toward higher ESR quantiles. Consequently, this evidence suggests that the positive nexus between climate change and ESR is particularly pronounced in regions with elevated ESR levels, potentially undermining energy security frameworks and resilience within the energy sector.

5 | Further Analysis

This section examines the varying effects of climate change on ESR across different countries, taking into account disparities in GDP size and population growth rates. By segmenting the sample, the analysis seeks to reveal the subtle ways in which economic magnitude and demographic dynamics influence the interplay between climate change and EST.

5.1 | High vs. Low GDP Countries

GDP represents the economic scale of a nation, shaping its ability to allocate resources for robust energy infrastructure while also reflecting its role in contributing to climate change via CO_2 emissions. Countries with higher GDP levels typically have greater financial and institutional resources to develop robust energy systems. However, these nations also tend to produce higher CO_2 emissions, exacerbating climate change and increasing ESR. To examine these dynamics, we divide the sample into two groups: countries with GDP above the median (top half) and those below the median (bottom half). This stratification allows us to assess whether economic size moderates the link between climate change and ESR.

Table 8, columns (1–2), display the outcomes of the regression analysis based on Equation (2), segmented by nations with smaller and larger GDPs. For countries with lower GDPs, the influence of climate change—quantified through CO_2 emissions—on ESR shows no statistically significant effect (coefficient $= 0.0087$, $p > 0.10$). This may reflect their limited capacity to invest in advanced energy infrastructure and their reliance on non-renewable energy sources, which could buffer short-term risks but increase long-term vulnerabilities. In contrast, for higher GDP countries, a one-unit increase in the climate change variable is associated with a 0.1744 unit increase in ESR ($p < 0.01$). This suggests that despite greater resources, larger economies are more exposed to the adverse effects of climate change on energy security.

Further analysis in Columns (3) through (8) of Table 8 incorporates interaction terms with institutional quality, green patents, and human capital. In higher GDP countries, investments in green patents, institutional quality, and human capital significantly moderate the impact of climate change on ESR. For example, the negative CO2*GP interaction term (-0.0452, $p < 0.05$) in Column (6) indicates that green innovations reduce vulnerability in wealthier nations. However, governance challenges such as corruption and political instability in some high GDP countries may undermine these benefits, as suggested by the positive CO2*IQ interaction term (0.0676, $p < 0.01$) in Column (4). These findings highlight the complex interplay between economic output, climate change, and energy security.

TABLE 8 | Heterogeneous effects of climate change on ESR by economic output.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
CO_2	0.0087	0.1744***	0.1839***	0.1026***	0.0363**	0.1201***	−2.5225***	−0.9211***
	(0.59)	(6.54)	(14.82)	(6.31)	(2.40)	(4.05)	(−44.82)	(−6.02)
GDP	−0.2498***	−0.4803***	−0.0487*	−0.1206***	−0.1086***	−0.3987***	−0.1423***	−0.3334***
	(−9.58)	(−20.65)	(−1.76)	(−4.30)	(−2.92)	(−17.17)	(−7.23)	(−12.61)
TNRR	0.2156***	0.0823***	−0.0579***	−0.0751***	0.0418*	−0.0795***	−0.1474***	−0.0540*
	(5.20)	(2.71)	(−2.90)	(−3.75)	(1.84)	(−3.41)	(−9.42)	(−1.80)
TO	0.1294***	−0.2219***	0.0395	0.0183	−0.0760**	−0.0633***	0.1785***	0.0752***
	(4.57)	(−10.97)	(1.42)	(0.73)	(−2.40)	(−3.04)	(8.06)	(3.64)
ENERGY	−0.7316***	0.0364***	−0.5164***	−0.0337***	−0.6954***	−0.0319***	−1.3447***	−0.0487***
	(−5.83)	(3.04)	(−6.22)	(−4.28)	(−6.05)	(−4.28)	(−20.38)	(−6.27)
INDS	0.4752***	0.2341***	0.3101***	−0.1201***	0.3114***	0.0339	0.2733***	−0.0658
	(17.92)	(7.42)	(14.43)	(−3.43)	(13.38)	(0.85)	(17.32)	(−1.26)
POP	2.0992***	0.7715*	1.9547***	2.2396***	2.3381***	0.4618	1.7661***	0.8022**
	(21.95)	(1.92)	(19.93)	(7.04)	(20.82)	(1.19)	(21.59)	(1.98)
IQ			5.4790***	−1.7074***				
			(15.48)	(−4.32)				
CO_2*IQ			−0.3783***	0.0676***				
			(−16.67)	(2.73)				
GP					−1.8823***	0.7785***		
					(−8.81)	(2.62)		
CO_2*GP					0.1254***	−0.0452**		
					(8.76)	(−2.45)		
HC							−69.944***	−26.775***
							(−42.83)	(−6.43)
CO_2*HC							4.7098***	1.5954***
							(44.52)	(6.16)
R^2	0.745	0.515	0.852	0.691	0.766	0.531	0.908	0.599

Note: Statistical significance is represented by *, **, and ***, corresponding to levels of 10%, 5%, and 1%, respectively.

5.2 | High vs. Low Population Growth Countries

Population growth intensifies climate change by increasing resource demand, waste generation, and CO_2 emissions, thereby complicating efforts to maintain energy security (Ganivet 2020). Since countries experience population growth at different rates, these variations may influence the weakness of their energy systems to climate change and the effectiveness of mitigation strategies such as institutional quality, green innovations, and human capital.

To investigate this, we divide the sample into two groups: countries with population growth rates above the median (faster growth) and those below the median (slower growth). Columns (1–2) in Table 9 present the results obtained from estimating Equation (2) for the specified groups. In countries with slower population growth, the impact of climate change on ESR is statistically insignificant (coefficient = 0.0027, $p > 0.10$). Conversely, in countries with faster population growth, a one-unit increase in the climate change variable is associated with a 0.1773 unit increase in ESR ($p < 0.01$), indicating greater vulnerability. Columns (3) and (4) of Table 9 include interaction terms with institutional quality. In slower-growing countries, strong institutions mitigate the impact of climate change on ESR, as shown by the negative and significant CO2*IQ interaction term (−0.2246, $p < 0.01$).

However, in faster-growing countries, institutional quality has little effect (CO_2*IQ = −0.0288, $p > 0.10$), suggesting that rapid population growth may overwhelm governance capacity.

TABLE 9 | Heterogeneous impacts of climate change on ESR by population growth rate.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
CO_2	0.0027	0.1773***	0.0346**	0.1561***	−0.0093	0.0564***	0.0581	−1.0160***
	(0.22)	(14.93)	(2.57)	(15.19)	(−0.69)	(3.18)	(1.10)	(−11.51)
GDP	−0.4472***	0.1223***	−0.2690***	0.1563***	−0.4493***	0.1121***	−0.5075***	0.2373***
	(−21.34)	(4.89)	(−9.93)	(8.38)	(−21.37)	(4.74)	(−24.88)	(9.44)
TNRR	−0.1299***	−0.1159***	−0.1760***	−0.1704***	−0.1289***	−0.1017***	−0.0116	−0.2188***
	(−8.71)	(−4.56)	(−11.60)	(−9.21)	(−8.59)	(−4.17)	(−0.74)	(−9.43)
TO	0.0824***	−0.1347***	0.0776***	0.1512***	0.0753***	−0.1048***	0.0192	−0.3006***
	(2.93)	(−6.40)	(2.82)	(8.08)	(2.62)	(−5.26)	(0.73)	(−14.58)
ENERGY	−0.5730***	−0.0142	0.5995***	0.0026	−0.5939***	−0.0207**	−0.8819***	−0.0591***
	(−8.60)	(−1.31)	(4.58)	(0.33)	(−8.81)	(−2.03)	(−13.78)	(−6.00)
INDS	−0.0096	0.3461***	−0.0379	0.2071***	−0.0073	0.3205***	−0.1452***	0.4781***
	(−0.42)	(8.99)	(−1.59)	(7.19)	(−0.32)	(8.75)	(−6.46)	(13.79)
POP	2.9188***	1.7185***	1.7039***	1.2144***	2.9234***	1.5139***	3.3558***	0.9934***
	(11.05)	(16.43)	(5.35)	(15.80)	(10.85)	(15.18)	(8.34)	(9.20)
IQ			3.3036***	−0.1094				
			(8.78)	(−0.24)				
CO_2*IQ			−0.2246***	−0.0288				
			(−9.14)	(−1.02)				
GP					−0.1762	−2.4390***		
					(−1.59)	(−9.21)		
CO2*GP					0.0121*	0.1613***		
					(1.68)	(9.49)		
HC							−1.4492	−33.838***
							(−0.90)	(−12.50)
CO_2*HC							0.0057	2.2214***
							(0.06)	(13.16)
N	1224	1224	1224	1224	1224	1224	1224	1224
R^2	0.579	0.728	0.615	0.859	0.581	0.760	0.651	0.789

Note: Columns (1) and (2) present baseline results for countries with population growth rates, respectively. Columns (3)–(8) include interaction terms with institutional quality (IQ), green patents (GP), and human capital (HC). SE is in parentheses. $*p<0.10$, $**p<0.05$, $***p<0.01$.

Columns (5) through (8) further explore interactions with green patents and human capital, revealing that eco-friendly innovations and skilled workforces demonstrate reduced effectiveness in mitigating ESR in nations experiencing accelerated growth. For instance, the CO_2*GP term (0.1613, $p<0.01$) in Column (6) indicates that green patents significantly moderate risks in faster-growing nations.

Figure 5 has been developed to provide a detailed visual representation of the interplay between climate change and ESR. This diagram maps out the various channels through which climate change influences ESR, thus offering a clearer understanding of these multifaceted relationships.

6 | Conclusion and Policy Suggestions

6.1 | Conclusion

The nexus between climate change and ESR represents a critical challenge for the GCC region, with important theoretical and practical implications for these hydrocarbon-dependent economies. Within the GCC context, climate change threatens energy infrastructure through extreme weather events and environmental disruptions, undermining the reliability, accessibility, and affordability of energy supplies across these nations. Simultaneously, the region's traditional strategies to bolster energy security through carbon-heavy resources intensify CO_2

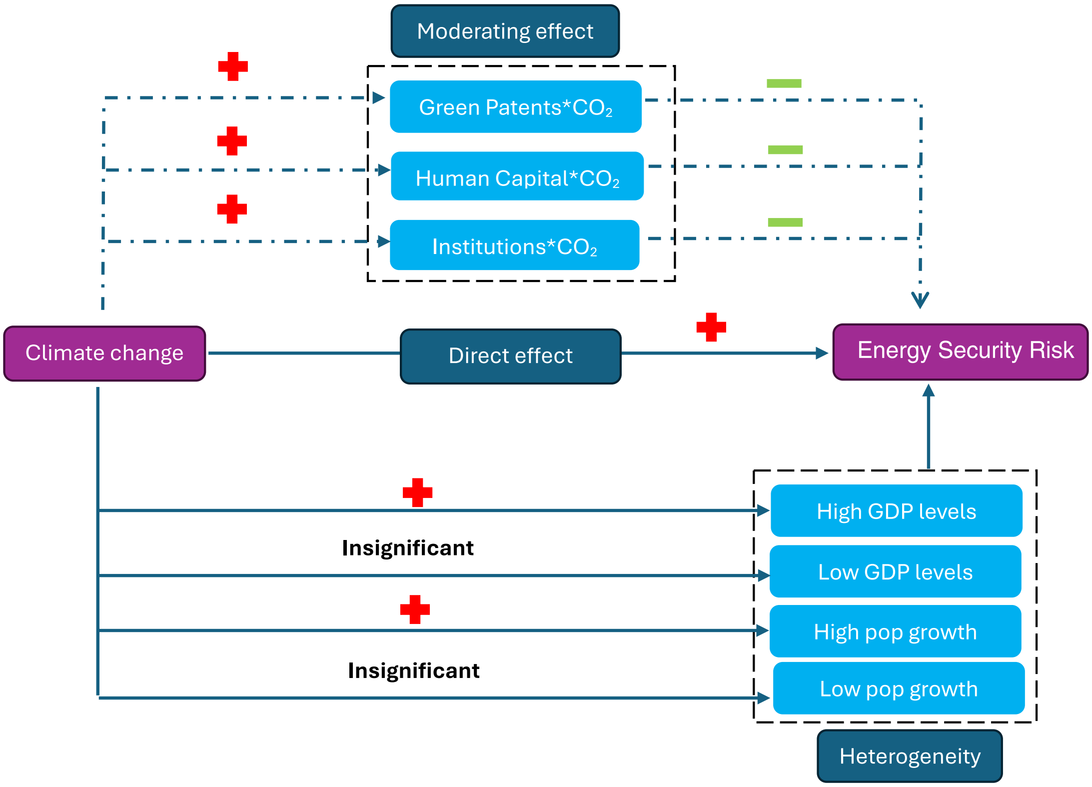

FIGURE 5 | Visualizing how climate change affects ESR.

emissions, perpetuating a cycle that accelerates climate change and further destabilizes regional energy systems. For GCC countries specifically, theoretical solutions such as advancements in green technology, robust governance, and enhanced human capital development offer potential pathways to reduce climate-induced energy security pressures. However, empirical evidence supporting these relationships within the GCC regional context has been limited. To address this knowledge gap, our research integrates newly compiled datasets on climate change indicators, energy security, green innovation, institutional quality, and human capital across GCC countries during 1990 to 2023.

Our findings demonstrate that within the GCC region, climate change markedly heightens ESR—a conclusion that holds robustly across diverse model specifications, including sensitivity analyses, alternative variable selections, and rigorous endogeneity checks. Moreover, our study reveals that for GCC economies, green patents, strong institutions, and human capital can substantially weaken the adverse effects of climate change on energy security. Our analysis identifies critical thresholds specific to the GCC context—namely, 1.43 for green patents, 0.03 for institutional quality, and 0.58 for human capital—that act as turning points for these economies. Below these levels, rising emissions directly amplify ESR across GCC nations. Once these thresholds are surpassed, however, GCC countries are better equipped to leverage innovation, adaptive policies, and skilled human resources, effectively decoupling emissions from energy security risks. Further analysis reveals that within the GCC regional context, the effectiveness of these mediating factors depends heavily on economic and demographic conditions. Regarding economic development, we observe patterns specific to GCC economies that challenge conventional assumptions. Climate change significantly elevates ESR in higher-GDP GCC economies, while its effect in relatively lower-GDP GCC countries remains statistically negligible. In lower-GDP GCC settings, stronger institutional quality mitigates climate change impacts, whereas in high-GDP GCC countries, better governance unexpectedly amplifies risks—potentially reflecting these advanced GCC economies' greater reliance on complex, climate-sensitive energy systems. Our analysis of population dynamics within the GCC reveals equally important regional insights. Climate change impacts on ESR are more pronounced in GCC nations experiencing rapid population growth compared to those with slower demographic expansion. In GCC countries with lower population growth, institutional quality significantly mitigates climate impacts, while in high-growth GCC settings, governance improvements show limited effectiveness, likely overwhelmed by expanding population pressures on regional energy demands and infrastructure.

6.2 | Policy Implications for GCC Countries

Our findings have significant policy implications specifically for GCC countries, where traditional reliance on fossil fuels has been central to economic prosperity and energy security strategies. The evidence clearly demonstrates that for the GCC region, climate change is a major driver intensifying ESR, requiring GCC policymakers to expedite transitions from carbon-intensive sources to sustainable alternatives tailored to regional conditions. Given the GCC's abundant solar resources and expansive territories, diversifying the regional energy mix toward solar and wind power represents a critical opportunity to stabilize energy systems while contributing to global climate mitigation efforts. Recognizing the unique economic and demographic dynamics across GCC economies, policy interventions must be specifically designed for regional realities, adapting strategies to the GCC's established energy infrastructures and rapid population growth patterns. For GCC countries, strengthening institutional frameworks and enhancing human capital have proven vital in buffering regional energy systems against emission-related destabilization. Therefore, targeted investments in green technology, governance reforms, and education are paramount for the GCC region. To stimulate this transformation across GCC economies, governments should implement comprehensive supportive measures addressing regional financial and institutional barriers. GCC-specific recommendations include: offering financial incentives like grants and subsidies to attract investments in regional renewable energy projects; streamlining regulatory reforms to ensure renewable energy initiatives progress efficiently within GCC regulatory frameworks; and fostering public-private partnerships that leverage the region's capital markets and expertise for large-scale clean energy development. Additionally, creating specialized green financial instruments—such as Islamic green bonds aligned with regional financial principles and GCC-focused renewable energy investment funds—can enhance market stability across the region.

Complementing these measures, GCC countries should prioritize community engagement and public education initiatives to foster regional acceptance of sustainable energy transitions. Enhancing local workforce capabilities through targeted education and reskilling programs will reduce the region's reliance on expatriate labor while building indigenous talent pools capable of sustaining clean energy sectors across GCC economies. Finally, by strengthening regional cooperation on climate initiatives and actively participating in international agreements, GCC countries can reinforce their collective role in sustainable energy development, effectively balancing economic diversification with environmental resilience to safeguard long-term energy security across the region.

Endnotes

[1] See: bloomberg.

[2] To address concerns about this temporal transformation, we use the quadratic match-sum methodology (Bergougui 2025a; Pata, Luo, et al. 2023; U. K. Pata 2025). This systematic temporal disaggregation preserves the integrity of the original annual series while enabling higher-frequency analysis. The procedure maintains consistency with annual benchmarks by ensuring the sum of the twelve-monthly observations equals the corresponding annual total, thus preventing artificial inflation of the sample size. Unlike simple interpolation, this theory-driven approach employs relevant high-frequency indicators to guide the monthly allocation and to capture within-year dynamics and cyclical variation that annual data obscure. As Shahbaz et al. (2017) demonstrate, the method also dampens erratic point-to-point fluctuations, producing more reliable estimates and effectively disentangling the underlying trend from seasonal effects.

[3] We employed the ***reghdfe*** command in Stata 18, which performs linear regression with multiple fixed effects, and the ***xtscc*** command for robustness, which estimates regression with Driscoll-Kraay standard errors with fixed effects.

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Appendix A

TABLE A1 | Cross-sectionally augmented Dickey–Fuller (CADF) test.

Variables	CADF—Level I(0)	CADF—Difference I(1)	CIPS—Level I(0)	CIPS—Difference I(1)
ESR	−2.900***	−4.051***	0.287	−3.819***
CO2	−2.775***	−4.696***	−2.264	−4.749***
TEM	−3.197***	−4.580***	−0.377	−4.474***
PRE	−2.314	−5.756***	−0.004	−5.949***
GUST	−3.862***	−4.968***	−0.791	−4.881***
SPEI	−3.007***	−4.096***	0.405	−4.279***
GP	−2.718***	−3.843***	−3.037***	−3.695***
IQ	−2.395**	−4.783***	0.461	−4.862***
HC	−2.910***	−4.736***	−1.322	−4.566***
GDP	−2.718***	−3.843***	−3.037***	−3.695***
TNRR	−2.395**	−4.783***	0.461	−4.862***
TO	−2.910***	−4.736***	−1.322	−4.566***
RE	−4.204***	−3.626***	−0.473	−3.900***
INDS	−3.759***	−5.074***	−1.563	−4.976***
POP	−1.178	−3.041***	−0.763	−2.989***

Note: *** and ** denote rejection of the null hypothesis of unit root (i.e., stationarity) at the 1% and 5%, significance levels, respectively.

TABLE A2 | Outcomes of Pesaran's test of cross sectional independence.

Models	*Pesaran CD*	*Prob.*
CO2	8.212	0.0000
TEM	8.505	0.0000
PRE	8.392	0.0000
GUST	6.961	0.0000
SPEI	8.208	0.0000

TABLE A3 | Pedroni test for cointegration.

Estimates	Statistic	*p*
Model 1 (CO_2)		
Modified Phillips–Perron t	4.618***	0.0000
Phillips–Perron t	6.299***	0.0000
Augmented Dickey–Fuller t	12.548***	0.0000
Model 2 (Temperature)		
Modified Phillips–Perron t	3.753***	0.0001
Phillips–Perron t	4.733***	0.0000
Augmented Dickey–Fuller t	9.028***	0.0000
Model 3 (Precipitation)		
Modified Phillips–Perron t	4.024***	0.0000
Phillips–Perron t	4.989***	0.0000
Augmented Dickey–Fuller t	8.104***	0.0000
Model 4 (Wind Gust)		
Modified Phillips–Perron t	4.227***	0.0000
Phillips–Perron t	5.460***	0.0000
Augmented Dickey–Fuller t	8.426***	0.0000
Model 5 (SPEI)		
Modified Phillips–Perron t	3.656***	0.0001
Phillips–Perron t	4.079***	0.0000
Augmented Dickey–Fuller t	2.443***	0.0073

Note: *** denotes statistical significance at the 1% level. H_0: No cointegration. All models include panel-specific cointegrating vectors, panel means, Bartlett kernel with 5 Newey-West lags, and 1 augmented lag.