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Energy transition under twin shocks: Geopolitical and macrofinancial risks

Mehmet Ulug [a,*], Roxana Andrei [b]

[a] Department of Social Sciences and Business, Roskilde University, Universitetsvej 1, 4000 Roskilde, Denmark
[b] Centre for International Studies, – University Institute of Lisbon (CEI-ISCTE), CEI-Iscte (Building 4), Room B1.131, Av.ª das Forças Armadas, 1649-026 Lisbon, Portugal

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ABSTRACT

The Greater North European Energy Corridor (GNEEC) – comprising Belgium, Denmark, Finland, Germany, the Netherlands, Norway, Sweden, and the United Kingdom - stands as a vital core for Europe's renewable energy ambitions, while facing rising geopolitical and macro-financial pressures. This study explores how Composite Geopolitical Risk (CGR) and macro-financial pressure have driven the energy transition within the GNEEC from 1990 to 2023, alongside the roles of economic growth and environmental innovation. Using the Method of Moments Quantile Regression (MMQR) approach, the results reveal strong heterogeneity along the green transition pathway. CGR has a consistently positive and rising effect on renewable deployment (≈ 1.05 *at* $\tau = 0.1$ *to* ≈ 1.81 *at* $\tau = 0.9$), showing that geopolitical tensions accelerate diversification, especially among transition leaders. In contrast, macro-financial pressures driven by monetary tightening hinder renewables (≈ -0.44 *at* $\tau = 0.1$ *to* ≈ -0.27 *at* $\tau = 0.9$), with financing costs constraining early-stage adopters more severely. Similarly, economic growth slows the clean share (≈ -77 *at* $\tau = 0.1$ *to* ≈ -1.25 *at* $\tau = 0.9$), as rebound and scale effects outweigh short-term efficiency gains. Environmental innovation fosters renewables at lower quantiles (≈ 1.50 *at* $\tau = 0.1$ *to* ≈ 0.73 *at* $\tau = 0.9$) but becomes insignificant at advanced stages, reflecting diminishing marginal returns. These findings highlight structural asymmetries: leaders convert geopolitical risk into faster deployment, while laggards remain more vulnerable to financial constraints. The study offers clear policy implications, including strengthening de-risking mechanisms, aligning growth with low-carbon strategies, and fostering innovation diffusion, in order to balance energy resilience, security, and financial sustainability across varying stages of the transition.

1. Introduction

The green energy transition (GrET) in Europe is unfolding under growing geopolitical tensions and financial uncertainty. This dual pressure is especially pronounced in the Greater North European Energy Corridor (GNEEC), which plays the role of Europe's renewable powerhouse and includes Belgium, Denmark, Finland, Germany, the Netherlands, Norway, Sweden, and the United Kingdom. Anchored by the North Sea and Baltic Sea basins, the corridor is a leader in the European GrET, accounting for approximately 47 % of the total of 848 GW renewable capacity installed in Europe. It has almost doubled its total renewable energy capacity in the past decade, rising from 213 GW in 2015 to 402 GW in 2024, with Germany and the UK leading in nominal terms, and with Denmark and Sweden surpassing 60 % renewables in their electricity mix by 2023 (IRENA, 2025).

However, this strategic corridor is not only a green energy powerhouse but also a frontier of geopolitical vulnerability, given the recent proliferation of hybrid threats against its critical energy infrastructure. Therefore, understanding how geopolitical risk (GPR) affects the pace of the GrET has become central to energy economics, climate policy, and policy development. Simultaneously, the inflationary pressures and monetary tightening that have accompanied the energy crisis have brought a second structural constraint into focus: the rising cost of capital, particularly for capital-intensive renewable technologies. These twin shocks -geopolitical and macro-financial- now define the ecosystem within which GrET strategies must evolve.

The observed dynamics reveal a growing discrepancy between political ambition and on-the-ground feasibility in the GNEEC region's energy transition. With its abundant renewable energy (REN) capacity, the region is the powerhouse of the European Union's offshore energy production (Glaum et al., 2024). Most of the European Union's (EU) offshore energy production originates from the North Sea-Atlantic area, which stands as the global leader in deployed offshore wind capacity and

* Corresponding author.
E-mail addresses: mehmetu@ruc.dk (M. Ulug), Roxana.Andrei@iscte-iul.pt (R. Andrei).

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Acronyms

BP-LM	Breusch-Pagan LM
CSD	Cross-section Dependency
ECM	Error Correction Model
EC	European Commission
GW	Gigawatts
GrET	Green Energy Transition
GPR	Geopolitical risk
SH	Slope Homogeneity
IRENA	International Renewable Energy Agency
OECD	Organization for Economic Cooperation and Development
IT	Inflation-targeting
USD	United States Dollar
BRIC	Brazil, Russia, India, and China
EU	European Union
MFP	Macro-financial Pressure

Dependent variable

REN	Renewable Energy Transition

Explanatory variables

CGR	Composite Geopolitical Risk
INTER	Interest rates

Control variables

EG	Economic Growth
EI	Environmental Innovation

Analysis scope

GNEEC	Greater North European Energy Corridor

Method

MMQR	Method of Moments Quantile Regression

expertise (European Commission, 2020). The EU member states -Belgium, Denmark, Germany, and the Netherlands- have jointly committed themselves to install 150 offshore wind power capacity (gigawatts) in their waters by 2050, more than half of the 260 GW total pledged by all North Seas Energy Cooperation (NSEC) member countries for the same period (North Seas Energy Cooperation, 2022). Furthermore, the region is at the forefront of decarbonization efforts and the application of cutting-edge technologies for clean energy production, and it hosts a robust large ports infrastructure, such as Rotterdam, Antwerp and Hamburg, essential for importing hydrogen and its derivatives (European Commission, 2020). The UK and Germany are particularly dominant players in the region, collectively responsible for over two-thirds of all the world's installed offshore wind power, followed by Denmark, Belgium, and the Netherlands (Kõrts, 2023).

While the GNEEC region is central to European GrET, Europe's critical energy infrastructure is currently facing an increasingly complex and diversified threat landscape, moving beyond traditional safety concerns toward urgent security challenges. Since the invasion of Ukraine in 2022, the GNEEC has become a frontline for intensified hybrid warfare activities around its critical energy assets, highlighting the intersection between green infrastructure and geopolitical conflict. The Nord Stream explosions in September 2022, the Balticconnector gas pipeline rupture between Finland and Estonia in October 2023, and the Estlink2 power cable damage in the Finnish Exclusive Economic Zone, in December 2024 have all demonstrated the specific vulnerabilities of underwater energy infrastructure, indispensable to all offshore installations. States of the region have also flagged a significant rise in suspicious activities, including intelligence collection and potential espionage, targeting the energy infrastructure in both the North Sea-Atlantic and Baltic Sea regions (Ministry of Defence Netherlands, 2023; Police Security Service of Norway, 2023). In this tense geopolitical environment, in November 2024, the Swedish government rejected 13 applications for the deployment of new offshore wind installations in the Baltic Sea. The decision was made based on the opposition expressed by the Ministry of Defense, which argued that constructing wind farms in the area would pose significant defense risks during a potential conflict. Specifically, the Ministry warned that wind turbines could interfere with the Swedish Armed Forces' radar systems, potentially halving the time available to detect incoming cruise missiles (Government Offices of Sweden, 2024). GPR and hybrid threats have thus echoed their effect on the fate of significant renewable projects in the GNEEC.

In parallel, geopolitical instability has elevated investor uncertainty, while rising interest rates (INTER) driven by global inflationary pressures have increased the cost of financing. Global inflation surged from under 2 % to over 10 % within a year during the post-pandemic period, marking the sharpest inflationary spike in recent decades (Ulug et al., 2023). This inflationary wave has prompted central banks across advanced economies to raise interest rates by tightening monetary policy. As reported by Isik et al. (2025), interest rates in these economies rose from near zero in mid-2022 to approximately 4 % by July 2023. Consequently, high INTER, compounded by inflation in turbine costs and supply chain bottlenecks, have strained the financial resilience of new renewable projects. In addition, auction failures, delayed investments, and project cancellations reflect this tightening. These developments have raised the cost of capital for long-term, infrastructure-heavy investments such as REN, particularly in offshore wind and hydrogen projects, thereby threatening the financial feasibility of key green transition initiatives (Battiston et al., 2021; Aguila and Wullweber, 2024; Vestergaard, 2024).

Nonetheless, despite the recent surge in studies on GPR and macro-financial pressures, significant thematic and geographical gaps remain. One striking omission is the near-total absence of focused empirical on the GNEEC, despite its critical role in the European GrET and EU's efforts to decouple from energy imports dependence. GNEEC not only constitutes the engine room of Europe's energy security and green transition, but it also hosts world-leading infrastructure in offshore and onshore wind, green hydrogen, and interconnectivity. Fig. 1 visualizes the distribution of total REN generation across Europe in 2023, with a specific focus on the countries that form the GNEEC. Although comprising just eight countries, the GNEEC collectively accounts for 42 % of total European REN, with Germany alone contributing 21 %. This highlights the strategic concentration of REN capacity in this corridor. In contrast, the rest of Europe accounts for 58 %, spread across a much broader set of countries.

However, high ambition does not guarantee uniform outcomes, nor does it render the advanced REN immune to external shocks. Differences in energy mix, institutional capacity, and exposure to a new threat landscape have led to asymmetric vulnerabilities, making this corridor a natural laboratory to assess the effects of exogenous variables – particularly GPR and INTER fluctuations - on REN trajectories. Fig. 2 illustrates the temporal evolution of REN consumption (left axis) and composite geopolitical risk (right axis) across GNEEC and their regional average. While most countries show upward REN trajectories over time, CGR trends remain volatile and asymmetrical, reflecting differing exposure to geopolitical shocks and institutional resilience capacities. (See Fig. 3.)

While prior research has addressed the impacts of geopolitical risks on the energy transition, it has yet to fully explore how the intersection of geopolitical disruption and macro-financial stress complicates the process and management of the green shift in Northern Europe. This

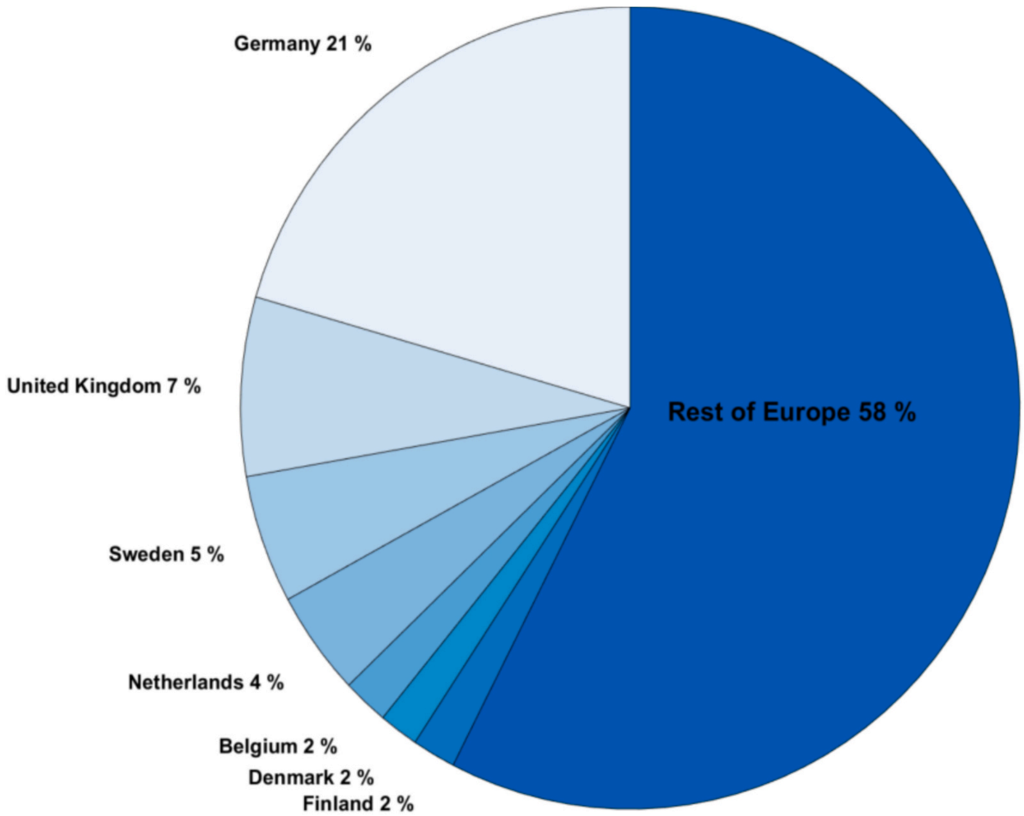

Fig. 1. Country shares of renewable energy in Europe.

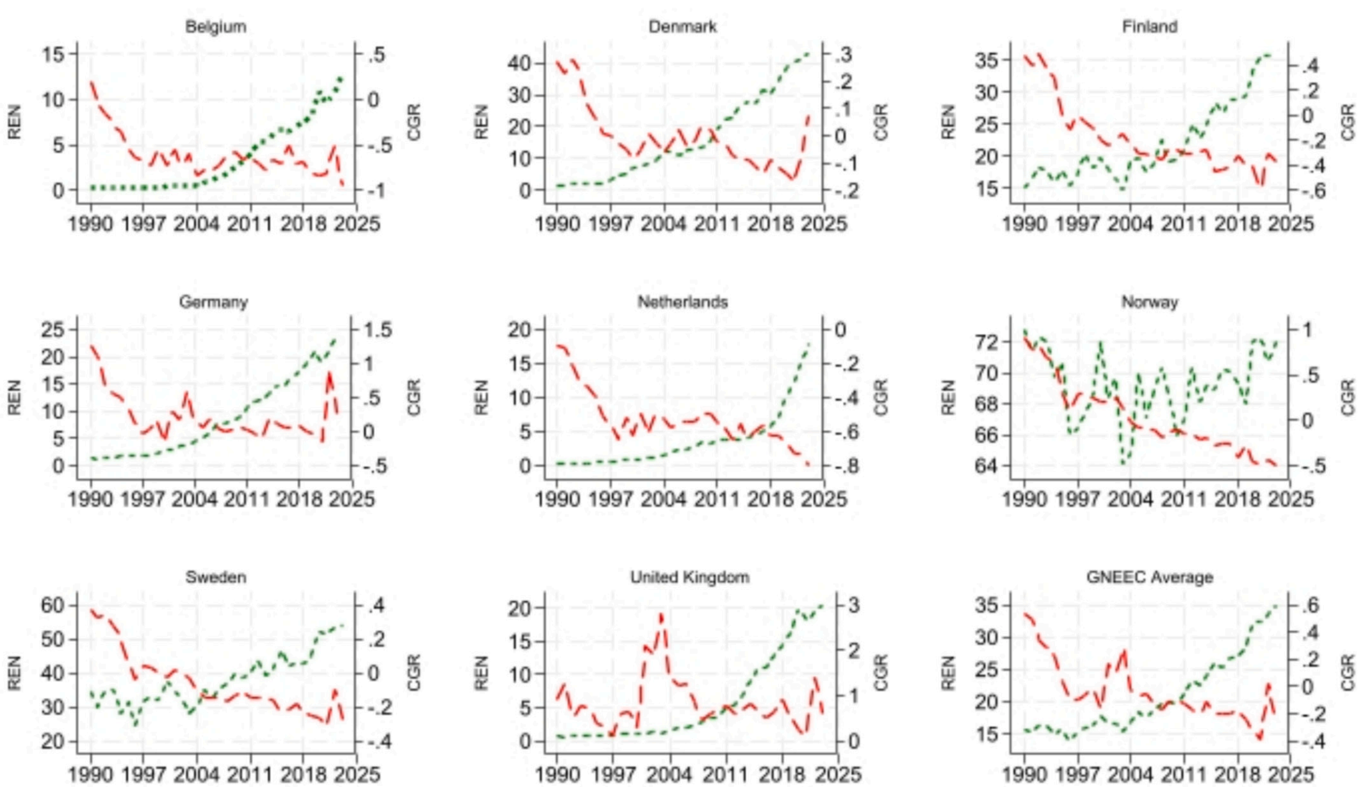

Fig. 2. REN and CGR across GNEEC countries and average (1990–2023).

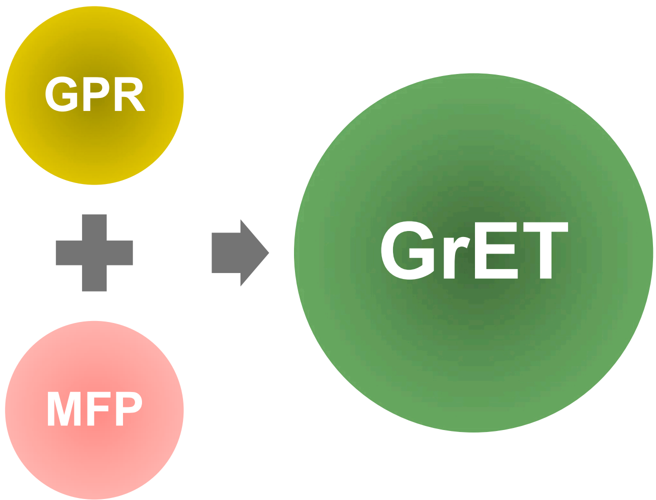

Fig. 3. Twin-shock transmission in corridor systems.

interplay reveals new trade-offs between energy security, financial sustainability, and climate goals. Some studies, such as Zhao et al. (2023), Wang et al. (2024b), and Shittu et al. (2025), find that GPR impedes GrET. Others, including Sweidan (2021) and He et al. (2025), suggest that under certain structural or regional conditions, GPR may in fact accelerate the shift toward renewables. Moreover, studies also show that higher economic policy uncertainty undermines energy security by reducing diversification and sustainability, whereas financial integration, political stability, and technological progress help to strengthen it (Dagar et al., 2024a, 2024b). However, there is a lack of dedicated empirical investigation into the GNEEC, leaving a major blind spot in the literature.

Motivated by this gap, this study addresses four core questions:

Q1. : How does geopolitical risk influence the pace and direction of the REN in the GNEEC?

Q2. : How do macro-financial pressures, such as rising INTER and tightening credit conditions, influence the REN in the GNEEC region?

Q3. : Does environmental innovation promote REN?

Q4. : What impact does economic growth have on REN?

1.1. Unique contribution, objective and novelty of research

The article tackles timely and stringent **topic**: the synergic impact of the twin shocks -geopolitical risk and rising interest rates- on the pace of the energy transition, unfolding within an unprecedented security threat landscape and a period of sustained macroeconomic pressures. Our **unique contribution** lies in bridging econometrics and geopolitics, delivering a rare interdisciplinary perspective that advances literature while offering evidence-based insights for policy and security communities. Thus, we aim to provide not only empirical clarification and systematic evidence on how these shocks affect renewable deployment in the Greater North European Energy Corridor but also suggestions for the key actors involved -policymakers, industry representatives, and the defense community- who must collectively ensure that the green transition remains resilient and aligned with long-term sustainability objectives. Although prior studies have investigated these drivers separately, they have not yet captured their combined and interacting effects in the GNEEC a region that is simultaneously Europe's renewable powerhouse and a frontline of geopolitical vulnerability. The **objective** of this paper is therefore to quantify and disentangle the impacts of geopolitical risk, rising interest rates, environmental innovation, and economic growth on renewable energy deployment across the corridor.

The article makes a significant, to-the-point contribution to achieving the United Nations **Sustainable Development Goals (SDGs)**, which require not only ambitious targets but also resilience against the structural shocks that threaten progress. This study thus contributes directly to three core SDGs. First, with respect to SDG 7 (Affordable and Clean Energy), the paper investigates how geopolitical risk and high interest rates influence renewable deployment, identifying conditions under which access to clean energy may be delayed or rendered more costly, and thereby providing insights for safeguarding affordability and accessibility. Second, in relation to SDG 9 (Industry, Innovation and Infrastructure), the study examines how macro-financial pressures affect investment in capital-intensive technologies, and how geopolitical risk to energy infrastructure impacts the deployment of new renewable projects. Third, regarding SDG 13 (Climate Action), the analysis demonstrates how external shocks can either accelerate or slow down the renewable transition, offering a quantile-based assessment that captures asymmetric risks and resilience patterns across the distribution of renewable energy deployment. In this way, the study links global sustainability goals to the practical realities of the energy transition, providing an evidence base for designing policies that can withstand geopolitical and macro-financial disruption.

The **novelty** of this study lies in four key contributions: *First*, we introduce an innovative dual-impact framework: the ***Geopolitical-Macrofinancial Twin-Shock Framework***, a new conceptual framework that explains how geopolitical risk (GPR) and macro-financial pressures (MFP) can work in tandem to create a compounded, nonlinear risk to the green transition. In this way, we aim to overcome the near-complete absence of research that models their joint, interactive effects on the energy transition, with GPR and macro-financial pressures being overwhelmingly analyzed individually. *Second*, the research provides the first empirical assessment dedicated to the GNEEC, the lifeline of Europe's decarbonization but overlooked in the existing literature, despite its crucial role for Europe's energy security in the current geopolitical and macroeconomic landscape. *Third*, while previous studies have largely relied on news-based GPR indices (e.g., Caldara and Iacoviello, 2022), this study adopts the newly developed Composite Geopolitical Risk (CGR) Index by Jiménez et al. (2025). Unlike traditional GPR measures, which are often stationary and prone to mean reversion, the CGR captures longer-term, structural GPR, providing a more comprehensive measure of geopolitical uncertainty. And *finally*, it employs the MMQR approach of Machado and Silva (2019), allowing for a distributional analysis of how geopolitical and macro-financial factors such as rate hikes affect REN at different levels of deployment. This method moves beyond average effects and captures heterogeneous impacts across the REN distribution. By combining a robust econometric approach with geopolitical analysis, this study offers a rare interdisciplinary perspective that connects the rigor of quantitative modelling with the strategic realities of international security and energy policy. In doing so, it advances both the energy economics and security literature strands by bridging the gap between geopolitical context and empirical modelling of the energy transition.

The paper is structured to reflect its dual ambition: to advance theory while offering practical insights. Section 2 lays the groundwork by reviewing the literature and highlighting the research gap, introducing the Geopolitical–Macrofinancial Twin-Shock Framework, a new conceptual lens designed to capture the compounded and nonlinear effects of geopolitical risk and macro-financial pressures. Section 3 details the data, variables, and econometric methodology, advancing the MMQR approach that allows for a distribution-sensitive analysis. Section 4 presents and interprets the empirical findings, emphasizing both the heterogeneity of impacts across transition stages and their broader societal implications. Finally, Section 5 consolidates the study's contributions through a focused conclusion, sets out clear and quantile-sensitive policy implications across both macrofinancial and defense dimensions, and points to future research directions.

2. Literature review: beyond a binary approach of geopolitical risk and macro-financial pressures

2.1. Theoretical background

The scholarly literature addressing the determinants of the green energy transition (GrET) has tended to treat geopolitical risk (GPR) and macro-financial pressures (MFP) as separate and largely independent variables. While this approach has yielded valuable insights, it risks obscuring the reality that these shocks rarely occur in isolation. In practice, geopolitical disruptions -such as wars, hybrid attacks, or threats to critical energy infrastructure- interact with financial dynamics, most notably interest-rate hikes and inflationary pressures, in ways that amplify uncertainty and undermine investment confidence. This interaction generates synergistic and nonlinear effects that cannot be captured by the existing models of analysis. To bridge this gap, the present study introduces the **Geopolitical-Macrofinancial Twin-Shock Framework**, a conceptual framework that views GPR and MFP not as parallel but as interdependent forces. In effect, a feedback loop emerges in which geopolitical crises fuel inflation and monetary tightening, which in turn raise the cost of financing renewable projects, thereby reinforcing the disruptive impact of the original shock. Taken together, these dynamics represent a compounded and systemic source of risk for the green transition, one that demands an integrated analytical approach.

2.2. The geopolitical-macrofinancial twin-shock framework: An integrated analysis of the green transition drivers

The existing literature on geopolitical risk (GPR) and macro-financial pressures (MFP) tends to analyze their impacts on energy transition independently. This approach, however, overlooks the synergistic and nonlinear effects that arise when these shocks occur in tandem. To address this critical research gap, this study introduces a dual-impact framework: **the Geopolitical-Macrofinancial Twin-Shock Framework**. This conceptual tool posits that GPR and MFP are not merely cumulative stressors acting on their own, but rather interconnected forces that can create a compounded, nonlinear risk to the green transition.

The framework's core premise is that a GPR shock, such as a major armed conflict or a politically motivated disruption of energy supply chains, rarely occurs in isolation. It is frequently accompanied by, or directly precipitates, a significant MFP shock. Geopolitical risks have been found to be directly linked to higher inflation, in the context of higher commodity prices, supply disruptions, currency depreciation and tighter financial conditions (Iacoviello et al., 2024), with increased geopolitical risk, in particular during crises and wars, driving higher inflation (Bouri et al., 2023; Kyriazis et al., 2023; Darwiche et al., 2025). As such, a conflict, such as the war in Ukraine, can trigger both a physical disruption of supply (a GPR shock) and a simultaneous surge in global commodity prices and inflationary pressures (an MFP shock). This confluence of events poses a unique and complex challenge to the energy transition that requires a new analytical lens.

Within this framework, the two shocks operate through distinct but reinforcing channels. The GPR shock primarily affects the supply side and strategic security dimensions of the energy transition. It can lead to a reprioritization of national energy security over climate goals, a disruption of critical supply chains, or a fragmentation of international collaboration. In parallel, the MFP shock operates on the demand side and financial viability of the transition. Rising inflation and interest rates directly increase the capital costs of renewable energy projects and reduce the financial incentives for private investment. These financial pressures can also erode public and political support for costly green initiatives, especially when energy bills are rising.

A GPR-induced surge in fossil fuel prices can exacerbate inflation (MFP shock), which in turn makes renewable energy investments less attractive and stalls clean energy deployment. This delay in the transition can then increase a nation's long-term vulnerability to future GPR shocks related to fossil fuel dependence and/or energy imports, where the case. Our dual-shock framework, therefore, provides a conceptual tool to unpack this complex interplay, moving beyond a simple cause-and-effect relationship to explain how GPR and MFP can work in tandem to amplify risks and create a more fragile green transition path.

This chapter thus concludes that a separate approach to geopolitical and macro-financial shocks is insufficient to explain their concerted impact on energy transition. The Geopolitical-Macrofinancial Twin-Shock Framework we introduce offers a crucial new lens for understanding how these interdependent forces combine to create a compounded, nonlinear pressure. Our study further advances the literature by employing a more comprehensive and multidimensional CGR index, which moves beyond traditional measures to capture deeper structural and political shifts. Furthermore, we provide a novel thematic and geographic focus on the Greater North European Energy Corridor (GNEEC), a strategically vital region that has been notably understudied. Finally, our utilization of the MMQR approach allows us to capture the asymmetric effects of these shocks, revealing how their combined impact varies across regions with different levels of renewable energy adoption -an insight conventional linear models cannot provide.

In light of this, our analysis next examines how existing literature has addressed the impact of geopolitical risks and macro-financial pressures on energy transition in a binary way. The prevailing research treats these two domains overwhelmingly separately from one another, providing valuable but ultimately incomplete insights into the drivers of the green energy transition. By systematically reviewing these approaches, we aim to highlight their contributions, while also exposing their conceptual limitations when analysing the stressors of energy transition in the current security and macroeconomic landscape. This critical assessment forms the foundation for defining the key gaps in the literature, moving beyond the binary approach that has characterized much of the scholarship to date, and advancing our Geopolitical–Macrofinancial Twin-Shock Framework as an integrated framework.

2.3. Bridging the literature gap: An integrated framework for compounded risk

2.3.1. The geopolitics–renewables Nexus: Disruption or catalyst?

GrET is increasingly impacted by external shocks, notably geopolitical tensions and financial instability, both of which introduce uncertainty into long-term climate and energy policy planning. Theoretically, transition risk frameworks (FSR, 2022; Battiston et al., 2021) emphasize that exogenous disruptions -such as wars or INTER hikes- can delay or distort decarbonization pathways. In this context, the primary driver for the GrET in Europe has undergone a notable reorientation. Prior to the outbreak of the war in Ukraine and the concurrent energy crisis, it was predominantly motivated by climate change mitigation. However, from 2022 onwards, the imperative to decouple from imports of fossil fuels from Russia has shifted the focus toward energy independence and resilience. Consequently, GrET has transformed from an environmentally driven choice into an urgent matter of survival (Andrei, 2022). Climate change and geopolitical goals nowadays co-exist as the main drivers of renewables deployment in Europe, grappling simultaneously with fluctuating inflationary rates and volatility of investment.

GPR has emerged in this context as a divergent element in the global push toward REN. The consensus about its impact on the GrET is divided, with two strands of literature emerging: one focusing on the disruptive effects of GPR on renewables, and another considering its potential catalytic role. On the inhibitory side, Zhao et al. (2023) provide findings that GPR significantly reduces REN demand across 20 OECD countries, weakening international collaboration on technology and threatening climate change mitigation policies. Their findings are echoed by Shittu et al. (2025), who find that GPR negatively impacts countries' overall energy transition, especially in more fossil-fuel-dependent and financially constrained economies. Similarly, Wang et al. (2024a) use a nonlinear panel simulation in 38 countries to reveal that GPR exerts a double threshold effect on GrET, where GPR intensifies its inhibitory influence when it crosses the threshold, followed by a limited diminution after this level. In a more nuanced approach, Zhu et al. (2025) argue that, while geopolitical risks are found to substantially hinder the energy transition -primarily by exacerbating price volatility, disrupting supply chains, and shifting policy focus- the impact is not uniform. Countries with strong renewable energy infrastructure, stable fiscal mechanisms, and adaptable labor markets are more resilient, whereas economies reliant on natural resources and those with high militarization experience more pronounced delays.

In contrast to the inhibitory effect approach, other scholars argue for a stimulating effect of GPR on the GrET. Opoku et al. (2025) find that rising geopolitical risks can accelerate a nation's energy transition by improving its resilience and ability to absorb energy system shocks. He et al. (2025) agree that GPR accelerates REN transition, especially in nations facing environmental degradation and higher energy reliance. Likewise, Sweidan (2021) demonstrates that in the United States GPR has acted as a catalyst on the REN deployment, stimulating GrET. Wang et al. (2024b) add nuance by applying multivariate models, incorporating both linear and nonlinear specifications, to demonstrate the favorable impact of GPR on energy transition within OECD countries. They argue that GPR leads to higher instability, which in turn can stimulate states to look for means to reduce their external energy dependence, while also prioritizing green innovation.

2.3.2. High interest rates: A brake on clean energy investment

Notwithstanding its valuable contributions, the scientific literature examines independently the impact of high interest rates on energy transition from that of geopolitical risk. Interest rate-based monetary policy is a standard practice of central banks operating under an inflation-targeting (IT) framework. The key policy instrument is the short-term interest rate, which is determined to achieve the inflation target. This short-term rate, set by the central bank, influences longer-term interest rates, which tend to reflect its trend over time. This is precisely how monetary policy is conducted in normal times. In response to post-pandemic inflationary pressures, central banks globally have adopted tighter monetary policy stances aimed at containing price instability (Ulug et al., 2023). Surging inflation across Europe prompted the European Central Bank (ECB) to raise INTER to multi-decade highs, reaching a benchmark rate of 4.5 % by late 2024 (ECB, 2024). While setting short-term INTER to ensure price stability is a standard practice of IT central banks, the broader debate on the causes of high inflation in Europe has led to differing evaluations of the ECB's policy response. Scholars are divided between those highlighting demand-pull factors and those focusing on cost-push dynamics, such as the energy price inflation spurred by the conflict in Ukraine (Isik et al., 2025). These macroeconomic challenges, particularly inflation volatility and monetary tightening, have added complexity to the broader policy landscape surrounding the GrET.

A growing body of literature converges on the conclusion that high INTER hinder the REN by raising the cost of capital, thus disproportionately affecting capital-intensive REN technologies (Tiwari et al., 2024; Akan, 2024; Chen and Lin, 2024; Coccia and Russo, 2025). INTER hikes by tightening monetary policy create barriers for capital-intensive clean energy investments, particularly in offshore wind and green hydrogen (IRENA, 2025). The literature on green monetary policy (Agliardi and Agliardi, 2019; Aguila and Wullweber, 2024, Vestergaard, 2024) suggests that constrained credit and higher borrowing costs can slow down the pace of the transition by making low-carbon projects less bankable. Moreover, financial development is closely linked to energy access, with stronger effects observed in advanced economies than in weaker infrastructures (Ali et al., 2025). Financial stress and financial development risk undermining progress toward the energy transition (Mariev and Islam, 2025; Irfan et al., 2023). These financial constraints are especially pronounced in countries with weaker institutional support or underdeveloped green bond markets. Together, these twin shocks -geopolitical volatility and monetary tightening- are theorized to exert asymmetric and nonlinear effects across regions, depending on structural conditions such as energy mix, technological maturity, and fiscal space.

2.4. Nonlinear, context-specific impact of GPR on REN

Recent empirical studies reveal that GPR influences REN in nonlinear and context-specific ways. He et al. (2025) show, across 41 countries, that GPR fosters REN, especially in vulnerable and energy-dependent nations. By contrast, Zhang et al. (2023) find no significant U.S. effect, while Liu et al. (2023a, 2023b) detect bidirectional, time-varying GPR–REN links. Similarly, Su et al. (2021) report mutual causality, suggesting both positive and negative pathways. Other work highlights inhibitory effects. Zhao et al. (2023) show GPR lowers REN demand in OECD countries, Shittu et al. (2025) confirm global adverse effects, and Yasmeen and Shah (2024) find negative impacts on energy consumption in G7 economies. Lee and Lee (2024) add evidence from China, where GPR constrains renewables, especially in western provinces, though green finance and innovation mitigate such effects. Moreover, evidence points to heterogenous impacts. According to Bakhsh et al. (2024), GPR moderates the link between governance and GrET, with economic complexity shifting effects across quantiles. Hille (2023) finds that GPR from fossil fuel suppliers spurred renewables in import-reliant Europe, linking higher electricity prices to strategic shifts. Fig. 4 illustrates an integrated framework for compounded risk, synthesizing the disruptive and catalytic perspectives of GPR, alongside macro-financial pressures, economic growth, and environmental innovation, in shaping the GrET.

2.5. Conceptual contributions and methodological innovations

Despite the growing literature on GPR and its impacts on macro-financial outcomes, there are several critical gaps. *First*, while existing studies analyze GPR and macro-financial pressures on energy transition individually, there is a near-complete absence of research that models their joint, interactive effects on the energy transition. For this reason, we introduce a dual-impact framework: the **Geopolitical-Macro-financial Twin-Shock Framework,** which we will detail in the section below. In this way, we aim to provide a conceptual tool that explains how these shocks can work in tandem to create a compounded, nonlinear risk to the green transition.

Second, most studies treat GPR as a homogeneous and external shock, typically measured using global indices like Caldara and Iacoviello's GPR (Caldara and Iacoviello, 2022). While useful, these indices lack regional specificity and fail to capture long-term political, ideological, and military shifts. This paper fills that gap by employing a CGR index that provides a more comprehensive and multidimensional measure of GPR. It is the first study to complement conventional GPR with structural indicators that reflect deeper geopolitical transformations, offering a more complete picture of how geopolitical disruption affects energy systems.

Third, despite the surge in research on GPR and macro-financial outcomes, there is a notable thematic and geographic blind spot concerning the GNEEC, despite the region being the lifeline of Europe's GrET and key to the continent's energy security, while at the same time at the frontline of hybrid threats against critical energy infrastructure. Surprisingly, there is a scarcity of empirical research dedicated to this strategically vital corridor. This study fills that gap by exploring how the dual impact of CGR and financial pressure influences the speed and strategic direction of the REN in the GNEEC.

Fourth, the GNEEC corridor provides a practical case study: countries operate under broadly shared institutions and policy frameworks yet face sharply different exposures (import dependence, grid topology,

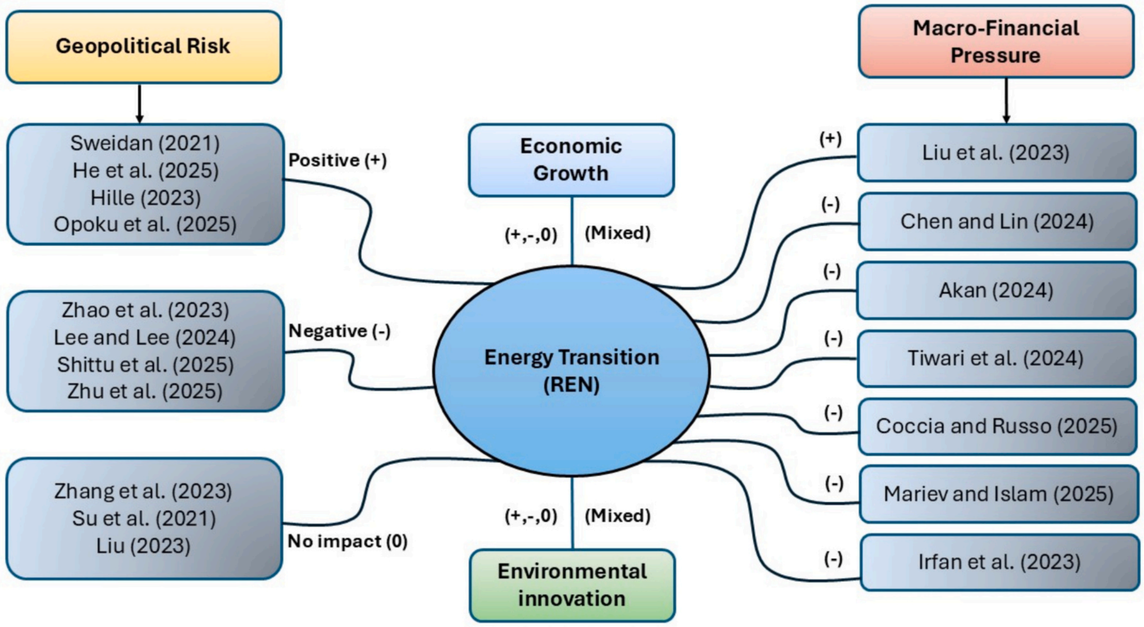

Fig. 4. Literature review on renewable energy transition (REN).

energy mix, trade routes, and finance depth). This combination yields a setting where other influencing factors and systemic spillovers can be observed, allowing us to identify how twin shocks transmit and interact in an interconnected energy system. The mechanism we study – how geopolitical-microfinancial twin shocks are passed through a system under common rules but with different levels of exposure - can be applied to other energy security corridors. These elements go beyond a regional case study; we provide a general theory for how these twin shocks spread through a corridor, a way to measure geopolitical risk, and specific estimates that can help inform policy-making during times of geopolitical and financial instability.

Finally, we apply the MMQR approach to capture asymmetric effects across different quantiles of renewable energy outcomes. This methodological choice allows us to identify how the combined shocks affect regions with low, moderate, and high renewable energy adoption differently, an insight that conventional linear models cannot capture. Our study therefore contributes to bridging the gap between geopolitical, financial, and empirical research on the energy transition, offering crucial insights for policymakers seeking to build resilience in an increasingly volatile world.

3. Data and methodology

3.1. Data and variables

This study investigates the impact of geopolitical risk, interest rates, economic growth, and environmental innovation on the energy transition in the GNEEC region. The empirical analysis is based on annual panel data spanning the period 1990–2023. The dependent variable is the energy transition (REN), measured as the share of primary energy consumption derived from renewable sources. The main explanatory variable is geopolitical risk (CGR), which reflects the broader geopolitical landscape affecting energy policy, trade, and infrastructure investment. Traditionally, studies in this field have treated geopolitical risk as a homogeneous and exogenous shock, most commonly proxied using global indices such as the Geopolitical Risk Index (GPR) developed by Caldara and Iacoviello (2022). While such indices are useful for capturing global volatility, they often lack regional specificity and fail to account for the long-term structural, political, ideological, and military developments that characterize the evolving geopolitical landscape in Europe. This study addresses that gap by adopting the CGR index recently developed by Jiménez et al. (2025).[1] While CGR is the core focus of this study, interest rates (INTER) play an equally vital role. The inflationary pressures and monetary tightening that have accompanied recent global energy crises have created a second structural constraint: the rising cost of capital. This is particularly critical for renewable energy technologies, which demand large upfront investments. The economic growth (EG) variable serves as a proxy for the level of economic development and potential demand-side dynamics influencing energy consumption. Energy innovation (EI) is another control variable that reflects technological progress in the green sector and the capacity of countries to foster innovation in support of decarbonization goals. Table 1 presents the measurement, symbol, and data sources of all variables included in the analysis.

3.2. Model construction

The study aims to investigate the impact of geopolitical risk and macro-financial pressure, controlling for economic growth (EG) and environmental innovation (EI) in the GNEEC region. The structural form is expressed as:

$$lnREN_{it} = f(CGR_{it}, INTER_{it}, lnEG_{it}, lnEI_{it}) \quad (1)$$

The corresponding linear specification can be written as follows:

$$lnREN_{it} = \vartheta_0 + \vartheta_1 CGR_{it} + \vartheta_2 INTER_{it} + \vartheta_3 lnEG_{it} + \vartheta_4 lnEI_{it} + \varepsilon_{it} \quad (2)$$

where, i indexes countries and t years, ϑ_0 is a constant, and ε_{it} is an error

[1] While Jiménez et al. (2025) present the full methodology for CGR construction, they do not provide complete CGR time series for all countries in the GNEEC region. Therefore, this study constructs the CGR series independently for Belgium, Denmark, Finland, Germany, the Netherlands, Norway, Sweden, and the United Kingdom by closely following their approach. In other words, we replicate and apply their approach to construct our own CGR indices for the countries under investigation. Specifically, CGR is constructed from a set of internal and external indicators, including indices of democracy, inequality, rule of law, and military spending, alongside external dimensions such as political risk with weights based on geospatial proximity and ideological distance. See Jiménez et al. (2025) for full details.

Table 1
Definition of variables.

Variable	Symbol	Measurement	Source
Renewables	REN	Share of primary energy consumption from renewable sources	OWD (2025) https://ourworldindata.org/renewable-energy
Composite Geopolitics Risk	CGR	Integration of structural indices with news-based geopolitical risk index	Jiménez et al., 2025https://www.bbvaresearch.com/en/publicaciones/global-a-new-set-of-structural-indicators-geopolitical-risk-and-economic-fragmentation/
Interest rates	INTER	Long-term interest rates	Müller et al. (2025) https://www.globalmacrodata.com/
Economic growth	EG	GDP per capita (constant 2015 US$)	WDI (2025) https://databank.worldbank.org/source/world-development-indicators
Environmental innovation	EI	Development of environment-related technologies (Index)	OECD (2025)[a] https://data-explorer.oecd.org/

[a] OECD patent data are available up to 2022. The value for 2023 is obtained by linear interpolation to ensure a balanced panel structure.

term. LnREN is the log share of primary energy from renewables. CGR is the composite geopolitical risk index (constructed from internal and external components following Jiménez et al. (2025). INTER is the long-term interest rate (macro-financial pressure). EG is the real economic activity (2015 constant USD), and EI is the share of environment-related patent applications.

3.3. Econometric framework

The estimates quantile-specific effects using the panel MMQR estimator of Machado and Silva (2019), which allows both the location and scale of the conditional of $lnREN_{it}$ to vary with covariates and unit effects.

3.3.1. Variables and notation

The dependent variable and the regressor vector are defined as follows:

$$REN_{it} \equiv lnREN_{it} \tag{3}$$

Where $i = 1,\dots,N$ indexes countries and $t = 1,\dots,T$ years. In Eq. (3), REN_{it} denotes the outcome variable, representing REN (the log share of primary energy from renewables) in country i at time t. And the $k \times 1$ regressor vector:

$$X_{it} = (CGR_{it}, INTER_{it}, lnEG_{it}, lnEI_{it})' \tag{4}$$

Following Machado and Silva (2019), we also allow for transformations of X_{it}.

$$\varphi(X_{it}) = (\varphi(X_{it}), \dots, \varphi_k(X_{it}))' \tag{5}$$

Which plays the same role as Z_{it} in Machado and Silva (2019). In our baseline, we set $\varphi(X_{it}) = X_{it}$, so that the conditional scale of REN_{it} depends directly on the covariates.

3.3.2. Location-scale representation

The panel location-scale model can be specified as:

$$REN_{it} = \alpha_i + X_{it}'\beta + (\theta_i + \varphi(X_{it})'\vartheta)\omega_{it} \tag{6}$$

Where α_i (location FE) and θ_i (scale FE) are unit-specific effects; β collects location slopes and ϑ scale slopes; ω_{it} is i.i.d., independent of X_{it}, with continuous CDF F_ω and quantile function $Q_\omega(\tau) = q(\tau)$.This structure yields the conditional quantile function in the following way:

$$Q_{REN_{it}} = (\tau \mid X_{it}) = \alpha_{it}(\tau) + X_{it}'\beta + \varphi(X_{it})'\vartheta q(\tau) \tag{7}$$

Where the quantile-specific intercept is $\alpha_{it}(\tau) = \alpha_{it} + \theta_i q(\tau)$, and the quantile-specific slopes for components in $\varphi(\bullet)$ are

$$\beta(\tau) = \beta + \vartheta q(\tau) \tag{8}$$

3.3.3. Identification and moment conditions

For a given quantile τ, define the quantile score as $\psi_\tau(u) = \tau - 1\{u \leq 0\}$ and the residual takes the following form:

$$r_{it}(\tau) = REN_{it} - \left(\alpha_i + \theta_i\, q(\tau) + X_{it}'\beta + \varphi(X_{it})'\, \vartheta q(\tau)\right) \tag{9}$$

At the true parameters, the MMQR moment conditions are given by the following:

$$\mathrm{E}[\psi_\tau(r_{it}(\tau))h(X_{it}, i)] = 0 \tag{10}$$

Where $h(\bullet)$ includes a constant, $X_{it}, \varphi(X_{it})$ and country dummies to absorb the fixed effects $\alpha_i(\tau)$. These moments identify $\{\alpha_i, \theta_i, \beta, \vartheta, q(\tau)\}$ up to the usual location/scale normalizations on ω_{it}.Intuitively, conditional on instruments, the proportion of negative residuals equals τ. For a grid $\mathrm{T} = \{\tau_1, \dots, \tau_J\}$ (we use $\tau = 0.10, \dots, 0.90$), stack the sample moments across τ and compute the MMQR estimator:

$$g_{NT}(\theta) = \frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T}\underbrace{\oplus}_{\tau\epsilon\mathrm{T}}\psi_\tau(r_{it}(\tau))\, h(X_{it}, i) \tag{11}$$

And estimate parameters using the two-step GMM estimator:

$$\hat{\theta} = \mathrm{arg}\underbrace{min}_{\theta}\, g_{NT}(\theta)'\, W\, g_{NT}(\theta) \tag{12}$$

Where W is heteroskedasticity- and dependence-robust weighting matrix. This procedure Jointly estimates $\{\beta(\tau)\}_{\tau\epsilon\mathrm{T}}$, $\{\alpha_i(\tau)\}$, and the quantile normalizers $\{q(\tau)\}$.In practice, software such as mmqreg in Stata reports the quantile-specific slopes $\beta(\tau)$ directly. When regressors may be endogenous (e.g., $CGR_{it}, INTER_{it}$), Machado and Silva (2019) propose an IV-MMQR estimator. Let D_{it} denote potentially endogenous regressors and C_{it}valid instruments. Identification uses GMM with the orthogonality conditions:

$$E[C_{it}\, U_{it}] = 0 \text{ and } E[C_{it}(|U_{it}| - 1\ ] = 0 \tag{13}$$

Where U_{it} is the structural error term. This addresses reverse causality and omitted variable bias at each quantile. An important feature of MMQR is that quantile estimates do not cross, by construction, ensuring consistent and interpretable results. This framework therefore provides a robust strategy to mitigate endogeneity concerns, as the fixed-effects location–scale design accounts for time-invariant omitted heterogeneity, while the IV-MMQR extension explicitly controls for potential reverse causality and omitted variable bias in the relationship between geopolitical risk, interest rates, and energy transition.

The MMQR approach offers several advantages over traditional estimators. First, MMQR allows for the examination of how the impact of explanatory variables differs across the entire distribution of the outcome variable. This holds true especially for understanding how drivers of the REN behave under low, medium, or high levels of renewable energy uptake. Second, unlike traditional quantile regression methods, MMQR provides consistent and efficient estimates even in the presence of extreme values, which are common in macroeconomic datasets. Third, MMQR works well in cases where variables deviate from normal distribution and where unobserved heterogeneity exists across units which are typical in cross-country panel data. Finally, a key strength of MMQR is its ability to address endogeneity, a known limitation in ordinary quantile regressions. Endogeneity is handled by MMQR's fixed-effects location–scale design (time-invariant omitted variables) and, where necessary, by IV-MMQR using GMM moment conditions $E[C_{it}\, U_{it}] = 0$, $E[C_{it}(|U_{it}| - 1\ ] = 0$ to address reverse causality/simultaneity at each quantile. Given these strengths, MMQR is particularly relevant for this study's objective.

3.4. Empirical strategy

The empirical strategy follows a stepwise procedure, beginning with pre-estimation diagnostics to account for potential cross-country dependencies and parameter heterogeneity. This process is illustrated in Fig. 5, which presents the methodological pipeline of the empirical analysis. Before estimating the MMQR, we obtained static panel estimates using ordinary panel methods. First, a poolability F-test comparing pooled OLS to fixed effects strongly rejected the null of no unit effects (F $=$ 107.06, $p < 0.001$), indicating significant country heterogeneity. Next, a Hausman test comparing FE and RE rejected the null of no systematic coefficient differences $\chi^2(4) = 26.08, p < 0.001)$. Accordingly, all baseline static panels are estimated with unit fixed effects, and, to maintain consistency in the distributional framework, the MMQR is specified with unit-specific quantile intercepts.

3.4.1. Cross-sectional dependence

Following preliminary statistics and panel specification diagnostics, the third step involves testing for cross-sectional dependence (CSD) employing the Pesaran (2004) test. In an increasingly globalized world, shocks originating in one country or region can readily spill over to others. As Li et al. (2025) note, uncertain shocks in energy markets affect all economies, though the impacts vary depending on national energy structures, technological capacity, and supply chain resilience. Therefore, testing for CSD is essential at the outset; ignoring it may lead to inconsistent and biased estimators in subsequent panel regressions. To address this, the Pesaran (2004) CSD test is employed, where the null hypothesis assumes no CSD among panel entities. The test statistic is specified by:

$$CSD_{test} = \sqrt{\frac{2T}{N(N-1)}} \sum_{i=1}^{N-1} \sum_{k=1+i}^{N} \widehat{\rho}_{ij} \tag{14}$$

where $\widehat{\rho}_{ij}$ denotes the pairwise correlation coefficient of the residuals. Asymptotically, under the null hypothesis, the statistic follows the standard normal distribution, and the p-value indicates whether CSD can be rejected.

3.4.2. Slope homogeneity

Alongside CSD, determines whether the slope coefficients are consistent across countries or vary significantly. To evaluate testing for slope homogeneity (SH) is equally critical when working with heterogeneous panels. Specifically, slope heterogeneity this, the study uses the test developed by Pesaran and Yamagata (2008), which provides both the delta (Δ_{SH}) and adjusted delta $\left(\widehat{\Delta}_{SH\_adj}\right)$ statistics. Following Zheng et al. (2023), the slope homogeneity is based on the following test statistics:

$$\widehat{\Delta}_{SH} = (N)^{\frac{1}{2}}(2q)^{-\frac{1}{2}}\left(\frac{1}{N}\widetilde{S} - Q\right) \tag{15}$$

$$\widehat{\Delta}_{SH\_adj} = (N)^{1/2}\left(\frac{2Q(T-Q-1)}{T+1}\right)^{-1/2}\left(\frac{1}{N}\widetilde{S} - 2Q\right) \tag{16}$$

Where $\widehat{\Delta}_{SH}$ indicates the slope coefficient homogeneity and $\widehat{\Delta}_{SH\_adj}$ represent the adjusted version accounting for small-sample bias. The null hypothesis states that slope parameters are assumed to be homogeneous across units, while the alternative indicates heterogeneity. Given the structural and institutional differences among the GNEEC states, the presence of both CSD and SH is expected in most specifications and will inform the choice of subsequent estimators.

3.4.3. Panel unit root test

Following the CSD and slope homogeneity diagnostics, the fourth step examines the unit root characteristics of the panel variables. This step is critical for determining the appropriate cointegration and estimation techniques in the subsequent phase of the analysis. However, traditional unit root tests for panel data (Levin-Lin-Chu, ADF, IPS) often fail to account for CSD, which is likely present in macro-panel datasets involving interconnected countries. In order to account for this, the analysis uses the Cross-sectionally Augmented Im, Pesaran, and Shin (CIPS) test, following Pesaran (2007). The CIPS test extends the IPS framework by including cross-sectional averages of lagged levels alongside first differences into the ADF regression, thus eliminating bias from unobserved common factors. The CIPS test's null hypothesis indicates that all panel series are non-stationary, with the alternative hypothesis allowing stationarity in at least a subset of cross-sectional units. This makes it robust to both CSD and heterogeneity in the panel. The CIPS test measure is computed as:

$$CIPS = \frac{1}{N} \sum_{i=1}^{N} CADF_i \tag{17}$$

Where $CADF_I$ denotes the cross-sectionally augmented Dickey-Fuller statistic for unit i. Zhao et al. (2023) notes that this formulation allows for panel-level inference while controlling for CSD and imbalances in the panel structure (i.e., whether $T > N$ or $N > T$).

3.4.4. Cointegration test

The fifth step assesses whether the variables share a long-run relationship, which is essential to obtain unbiased regression results. While the cointegration test of Westerlund (2007) is appropriate as a second-generation cointegration it does not account for CSD and SH across countries. The test employs four statistics (group-mean (Gt, Ga) and panel-mean (Pt, Pa)) to assess the null hypothesis of no cointegration. Rejection of the null suggests that at least a subset of countries have a consistent long-run association between the variables. Following Li et al. (2025), the four test statistics are defined as follows:

$$G_t = \frac{1}{N} \sum_{i=1}^{N} \frac{\widehat{\alpha}_i}{SE(\widehat{\alpha}_i)} \tag{18}$$

$$G_\alpha = \frac{1}{N} \sum_{i=1}^{N} \frac{T\widehat{\alpha}_i}{\widehat{\alpha}_i(1)} \tag{19}$$

$$P_t = \frac{\widehat{\alpha}}{SE(\widehat{\alpha})} \tag{20}$$

$$P_\alpha = T\widehat{\alpha} \tag{21}$$

The test evaluates this through four statistics, two based on the group-mean and two on the panel-mean. However, when testing for the existence of a long-run relationship among the variables while accounting for cross-sectional dependence, the results of Westerlund (2007) may not be fully informative. Therefore, the Westerlund and Edgerton (2007) panel bootstrap LM test is employed. This residual-based, KPSS-type procedure accommodates cross-sectional dependence via a sieve bootstrap and reverses the null hypothesis to H0: cointegration.

3.4.5. Robustness check and sensitivity analysis

The last stage of the empirical procedure involves a robustness check and sensitivity analysis to assess the reliability of the results obtained from the MMQR estimator. For this purpose, the empirical procedure incorporates robustness exercises, including alternative quantile grids, leave-one-country-out re-estimations, substitution of macro-financial proxies, and complementary inference/estimation methods (e.g., DK estimator proposed by Driscoll and Kraay (1998) and bootstrap quantile regressions (BSQR)).

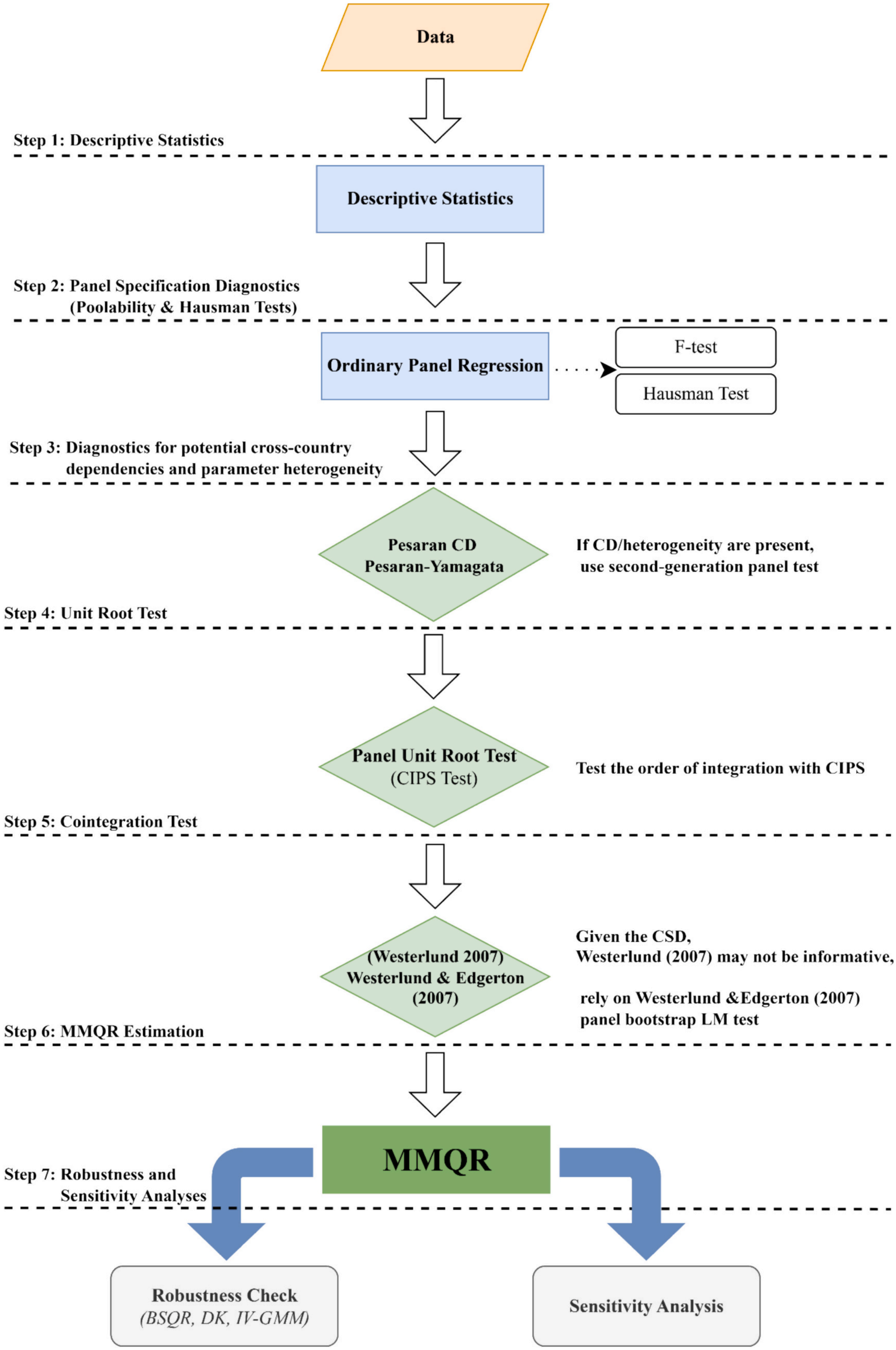

Fig. 5. Methodological pipeline of the empirical analysis.

3.5. Preliminary analysis findings

3.5.1. Descriptive statistics

The empirical investigation begins with a summary of statistics for the key variables shown in Table 2. The mean and maximum values reveal substantial variation across the panel. For instance, EG reaches an average of 995.18, with a maximum of 3,700,000.00 while REN spans from a minimum of 0.24 to a peak of 72.81. Such wide dispersion is also observed in EI and CGR, highlighting significant cross-country and temporal heterogeneity. In addition, significant Jarque-Bera statistics at the 1 % level are observed for all variables, pointing to departures from normality alongside nonlinear characteristics in the data distribution. This outcome is reinforced visually by the histogram plots in Fig. 6, which shows clear signs of skewness and heavy tails across all variables. Furthermore, Fig. 6 displays the quantile-quantile (Q-Q) plots for each variable, confirming abnormal distributions relative to the normal reference line. Together, statistical and graphical diagnostics (Table 2, Fig. 6, and Fig. 7) affirm the non-normal nature of the panel data and motivate the use of nonlinear regression techniques in the subsequent econometric analysis.

3.5.2. CSD and SH

Following the descriptive statistics and distribution characteristics, a set of preliminary econometric tests was conducted to validate the robustness and consistency of the panel data estimations. The analysis proceeds by testing for the presence of CSD across countries in the GNEEC region. To this end, the Breusch-Pagan LM (BP-LM) test was employed. As shown in Table 2, Panel A, across all specifications, the null hypothesis of CSD is rejected at the 1 % significance threshold. This finding indicates a significant degree of interdependence among countries, implying that economic or geopolitical shocks in one nation may propagate across borders, potentially influencing the entire region. Subsequently, the issue of SH was examined using the $\widetilde{\Delta}$ and $\widetilde{\Delta}_{adj}$ statistics formulated by Pesaran and Yamagata (2008). As reported in Table 3, Panel B, also rejects the null hypothesis of SH at the 1 % level. This finding suggests that the underlying relationships between REN and explanatory CGR, INTER, EG, and EI are not uniform across countries.

3.5.3. Panel unit root

Given that the previous findings indicate the presence of both CSD and slope SH, the CIPS test was employed to check the stationarity conditions of the variables. As presented in Table 3, Panel C, all variables are found to be non-stationary at levels (meaning the series is integrated of order zero, I(0)), but become stationary upon taking the first difference, indicating they are first-order integrated (I(1)). This finding confirms the next step, which is the appropriateness of conducting cointegration analysis to analyze potential long-run dynamics among the variables.

3.5.4. Westerlund cointegration results

To test for the existence of a long-run relationship among the variables, we first apply the Westerlund (2007) second-generation panel cointegration test. As reported in Table 3, Panel D, although the asymptotic (standard) *p*-values for the Westerlund (2007) ECM statistics Ga, Pt, and Pa are large; given their H_0: no cointegration and the presence of cross-sectional dependence, these results are not informative. Therefore, we implement the Westerlund and Edgerton (2007) panel bootstrap LM test, a residual-based, KPSS-type procedure that accommodates cross-sectional dependence via a sieve bootstrap and reverses the null to H0: cointegration. For our 8-country panel (1990–2023), the LM statistic equals 5.635 with a bootstrap p-value = 0.905. Because this p-value far exceeds the 10 % threshold, the null hypothesis of cointegration cannot be rejected, indicating results consistent with a long-run equilibrium. Given its robustness to cross-sectional dependence, we emphasize the bootstrap LM result in our inference.

Table 2
Summary statistics of variables.

	EG	INTER	REN	CGR	EI
Mean	995.18	4.1411	20.913	−0.034183	1.0505
Median	430.00	4.0739	12.778	−0.095415	1
Maximum	3,700,000.00	13.21	72.811	2.7925	2.05
Minimum	140,000.00	−0.5110	0.2427	−0.93834	0.24
Std. Dev.	1,088,300.00	2.9324	22.475	0.52556	0.2777
Skewness	1.2703	0.6097	1.1152	1.3907	1.1248
Kurtosis	2.939	1.678	3.0577	6.8454	5.7365
Jarque-Bera	73.27	16.86	56.42	255.3	142.2
Probability	0.000	0.000	0.000	0.000	0.000
Observations	272	272	272	272	272

3.5.5. MMQR estimates

Table 4, Fig. 8, and Fig. 9 present the regression estimates of the MMQR model across various quantiles (0.1 to 0.9) for the key explanatory variables. Unlike traditional mean-based approaches (Koenker and Bassett Jr, 1978), the MMQR model provides further details on how the effects of independent variables vary across the conditional distribution of the target variable (dependent). This approach captures potential heterogeneity in the impact of covariates, particularly at the tails of the distribution. (See Fig. 10.)

3.5.6. Robustness and sensitivity analysis

This section presents sensitivity and parameter-robustness checks. To verify the robustness of our MMQR results, we conduct the following exercises:

3.5.6.1. Quantile grid & coverage. Beyond the baseline MMQR at $\tau \in \{0.10, \ldots, 0.90\}$, we re-estimated on a coarser grid $\tau \in \{0.25, 0.50, 0.75, 0.90\}$ and a finer grid centered on the median. The sign, pattern across quantiles, and statistical significance of the key coefficients (geopolitical risk and interest rates) are qualitatively unchanged; effect sizes differ only modestly, and the shape of $\beta(\tau)$ is preserved. (Appendix Table A.1; Fig. A.1).

3.5.6.2. Leave-one-check-out. In addition to our baseline checks, we re-estimated the MMQR models excluding Belgium. The CGR and INTER coefficients retain their signs and significance across quantiles and closely match the baseline profiles. (Results are reported in Appendix Table A.2).

3.5.6.3. Alternative proxies for macro-financial pressure. We re-estimate MMQR replacing the long-term interest rate with (i) a short-term market rate (STRATE) and (ii) the policy rate (CBRATE). Results are in Appendix Table A.3.1 and Table A.3.2. Coefficients on the interest-rate proxy (short-term rate and policy rate) are qualitatively unchanged across $\tau \in \{O.10, \ldots, 0.90\}$, confirming that findings are not sensitive to the choice of proxy.

3.5.6.4. Alternative inference and estimator. We complemented DK inference with Bootstrap Quantile Regressions (BSQR) across $\tau \in \{0.10, \ldots, 0.90\}$. The BSQR results closely track the MMQR patterns, with the signs and cross-quantile profiles of the CGR and interest-rate coefficients remaining qualitatively unchanged. This provides an estimator that does not depend on the same large-T approximation and supports the robustness of our conclusions. (See Appendix Table A.5 and Fig. A.2.) Overall, across alternative quantile grids, interest-rate proxies, and estimators (MMQR vs. DK, and BSQR), the qualitative conclusions are unchanged. This confirms that our results are robust to both quantile coverage and macro-financial measurement choices, and are estimator-robust. All these sensitivity analysis results and parameter-robustness checks are reported in Appendix. (for DK results, see Appendix Table A.4, and for BSQR results, see Appendix Table A.5 and Fig. A.2.)

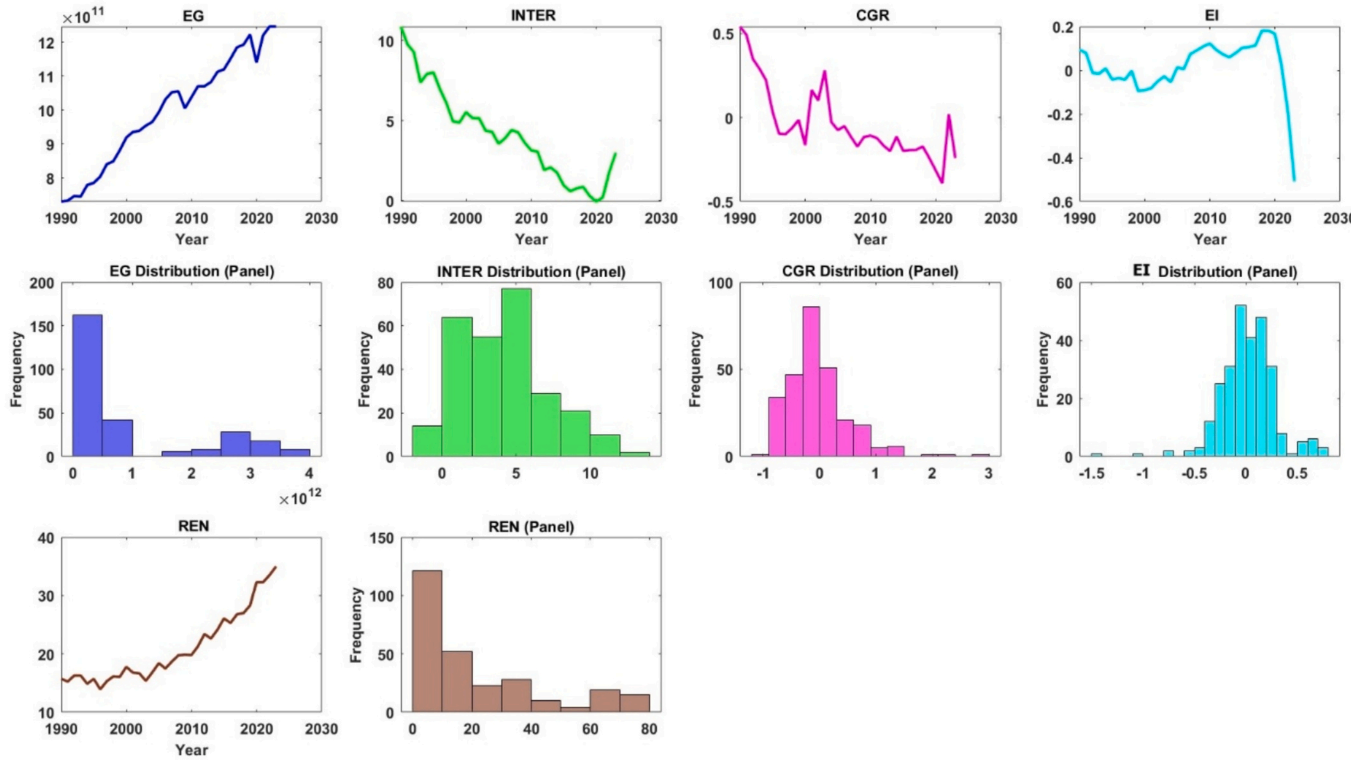

Fig. 6. Trends and distributions of the variables.

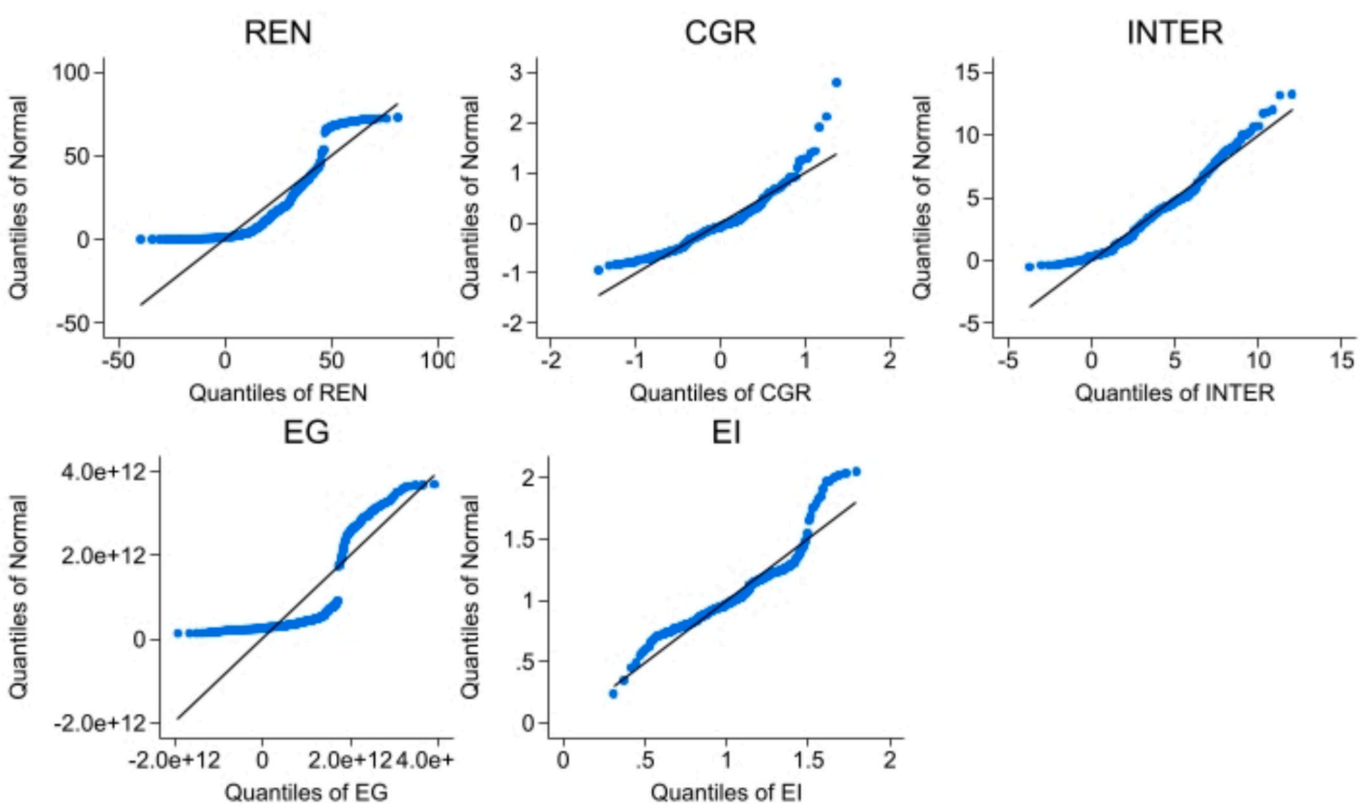

Fig. 7. Quantile Distribution plots.

Table 3
Pre-estimation findings.

Panel A: CSD test					
Tests	Variables REN	CGR	INTER	EG	EI
BP-LM	22.576*	20.413*	30.333*	30.255*	8.216*
Panel B: Slope tests					
	stat.	p-value			
$\widetilde{\Delta}$	24.052	0.000			
$\widetilde{\Delta}_{adj}$	26.504	0.000			
Panel C: CIPS test					
Variables	Stats.		Variables	Stats.	
REN	−2.067		ΔREN	−5.314*	
CGR	−2.652		ΔCGR	−5.921*	
INTER	−2.746		ΔINTER	−5.441*	
EG	−2.659		ΔEG	−4.409*	
EI	−2.592		ΔEI	−5.588 *	
Panel D: Westerlund ECM test					
Statistics	value	z-value	p-value	LM-stat	Bootstrap P-value
Gt	−1.389*	3.129	0.999	5.635[a]	0.905
Ga	−4.269*	3.207	0.999		
Pt	−3.566*	2.317	0.990		
Pa	−4.853*	1.661	0.952		

Note: ***,** and * show %10, 5 % and 1 % at the significance level and [] denotes *p*-values. "a" indicates that the LM test reverses the null to H_0 = cointegration. For the LM statistic (Westerlund and Edgerton, 2007) the null is cointegration, thus a large bootstrap *p*-value indicates results consistent with cointegration.

4. Results and discussion

4.1. Interpretation of main findings

The MMQR results presented in Table 4 reveal important distributional dynamics in the effects of CGR, INTER, EG, and EI across different levels of REN. One of the most outstanding findings of this analysis is that CGR is positively associated with REN deployment and consistently significant across all quantiles - rising from 1.05 at Q0.1 to 1.81 at Q0.9. This effect strengthens across quantiles, challenging in this way the conventional narrative that geopolitical tensions disrupt or slow down energy transition. Instead, the evidence suggests that in the GNEEC region, geopolitical uncertainty serves as a booster, and not as a constraint to the net-zero transition, especially in countries with more advanced renewable infrastructure and capacity. By construction, the CGR index explicitly incorporates military expenditure and the military risk from other countries, weighted by contiguity, geographic proximity, and rivalry, thereby directly capturing the security-related pressures relevant for the energy transition. In the case of the GNEEC, this external dimension is particularly salient: the region lies on the frontline of the Ukraine war, faces recurrent hybrid threats in the Baltic Sea (including subsea infrastructure sabotage), and is exposed to Russia's persistent military presence and energy weaponization. The CGR thus captures not only abstract measures of risk but the very security pressures that have prompted governments in Denmark, Germany, Poland, and the Baltic states to accelerate offshore wind and grid integration projects as part of their broader defense and resilience strategies. This context supports our interpretation that geopolitical shocks act as a "security booster," accelerating renewable deployment as states respond to external threats with accelerated decarbonization and infrastructure diversification.

This aligns with a security-of-supply/strategic substitution channel: as GPR rises, countries, especially those already advanced in the transition (upper quantiles), accelerate renewables to hedge fuel-price volatility and import risk. The stronger slope at higher τ indicates that leaders convert geopolitical pressure into faster clean deployment. Put differently, the finding suggests that CGR consistently accelerates the GrET across all quantiles, but more so at higher levels of renewable penetration. In lower-quantile countries (those lagging in renewables deployment), CGR acts as a moderate driver, possibly triggering the urgency to decouple from imported fossil fuels. In high-quantile cases (already more advanced in renewables rollout), CGR appears to amplify the existing momentum, perhaps due to better infrastructure and institutional readiness to respond to geopolitical shocks (e.g. the offshore wind expansion in the UK and Germany following the war in Ukraine). The findings align with a growing body of literature that identifies geopolitical shocks as transition accelerators under specific structural conditions (He et al., 2025; Wang et al., 2024b; Sweidan, 2021). Nonetheless, this study provides a more granular, case-sensitive view, showing that the geopolitical impact is not uniform but intensifies with the level of transition maturity. Countries with more advanced renewable rollout, with a well-diversified energy mix and less dependent on energy imports, are thus more prone to accelerate their GrET when faced with geopolitical shocks, which they regard as an impetus to forward their decoupling from high-risk energy providers, while continuing to boost their climate change targets.

In contrast to the stimulating role of CGR, macro-financial pressures consistently impose a negative impact on renewable energy deployment, throughout all quantiles, ranging from −0.44 at Q0.1 to −0.27 at Q0.9. A 1 percentage point increase in INTER brings about a 0.3–0.4 % reduction in REN. This negative effect is stronger in countries with lower renewable penetration, indicating higher sensitivity to financing costs.

The findings indicate that higher INTER consistently impedes the renewable energy transition, with the largest negative effect at the lower quantiles. This supports a financing-cost/credit-constraint channel: when countries are early in the transition (lower τ), green CAPEX is marginal and more sensitive to borrowing costs; at higher τ, deeper capital markets, de-risking, and policy support buffer the rate sensitivity. This reflects financing constraints for early-stage countries/projects that are more sensitive to borrowing costs. Moreover, at higher quantiles (where more renewables are already deployed), the impact is still negative but slightly weaker, suggesting that mature green sectors are less vulnerable to rate hikes. This asymmetry highlights the vulnerability of early-stage or less mature renewable energy systems to capital cost fluctuations. Renewable technologies are highly capital-intensive and rely heavily on debt financing. In low-quantile contexts, rising INTER can lead to project delays or even cancellations. At higher quantiles, the discouraging effect of interest rates persists but is less pronounced, as even in mature markets, rate hikes can affect the economic competitiveness of renewables vis-à-vis less expensive alternatives, such as the temporary reliance on LNG or on pipeline gas imports from risk-free countries, as Norway. These findings corroborate the results reported in recent studies such as Tiwari et al. (2024), Coccia and Russo (2025), Akan (2024), and Chen and Lin (2024). In line with our

Table 4
Quantile method of moments estimator results.

Variables	$Q_{0.1}$	$Q_{0.2}$	$Q_{0.3}$	$Q_{0.4}$	$Q_{0.5}$	$Q_{0.6}$	$Q_{0.7}$	$Q_{0.8}$	$Q_{0.9}$
CGR	1.05*	1.15*	1.23*	1.30*	1.41*	1.52*	1.66*	1.74*	1.81*
INTER	−0.44*	−0.41*	−0.40*	−0.38*	−0.36*	−0.33*	−0.30*	−0.28*	−0.27*
EG	−0.77*	−0.84*	−0.88*	−0.93*	−0.99*	−1.06*	−1.15*	−1.21*	−1.25*
EI	1.50*	1.27*	1.11*	0.95*	0.73**	0.50	0.19	0.01	0.13
C	23.35	25.52	27.11	28.59	30.66	32.85	35.76	37.48	38.87

Note: ***$p < 0.01$,**$p < 0.05$, *$p < 0.10$.

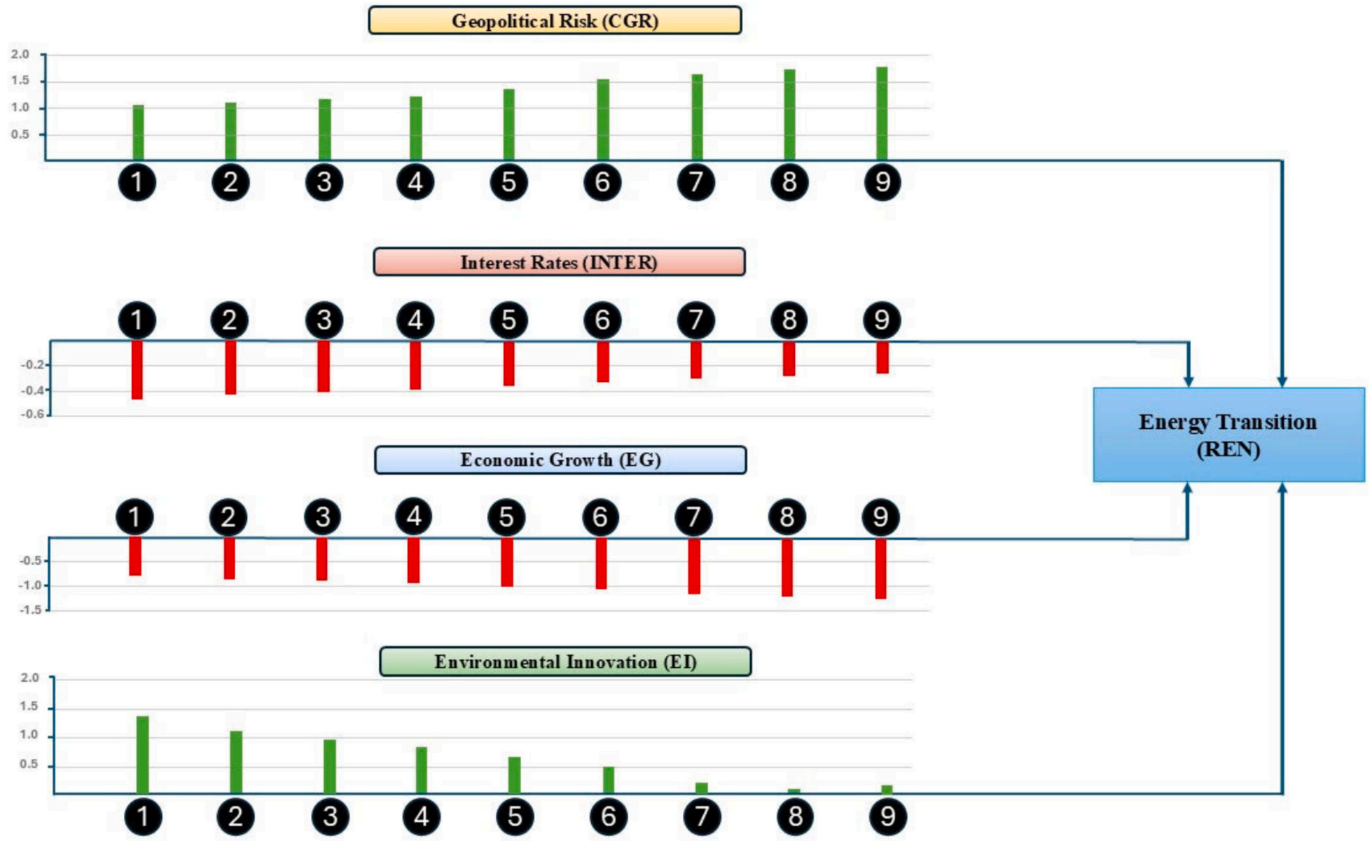

Fig. 8. Visual representation of quantile-specific effects of geopolitical risk, key macro-financial and innovation variables on energy transition, based on MMQR estimation.
Note:
Quantile: Numbers 1,..,9 represent quantiles τ =0.10, …,0.90 accordingly.
Scale: The size of rectangles at each quantile corresponds to the actual magnitude of the coefficient at that quantile.

results, these studies highlight that increased monetary tightening, reflected in higher INTER, adversely affects REN investment and deployment.

A particularly counterintuitive finding of this study is the consistently negative association between economic growth and the share of renewable energy. The effect strengthens slightly from −0.77 at Q1 to −1.25 at Q0.9. An increase of 1 % in GDP is associated with a 0.77 to 1.27 % reduction in REN.

This suggests that short-run scale and rebound effects dominate: faster growth raises overall energy demand, which is often met by incumbent fossil-fuel capacity, thereby delaying the clean share. Moreover, growth-driven investments tend to reinforce capital stock lock-in, where energy-intensive industries and existing fossil-based infrastructure are expanded or maintained. This lock-in effect is particularly visible in advanced economies within the GNEEC, where strong export orientation and industrial demand exacerbate reliance on conventional energy sources. Our findings are consistent with the composition effect outweighing immediate technology upgrading, a mechanism supported by recent empirical studies on the growth–renewables nexus.

Intuitively, higher GDP levels in advanced economies are accompanied by rising overall energy demand. To sustain growth, these economies sometimes rely on non-renewable sources, whether fossil fuels or alternative low-carbon but non-renewable options such as nuclear, which can lower the relative share of renewables in the overall energy mix. Moreover, national energy mix preferences may shape this relationship: for example, Finland's use of 35.6 % nuclear power for electricity generation (Low-Carbon Power, 2025) as a strategic component of its low-carbon system reduces the proportionate weight of renewables. Recent developments further illustrate the structural mechanisms behind this finding. In Denmark, despite robust growth, the offshore wind sector faced a critical slowdown in December 2024, when a 3 GW tender failed to attract a single bid under a subsidy-free auction model. The combination of rising capital and financing costs, weak demand signals, uncertain revenue prospects, and insufficient policy support rendered the auction commercially unviable, forcing the government to suspend tenders and redesign a state-supported framework (Danish Energy Agency, 2025; WindEurope, 2024). Similarly, in Germany, strong economic performance has coincided with stalled renewable deployment, as permitting bottlenecks, grid congestion, and fragmented support frameworks have slowed the rollout of both offshore and onshore wind projects. These examples underscore that beyond a certain threshold, renewable energy deployment is no longer driven by economic growth per se, but increasingly by the alignment of policy frameworks, institutional capacity, and macroeconomic realities. These findings are in line with Estevão and Lopes (2024), who report a similar negative relationship between EG and REN in their analysis of the UK, US, Japan, and the Eurozone. However, contrasting evidence is presented by Pata et al. (2023), who find that EG significantly improves REN investments in G7 countries. Similarly, Bamati and Raoofi (2020) report that EG drives REN production in developing economies. Supporting this view, Zhao et al. (2023) find that higher income per capita significantly increases REN in OECD countries. These contrasting results suggest that the growth–renewables nexus may be context-dependent, varying with economic structure, development level, and energy policy design.

Finally, MMQR results reveal another distributional dynamic in the

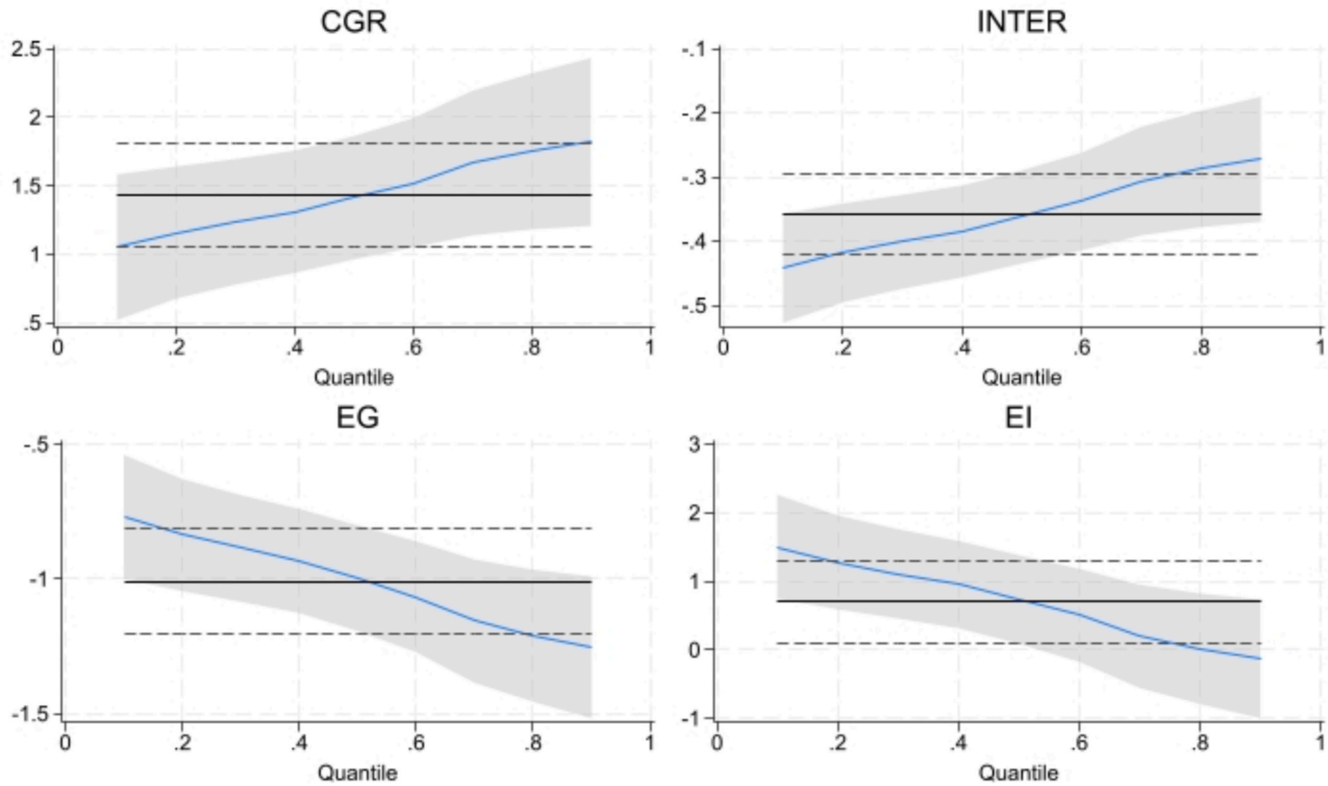

Fig. 9. MMQR plots of the model.

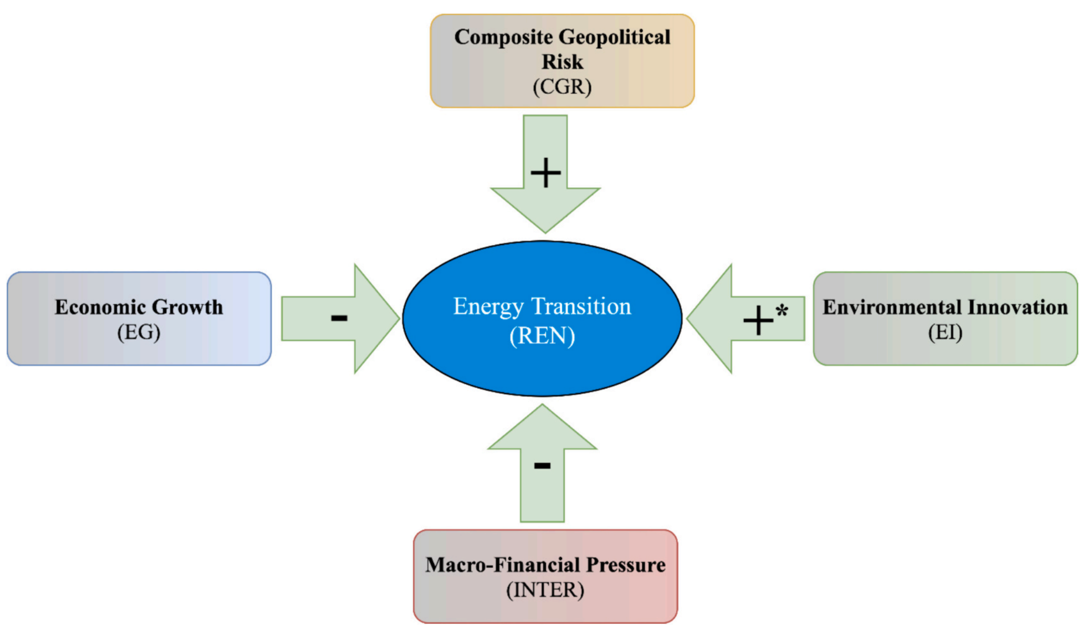

Fig. 10. Graphical representation of the effects of CGR, macro-financial pressure, economic growth, and environmental innovation (EI) on energy transition (REN). **Note:** * indicates that EI shows a positive effect at lower quantiles, which diminishes and becomes insignificant at higher quantiles.

role of EI across different levels of REN. At the lower quantiles (Q0.1 to Q0.4), EI is associated with a significant positive effect on REN. Notably, at Q0.1, an increase of 1 % in EI leads to a 1.50 % growth in REN, indicating that innovation serves as a strong catalyst at the early development phase of the energy transition. EI is positive at lower and mid quantiles (1.50 to 0.73) but fades toward the top (approximately 0 by $\tau \geq 0.7$). Two mechanisms fit: (i) deployment lags, where patents precede diffusion; and (ii) diminishing returns, where leaders may already exploit the "easy" innovation margins, so additional patenting has less impact on the clean share. This indicates the transformative potential of innovation in countries or periods where REN adoption remains relatively low. However, the effect of EI diminishes as we move toward higher quantiles of the REN distribution. From Q0.5 onward, the magnitude of the coefficient progressively declines and eventually becomes statistically insignificant beyond Q0.6. This finding suggests that in more advanced stages of REN deployment, innovation alone is insufficient to drive further progress. While innovation plays an important part in the early phases, long-term advancement requires a broader enabling environment, including supportive institutions, infrastructure, and policy frameworks. Previous studies support this role of EI. For example, Zheng et al. (2023) show it improves environmental sustainability, and Rao and Kumar (2024) associate it with reduced energy intensity. However, their findings indicate stronger effects at higher quantiles, in contrast to this study. He et al. (2025) and Lee and Lee (2024) also emphasize innovation's role in improving resilience to geopolitical risks. These findings confirm that EI is essential to the green transition, but its impact varies by context and development stage.

4.2. Societal benefits

The research carries important societal benefits by adopting a *whole-of-society* perspective on the green energy transition ecosystem in the GNEEC, based on four pillars. *First*, society at large benefits from the findings as they provide evidence on how to safeguard affordability, security, and sustainability of energy systems under geopolitical and macro-financial shocks, thereby ensuring that the transition remains feasible rather than generating new vulnerabilities. *Second*, policy-makers are directly informed by the results, gaining an empirically grounded understanding of how twin shocks affect renewable deployment in Europe's strategic energy corridor, which can guide the design of robust, adaptive, and forward-looking policy frameworks. *Third*, the study provides insights for the defense sector, highlighting how geopolitical risk and hybrid threats intersect with the deployment of renewable infrastructure, offering mitigation solutions and allowing defense planners to anticipate vulnerabilities and integrate energy resilience into broader security strategies. *Finally*, the paper informs industry and project developers, who must operate in a tightening financial environment, by clarifying how interest rate dynamics and geopolitical disruptions condition the bankability of renewable projects. Taken together, these four dimensions ensure that the study contributes to a comprehensive, whole-of-society effort to secure a resilient and sustainable energy transition.

4.3. Research problem, solutions, and theoretical contribution

The results presented in this study respond to a pressing **research problem**: existing scholarship overwhelmingly treats geopolitical risk (GPR) and macro-financial pressures (MFP), such as rising interest rates, as separate drivers of the green energy transition. This binary treatment obscures the reality that these shocks frequently occur in tandem, generating compounded and nonlinear effects. Against the backdrop of the war in Ukraine, escalating hybrid threats to infrastructure, and sustained monetary tightening across Europe, the lack of an integrated analytical framework represents a critical gap in both academic research and policy practice. For the strategically vital GNEEC, this gap has profound implications: without acknowledging the twin nature of these shocks, policymakers, industry actors, and security planners risk misjudging the vulnerabilities and resilience of the green transition.

This study proposes two key **solutions** to the research problem. First, it introduces an innovative dual-impact framework, the Geopolitical–Macrofinancial Twin-Shock Framework, that conceptualizes GPR and MFP not as additive but as interdependent forces. By doing so, it captures the feedback loops revealed in the empirical results: geopolitical disruptions fuel inflationary pressures and monetary tightening, while higher financing costs further magnify the disruptive impact of geopolitical shocks on renewable deployment. Second, the paper applies a distribution-sensitive methodology (MMQR) that uncovers heterogeneous impacts across the renewable energy spectrum. The results clearly show that geopolitical risk acts as a driver of renewable deployment across all quantiles, with effects strengthening in countries with higher levels of renewable penetration. By contrast, interest rate hikes exert a consistently negative impact across the distribution, with the sharpest braking effects at the early stages of transition. These findings demonstrate that the twin shocks are not symmetrical: GPR can accelerate the transition under certain structural conditions, whereas MFP represents a structural brake, particularly for less mature renewable systems.

The **theoretical contribution** of this study lies in extending energy transition research beyond linear or binary models toward a more integrated and dynamic framework of compounded risk. The newly-introduced Geopolitical–Macrofinancial Twin-Shock Framework advances theory in three ways. First, it redefines the nexus between geopolitics, macroeconomics, and sustainability by moving away from isolated analyses toward an interdependent conceptualization. Second, it highlights the distributional nature of these effects, demonstrating that vulnerability and resilience are contingent on transition maturity, institutional capacity, and financial structures. Third, by applying a multidimensional Composite Geopolitical Risk index, the study embeds structural and persistent forms of geopolitical uncertainty into transition analysis, going beyond conventional news-based measures that capture only short-term volatility.

Taken together, these contributions bridge the gap between econometrics and geopolitics, offering a rare interdisciplinary perspective that connects quantitative modelling with the strategic realities of international security and energy policy. The results suggest that resilience in the energy transition cannot be achieved through technological or financial measures alone but requires integrated strategies that account for the compounded pressures of security threats and macro-financial tightening. In this sense, the findings advance the theoretical debate on transition risk and provide practical insights for policymakers, industry stakeholders, and the defense community, who must collectively safeguard the pace and integrity of the green transition in the GNEEC and beyond.

5. Conclusion

The European green energy transition is advancing under unprecedented geopolitical and macro-financial pressures. The Greater North European Energy Corridor (GNEEC) embodies this dual reality: it is both Europe's renewable powerhouse and a frontline of hybrid threats. Proximity to the war in Ukraine, acts of sabotage in the Baltic Sea, and sustained monetary tightening have shown that security shocks and financial constraints rarely occur in isolation. This study demonstrates that their interaction creates compounded, nonlinear risks that undermine investment confidence and expose structural vulnerabilities in the transition.

By introducing the Geopolitical–Macrofinancial Twin-Shock Framework and applying a quantile-based methodology, we show that geopolitical risk, while disruptive, can act as a catalyst in transition-mature economies, accelerating deployment under conditions of strong institutional capacity. In contrast, monetary tightening consistently brakes renewable growth, with the sharpest effects in early-stage systems most sensitive to surging financing costs. These findings highlight that resilience will not emerge spontaneously: it must be deliberately built at the intersection of security, finance, and sustainability.

Looking forward, the GNEEC stands as a strategic testbed for Europe's ability to sustain its decarbonization trajectory under compounded shocks, offering lessons that extend well beyond the region. For policymakers, industry stakeholders, and defense actors, the challenge is clear: to anticipate these twin shocks, design adaptive mechanisms, and ensure that the green transition remains both secure and financially viable.

5.1. Policy implications

The results of this study carry important implications for both macrofinancial policy design and geopolitical/defense planning. By combining quantile-specific insights with a dual focus on financial and security dimensions, we provide recommendations that respond to the heterogeneous vulnerabilities of GNEEC countries at different stages of the energy transition.

5.1.1. Macroeconomic and macrofinancial implications

Our findings confirm that high interest rates exert a consistently negative effect on renewable deployment across all quantiles, with the strongest brake at the lower quantiles. These results call for differentiated policy interventions:

5.1.1.1. Low-quantile countries (early-stage transition). In countries where renewable penetration remains low, the burden of financing costs is particularly acute. Limited market maturity and higher perceived investment risk amplify the sensitivity to interest rates. These countries often lack deep capital markets, stable regulatory frameworks, and credible track records of renewable deployment, making them more dependent on concessional finance and external investors. Policy interventions should therefore prioritize:

- Lowering the cost of capital through public credit guarantees, green development banks, and blended finance instruments.
- Mobilizing international climate finance to de-risk early-stage projects and attract private investors.
- Building investor confidence by strengthening regulatory clarity and reducing policy volatility.
- Targeted subsidies or tax incentives to encourage first movers, coupled with infrastructure investments (e.g., grid upgrades) that lower entry barriers.
- Expanding green-oriented public policy tools and monetary policy support, such as preferential refinancing for banks lending to green projects, central bank green bond purchases, or differentiated reserve requirements to incentivize investment in renewables.

5.1.1.2. High-quantile countries (advanced transition). In economies with already high renewable shares, the negative effect of interest rates is weaker but still relevant. These countries tend to have more sophisticated financial markets, established renewable industries, and greater resilience to financing shocks. However, macrofinancial pressures can still undermine momentum if left unchecked. Policy focus here should shift toward stability and predictability rather than direct subsidies. This includes:.

- Long-term power purchase agreements (PPAs) and inflation-indexed contracts that shield investors from volatility.
- Transparent, rule-based auction frameworks that minimize uncertainty in project costs and risk allocation.
- Green bond markets and sustainable finance taxonomies to broaden funding sources and reduce reliance on bank lending.
- Macroprudential coordination to ensure that climate-related risks are integrated into financial supervision without creating undue tightening of credit for renewable projects.

At the regional level, policymakers should improve transparency in auction frameworks by requiring that all additional costs (including security-related mitigation) are clearly communicated prior to bidding, enabling developers to internalize them in their financial models. In sum, while early-stage transition countries need policies that directly reduce financing costs and de-risk investment to kick-start deployment, advanced transition countries require stable and predictable macrofinancial conditions to sustain momentum and scale up. Tailoring interventions to these different contexts is crucial for aligning macroeconomic and financial systems with long-term energy transition goals.

5.1.2. Geopolitical and defense implications

Geopolitical risk, in contrast, is found to act as a catalyst for the energy transition, especially at higher quantiles where institutional readiness and renewable maturity enable rapid acceleration. Yet this "security booster" effect also creates operational challenges for defense actors and developers. Policy action is needed along the following lines:

5.1.2.1. Low-quantile countries (lagging in renewables). Geopolitical pressures create urgency but can overwhelm weak institutional and infrastructure capacity. These countries should prioritize civil-military coordination early in the planning phase of renewable projects to ensure defense concerns do not stall deployment. Enhancing the civilian-military cooperation and information exchange is critical, by adopting the existing best practices of deploying dual-use technologies, where renewable assets can serve both economic and military needs. At the same time, extending the cooperation with the industry by transposing established North Sea practices to the Baltic Sea region will significantly ease security concerns and encourage new projects, rather than impeding their development. To this goal, mitigation solution are already available in Norway, Belgium, the Netherlands, the UK and Denmark, such as developing air-surface-subsea integrated situational awareness mechanisms, subsea monitoring and early threat detection with the assistance of unmanned devices (AUVs and USVs), the use of drone detection and turbine-friendly radars, mounting sensors on windfarms for visual and acoustic surveillance, or the installation of smart sensors on cables for incident reporting.

5.1.2.2. High-quantile countries (renewable leaders). At advanced stages, geopolitical risk accelerates deployment but also increases the operational overlap between offshore renewable projects and sensitive defense activities. Expanding renewable projects, especially in the offshore sector, can overlap with sensitive military operational areas and thus significantly impact defense activities by interfering with radar and communication systems. Nevertheless, mitigation measures are available and GNEEC stakeholders must prioritize them as a viable alternative to project cancellation. Mitigation should focus on advancing the defense sector-renewable industry cooperation, to integrate scalable technological solutions and on embedding structured civil-military consultation mechanisms into permitting and auction processes. Developers in these markets should be incentivized to integrate defense-compatible technologies from the outset, reducing costly adjustments at a later stage.

At both levels, it is strongly recommended that all relevant GNEEC actors – policymakers, industry stakeholders, energy developers, and defense authorities - actively engage with two key initiatives led by European Defense Agency: the *Consultation Forum for Sustainable Energy in Defense and Security* (CF *SEDSS*)[2] – the largest energy-related defense community in Europe, which facilitates the integration process for sustainable energy into defense planning and infrastructure; and *SYMBIOSIS,*[3] a strategic project aimed at improving the coexistence of offshore renewable energy systems with defense and surveillance capabilities in shared maritime spaces.

5.2. Limitations and future research avenues

While this study sheds new light on the effects of geopolitical risk, macro-financial factors on renewable energy in the GNEEC region, several limitations remain. A key issue lies in the treatment of GPR as a homogeneous factor, typically measured through global indices that lack country-specific context or granularity. This may obscure localized threats such as cyberattacks or infrastructure sabotage that vary in intensity and impact across countries. Moreover, a broader methodological divide persists in literature. Empirical studies often lack geopolitical

[2] https://eda.europa.eu/what-we-do/eu-policies/consultation-forum
[3] https://eda.europa.eu/what-we-do/eu-policies/symbiosis

nuance, while international relations research remains largely qualitative and weak in empirical validation. Future research could strengthen this interdisciplinary approach by incorporating event-based or spatial data, developing more granular risk metrics, and applying asymmetric models to distinguish the effects of positive versus negative shocks. Such efforts would improve our understanding of how evolving geopolitical and financial conditions shape the direction and speed of the energy transition.

Although our study rigorously examines macro-level dynamics of renewable energy deployment, focusing explicitly on the role of geopolitical and macrofinancial risks, we note that the full sustainability of the supply chain -particularly environmental and social externalities associated with critical mineral extraction- must be further explored. For instance, nickel mining to support EV battery production has been found to cause extensive deforestation and biodiversity damage, while the environmentally-safe recycling of decommissioned wind turbines is still a largely unresolved problem. Whilst this lies beyond the current scope of our analysis, we acknowledge that transition outcomes should be evaluated in terms of both scale and sustainability. Future research would benefit from integrating supply-chain lifecycle assessments into econometric models, thereby advancing understanding of not only how fast renewables are deployed, but also how green the transition truly is.

Future research could extend the Geopolitical–Macrofinancial Twin-Shock Framework beyond the GNEEC to other strategically exposed regions, such as the Mediterranean or the Black Sea. Each of these areas faces its own constellation of geopolitical tensions, macro-financial vulnerabilities, and renewable energy trajectories, which makes them suitable testbeds for applying and refining the framework. A comparative application across regions would not only validate its robustness but also reveal context-specific dynamics -for instance, how energy import dependence, financial capacity, or institutional maturity impact the compounded impact of twin shocks. Such cross-regional analysis would deepen our understanding of transition risk and resilience, and contribute to designing globally relevant strategies for securing the green transition under conditions of geopolitical and macroeconomic uncertainty.

CRediT authorship contribution statement

Mehmet Ulug: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Roxana Andrei:** Writing – review & editing, Writing – original draft, Resources, Investigation, Conceptualization, Visualization.

Appendix A. Robustness and sensitivity analyses

A.1. Quantile grid & coverage

Appendix Table A.1 reports MMQR estimates at $\tau \epsilon \{O.25, 0.50, 0.75, 0.90\}$ and a finer grid around the median ($\tau = 0.40 - 0.60$ at 0.05 steps). Fig. A.1 plots the coefficient paths and 95 % CIs across τ. The sign, magnitude, and cross-quantile profile of CGR and INTER remain materially unchanged relative to the baseline $\tau \epsilon \{O.25, 0.50, 0.75, 0.90\}$ grid

Table A.1
Alternative quantile coverage.

Variables	Location	Scale	$Q_{0.25}$	$Q_{0.50}$	$Q_{0.75}$	$Q_{0.90}$
CGR	1.42*	0.25**	1.20*	1.41*	1.70*	1.81*
INTER	−0.36*	0.06*	−0.41*	−0.36*	−0.29*	−0.27*
EG	−1.01*	−0.16*	−0.87*	−1.00*	−1.18*	−1.25*
EI	0.69**	−0.54*	1.17*	0.73**	0.10	−0.13
C	31.02	5.15	26.53	30.66	36.28	38.87

Note: ***p < 0.01,**p < 0.05, *p < 0.10.

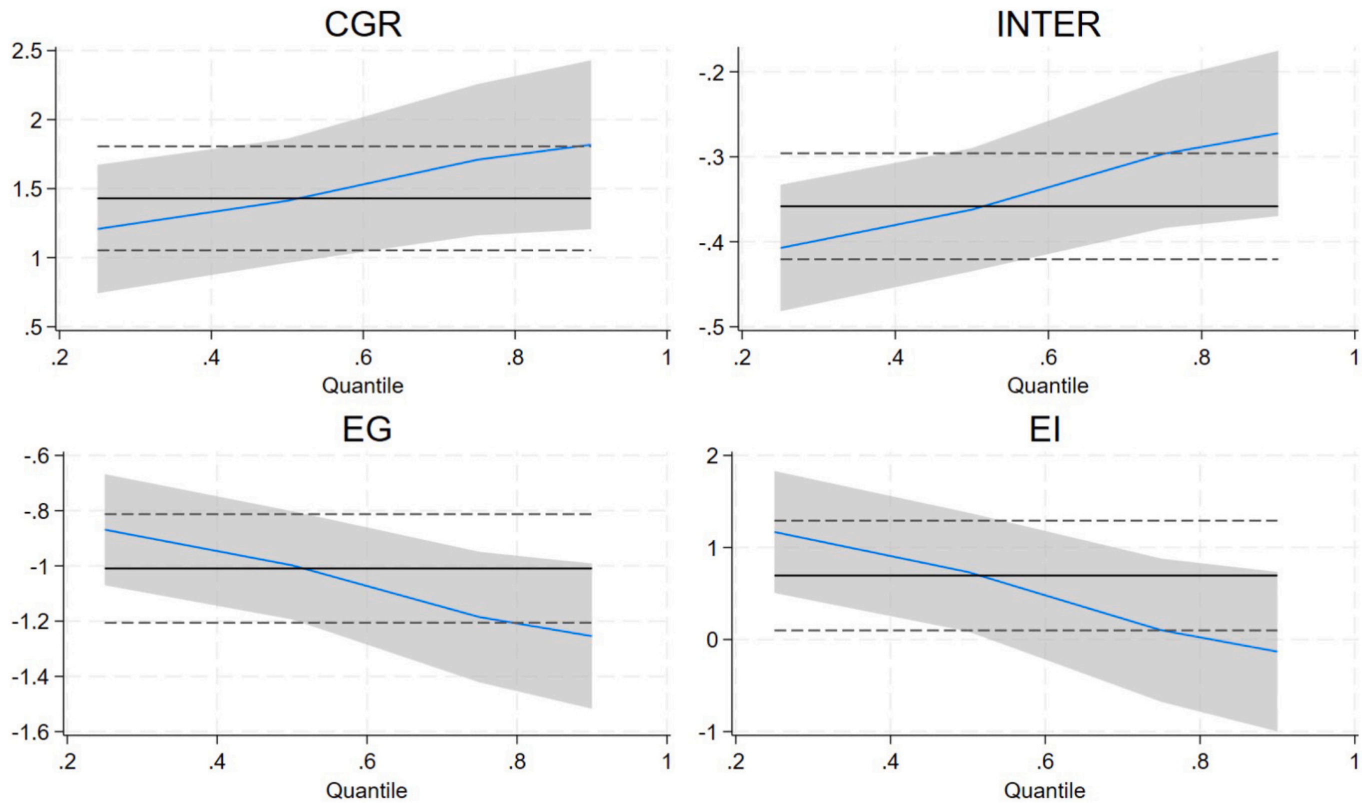

Fig. A.1. MMQR plots of the model ($Q_{0.25}$, $Q_{0.50}$, $Q_{0.75}$, $Q_{0.75}$).

A.2. Leave-one-out check

We re-estimated all MMQR specifications after excluding Belgium from the sample. The signs, significance, and cross-quantile profiles of the CGR and INTER coefficients remain essentially unchanged across $\tau \epsilon \{O.10, \ldots, 0.90\}$; effect magnitudes lie within the original 95 % CIs. (See Appendix Table A.X).

Table A.2
MMQR estimation after excluding Belgium.

Variables	$Q_{0.1}$	$Q_{0.2}$	$Q_{0.3}$	$Q_{0.4}$	$Q_{0.5}$	$Q_{0.6}$	$Q_{0.7}$	$Q_{0.8}$	$Q_{0.9}$
CGR	0.73*	0.76*	0.78*	0.81*	0.85*	0.89*	0.91*	0.94*	0.95*
INTER	−0.37*	−0.35*	−0.33*	−0.31*	−0.29*	−0.26*	−0.24*	−0.22*	−0.21*
EG	−0.85*	−0.88*	−0.90*	−0.93*	−0.97*	−1.01 *	−1.03*	−1.06*	−1.08*
EI	0.99 *	0.83*	0.70*	0.54**	0.36	0.14	−0.00	−0.13	−0.24
C	25.66	26.70	27.61	28.67	29.93	31.44	32.41	33.33	34.06

Note: ***p < 0.01,**p < 0.05, *p < 0.10.

A.3. Alternative proxies for macro-financial pressure

We re-estimate MMQR replacing the long-term interest rate with (i) a short-term market rate and (ii) the policy rate. Results are in Table A.3.1 (point estimates and SEs by τ). Coefficients on the interest-rate proxy (STRATE and LTRATE) are qualitatively unchanged across $\tau \epsilon \{O.10, \ldots, 0.90\}$, confirming that findings are not sensitive to the choice of proxy.

Table A.3.1
MMQR model replacing the long-term rate with a short-term market rate.

Variables	$Q_{0.1}$	$Q_{0.2}$	$Q_{0.3}$	$Q_{0.4}$	$Q_{0.5}$	$Q_{0.6}$	$Q_{0.7}$	$Q_{0.8}$	$Q_{0.9}$
CGR	1.09*	1.15*	1.19*	1.21*	1.25*	1.30*	1.35*	1.40*	1.42*
STRATE	**−0.36***	**−0.32***	**−0.30***	**−0.28***	**−0.26***	**−0.23***	**−0.20***	**−0.17***	**−0.15***
EG	−0.72*	−0.77*	−0.81*	−0.83*	−0.87*	−0.91 *	−0.96*	−1.00*	−1.03*
EI	2.30*	1.80*	1.48*	1.30*	1.01**	0.64	0.18	−0.14	−0.41
C	21.23	23.52	24.53	25.28	26.48	32.85	29.88	31.24	32.34

Note: ***p < 0.01,**p < 0.05, *p < 0.10.

Table A.3.2
MMQR model replacing the long-term rate with the central bank policy rate.

Variables	$Q_{0.1}$	$Q_{0.2}$	$Q_{0.3}$	$Q_{0.4}$	$Q_{0.5}$	$Q_{0.6}$	$Q_{0.7}$	$Q_{0.8}$	$Q_{0.9}$
CGR	1.22*	1.22*	1.22*	1.22*	1.22*	1.22*	1.22*	1.22*	1.22*
CBRATE	**−0.37***	**−0.34***	**−0.30***	**−0.28***	**−0.26***	**−0.23***	**−0.19***	**−0.17***	**−0.14***
EG	−0.79*	−0.82*	−0.84*	−0.85*	−0.87*	−0.88 *	−0.91*	−0.93*	−0.94*
EI	2.21*	1.78*	1.41*	1.18*	0.89**	0.52	0.06	−0.25	−0.51
C	23.11	24.19	25.10	25.68	26.40	27.31	28.46	29.24	29.91

Note: ***p < 0.01,**p < 0.05, *p < 0.10.

A.4. Driscoll-Kraay standard errors

To verify the consistency of the MMQR results, a robustness analysis was conducted using the DK standard error approach. As shown in Table A.3, the results align closely with the core findings of the quantile analysis.

Table A.4
Robustness check via Driscoll-Kraay standard errors.

Variables	Coeff.	Std. Err.	t-stat	p-value
CGR	1.42	0.426	3.36	0.002
INTER	−0.35	0.040	−8.81	0.000
EG	−1.01	0.126	−7.95	0.000
EI	0.69	0.776	0.90	0.377
C	31.02	3.529	8.79	0.000

Note: ***p < 0.01,**p < 0.05, *p < 0.10.

A.5. Bootstrap Quantile Regressions (BSQR)

We complemented DK inference with Bootstrap Quantile Regressions (BSQR) across $\tau \epsilon \{0.10, \ldots, 0.90\}$. The BSQR results closely track the MMQR patterns, with the signs and cross-quantile profiles of the CGR and interest-rate coefficients remaining qualitatively unchanged. This provides an estimator that does not depend on the same large-T approximation and supports the robustness of our conclusions. (See Table A.5 and Fig. A.2.)

Table A.5
Bootstrap Quantile Regression (BSQR)

Variables	$Q_{0.1}$	$Q_{0.2}$	$Q_{0.3}$	$Q_{0.4}$	$Q_{0.5}$	$Q_{0.6}$	$Q_{0.7}$	$Q_{0.8}$	$Q_{0.9}$
CGR	0.50***	1.43*	1.50*	1.59*	1.81*	2.09*	2.47*	1.42*	0.81*
INTER	−0.38*	−0.47*	−0.45*	−0.42*	−0.38*	−0.37*	−0.35*	−0.22*	−0.17*
EG	−0.11	−0.73*	−0.79*	−0.85*	−1.07*	−1.10*	−1.10*	−0.91*	−0.89*
EI	2.23	0.87**	0.38	0.95	0.25	0.70	−0.25	−0.05	0.03
C	5.39	23.08	26.51	32.94	30.66	33.94	34.32	29.05	28.68

Note: ***p < 0.01, **p < 0.05, *p < 0.10.

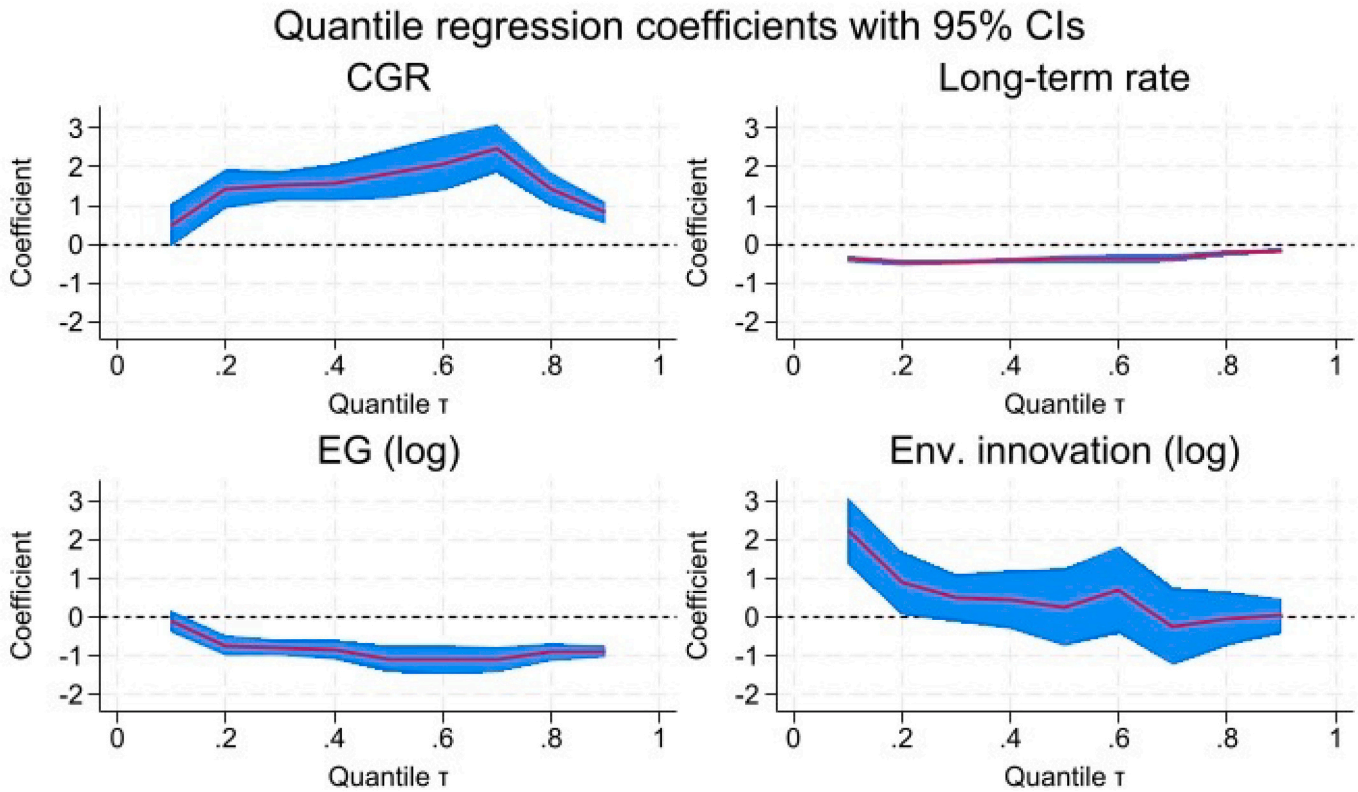

Fig. A.2. Graphical illustration of coffecieints obtained from Bootstrap Quantile Regressions.

Appendix B. Data & measurement: composite geopolitical risk

B.1. Why CGR over traditional GPR?

News-based indices capture short-run salience but miss persistent institutional/military shifts. By construction, CGR embeds both level (structural) and shock (news) dimensions, yielding a more policy-relevant signal for long-horizon energy transitions. In our sample, the structural block prevents over-weighting transient headlines and improves cross-country comparability. To proxy geopolitical conditions relevant for energy policy and investment, we construct a country-specific CGR series that integrates (i) a structural component—slow-moving internal and external risks—and (ii) a news-based component (conventional GPR). This follows Jiménez et al. (2025), which models both the internal situation (democracy, rule of law, inequality, military readiness) and the external environment (political risk, ideological distance, and military risk of other countries weighted by contiguity, geographic proximity, and rivalry). This allows CGR to reflect long-run geopolitical shifts as well as high-frequency shocks.

B.2. Internal structural risk

We standardize institutional and military indicators and aggregate them with the weights specified by Jiménez et al. (2025) to obtain an annual internal risk index per country. Note also that while internal structural risk of Jiménez et al. (2025) draws on indicators such as electoral democracy, rule of law, and military expenditure/GDP, in our construction we excluded inequality due to data gaps.

B.3. External structural risk

For every country–year, we compute weighted averages of other countries' political risk, ideological distance, and military risk using the contiguity / proximity / rivalry weighting scheme in Jiménez et al. (2025):

External political risk:

$$0.4 \times \mathit{Pol.Risk}\ \text{contiguous} + 0.2 \times \mathit{Pol.Risk\ Neighbors} + 0.4 \times \mathit{Pol.Risk\ Rivals}$$

External Ideological Distance Risk:

$$0.4 \times \mathit{Ideol.Dist.Contiguous} + 0.2 \times \mathit{Ideol.Dist\ Neighbors} + 0.4 \times \mathit{Ideol.Dist\ Rivals}$$

External military risk:

$$0.4 \times \mathit{Mil.Risk.Contiguous} + 0.2 \times \mathit{Mil.Risk\ Neighbors} + 0.2 \times \mathit{Mil.Risk\ Rivals} + 0.2 \times \mathit{Mil.Gap\ vs\ RoW}$$

While this framework was originally developed by Jiménez et al. (2025), our construction focuses only on the political and military components, excluding external ideological distance risk. We then aggregate these into an external risk index and combine internal and external risks into Structural

Geopolitical Risk (SGR).

B.4. Composite index

Finally, we merge the structural SGR with a news-based GPR measure (standardized) to obtain CGR, which better tracks episodes where structural tensions amplify or dampen media-driven spikes. This composite delivers country-specific annual series suited to cross-country panels. Using our country panel (Belgium, Denmark, Finland, Germany, Netherlands, Norway, Sweden, UK; 1987–2023), we standardized internal inputs (electoral democracy, rule of law; military expenditure ratios); built external political/military via the Jiménez et al. (2025) weights; formed annual SGR by combining internal and external risks; and combined SGR with a standardized news-based GPR to obtain CGR.

Appendix C. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eneco.2025.108949.

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