How green growth affects environmental quality in some Central and Eastern European countries: an asymmetric analysis

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Previous studies overlooked the impact of green growth (GRE) on load capacity factors (LCF). Additionally, environmental modelers, especially in the Central and Eastern European (CEE) countries, did not account for LCF perspectives. Notably, LCF provides valuable insights into the unique dynamics of the natural environment's demand and supply sides. This study explores the asymmetric association between these indicators using quantile-on-quantile regression (QQR) and spectral Granger causality approaches. The empirical findings highlight that GRE exerts a negative impact on LCF in the low and middle quantiles of LCF, whereas it has a positive effect in the higher quantiles of LCF across all GRE quantiles in the CEE countries. In addition, there are causal linkages between GRE and LCF over the range of time frames such as the short, middle and long runs. The paper concludes with comprehensive policy recommendations aimed at improving environmental quality.

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Introduction

Sustainable development is a comprehensive concept that encompasses ecological, social, and economic dimensions (Saleem et al. 2022). It extends beyond mere economic growth, which focuses on quantitative expansion, by incorporating structural enhancement and qualitative improvement. Sustainable development is a framework that can fulfill current needs while ensuring future generations can also meet their own needs without compromise (Abid et al. 2022). In this context, the United Nations (UN) 2030 Agenda for Sustainable Development outlined 17 goals that all UN member states must strive to achieve as an urgent call to action. Successfully attaining these Sustainable Development Goals (SDGs) can help pave the way for sustainable growth by addressing the imbalance between economic development and environmental sustainability (Dogan et al. 2022).

In the quest to develop effective sustainable development strategies, recent research has increasingly focused on identifying the factors driving environmental degradation within the UN SDG framework. In this context, studies have used CO_2 emissions and ecological footprint (EF) as response variables, as both indicators offer some insights into environmental degradation (Razzaq et al. 2023, Sun et al. 2022). However, CO_2 emissions have been criticized by scholars for primarily reflecting the impact of energy consumption, given that emissions largely stem from fossil fuel combustion (Gattone et al. 2025). In contrast, the EF measures human demand for natural resources across six land-use categories and is a more comprehensive indicator of resource consumption (Wei et al. 2024). Nevertheless, while EF effectively represents demand, it overlooks the supply factor (biocapacity), which reflects the planet's ability to generate resources and absorb waste. Neglecting biocapacity in assessments may produce an incomplete evaluation of environmental degradation (Pata et al. 2023).

In contemporary research, green growth (GRE) and load capacity factor (LCF) are interconnected concepts that have a significant influence on sustainable development (Caglar et al. 2024). As noted above, GRE is intended to promote economic development while ensuring the sustainable use of natural resources (Raihan et al. 2025, Ramesh et al. 2024). In contrast, the LCF quantifies system or resource utilization efficiency, indicating how effectively it is used over time (Huttmanová et al. 2019, Kasztelan 2017, Lu et al. 2024).

Accordingly, this study examines the relationship between GRE and environmental degradation using the widely recognized LCF variable as a proxy for environmental quality. Recent research suggests that this indicator is a more suitable alternative to EF or CO_2 emissions, as it encompasses supply and demand considerations, providing a more comprehensive measure of environmental quality (Jin et al. 2024, Dilanchiev et al. 2024). As a result, the findings and policy recommendations of this study are expected to be more impactful than those based on traditional environmental indicators.

This study focuses on some Central and Eastern European (CEE) countries – Hungary, Croatia, Romania, Poland, and the Czech Republic – as a case study, given these countries' active pursuit of GRE to promote sustainable development, reduce reliance on fossil fuels, and improve energy efficiency (Mengxuan et al. 2024, Bartha–Matarrese 2024, Hung 2022). These nations have faced the considerable challenge of modernizing outdated and inefficient energy infrastructure, and have strong incentives to advance GRE and adopt technological innovations (Dong et al. 2022). Consequently, this study investigates the relationship between these indicators, emphasizing the urgent need to examine these connections for effective strategy development. By analysing the impact of GRE on environmental quality in the CEE region, our findings contribute valuable insights to research on green investment and environmental responsibility, highlighting their influence on fostering a sustainable future. The originality of our approach, combined with a comprehensive analysis of how green innovation influences environmental quality through the lens of GRE, underscores the study's significance for shaping a more sustainable and environmentally conscious economic framework in the CEE region.

The rapid expansion of GRE has garnered significant attention from researchers and scholars worldwide. Numerous studies have explored the intrinsic relationship between GRE and environmental quality, concluding that shifts in GRE substantially influence environmental conditions (Razzaq et al. 2023, Wei et al. 2023, Lin–Ullah 2024, Jiang et al. 2024, Nguyen–Khominich 2024). However, the majority of existing research has primarily focused on changes in CO_2 emissions and EF, largely neglecting the influence of LCF. According to Zahra et al. (2025), GRE has a significant influence on mitigating environmental degradation. Therefore, we examine the heterogeneous effects of GRE on LCF in CEE economies, providing policymakers with valuable insights for developing effective energy policies that support the sustainable development of the clean energy market.

While some studies have explored this topic, most mainstream research on the CEE countries employs advanced econometric techniques (e.g. (Neagu–Neagu 2024). Quantile-on-quantile regression (QQR) and the spectral Granger causality test are not explicitly mentioned. In this context, this study is intended to bridge these research gaps by examining the relationship between GRE and environmental quality in the CEE countries using quantile- and frequency-based methodologies.

This study contributes to existing literature in several ways. First, recognizing the significant impact of GRE on environmental quality, we conduct a comprehensive analysis using an extensive dataset spanning 1991–2022. Second, unlike previous studies that have primarily used CO_2 emissions or EF as environmental quality indicators, we employ the LCF index for a more in-depth assessment. To achieve this, the study uses the QQR model and the spectral Granger causality test, both of which are robust against misspecification errors, structural breaks, and frequent outliers – common challenges in economic time series analysis (Cheng et al. 2022, Su et al. 2019). The QQR method offers greater flexibility than standard quantile regression by providing a holistic view of the GRE–LCF relationship across different quantiles and economic conditions (Qureshi et al. 2020). Unlike ordinary least squares, QQR allows the dependence parameter to vary across quantiles, offering a more nuanced understanding of this relationship. We also apply the spectral causality test to examine the causal dynamics between GRE and LCF, uniquely capturing causality across short-, medium-, and long-term time horizons.

This study enhances existing literature by examining the asymmetric relationship between the selected variables in the CEE countries. The findings reveal a significant connection between GRE and LCF across various quantiles and frequencies. Emphasizing the critical role of GRE investment, our findings also provide valuable insights for policymakers seeking to achieve SDGs in the CEE countries.

The remainder of this paper is structured as follows. First, the study provides an overview of the related literature, then the methodology and data used are outlined, followed by a presentation and discussion of the empirical results. Finally, the study concludes with a summary of the key findings and practical policy recommendations.

Literature review

GRE primarily highlights the process of making an economy more environmentally sustainable and efficient. While it differs in focus from concepts like the circular, low-carbon, and ecological economies, its fundamental essence remains the same (Lin−Ullah 2024). At its core, GRE promotes a holistic approach to ensure balanced and sustainable development across the economy, society, ecological environment, and natural resources. To accelerate the balanced development of economic growth and environmental sustainability, local governments will introduce policies and regulations to reduce carbon emissions and promote green innovation, cultivating a supportive policy environment for GRE (Dogan et al. 2022, Li et al. 2022, Abid et al. 2022).

GRE is a crucial necessity in light of the increasing natural disasters worldwide (Lin−Ullah 2024). One of its key advantages is the simultaneous promotion of economic growth and environmental sustainability, implying that economies striving for higher income levels can prioritize GRE without significantly harming the environment (Zahra et al. 2025). Various strategies can enhance GRE, including the adoption of renewable energy sources, technological innovation, and investment in human capital (Wei et al. (2024).

A significant framework for assessing the balance between environmental sustainability and economic growth is the environmental Kuznets curve (Simionescu 2021), which has been empirically analysed in multiple settings (Li et al. 2022, Sun et al. 2022, Marinaș et al. 2018). Additionally, increased GRE directly boosts renewable energy production while reducing reliance on fossil fuels (Razzaq et al. 2023). These developments contribute to lowering emissions and enhancing economies' environmental sustainability.

GRE is one of the most effective strategies for reducing environmental degradation, conserving energy resources, boosting economic growth, and lowering carbon emissions. Subsequently, various countries are endeavouring to advance the integration of green energy into their economies. Hao et al. (2021) examined the impact of GRE on carbon dioxide (CO_2) emissions in G7 countries from 1991 to 2017, finding that the linear and nonlinear terms of GRE contribute to reducing CO_2 emissions. Dogan et al. (2022) assessed the effects of GRE and environmental taxes on CO_2 emissions, incorporating sustainability indicators for 25 eco-friendly countries. The findings demonstrated that the coefficients for GRE, environmental taxes, renewable energy, and energy efficiency are negative across lower, medium, and higher quantiles. Saleem et al. (2022) studied the effects of GRE, income, environmental taxes, eco-friendly technology, renewable energy, and financial development on CO_2 emissions across 12 Asian economies, confirming that CO_2 emissions are significantly influenced by GDP growth, GRE, and technological advancements. Li et al. (2022) examined the impact of green investment, economic growth, technological innovation, non-renewable energy consumption, and globalization on CO_2 emissions in Mexico, Indonesia, Nigeria, and Turkey (MINT countries) between 2000 and 2020. The results revealed that globalization and green investment have a significant influence on lowering long-term CO_2 emissions. Abid et al. (2022) concentrated on Pakistan, determining that energy consumption is an obstacle to GRE development amid the country's environmental challenges because the nation's energy mix is primarily composed of fossil fuels rather than renewables. Similarly, Lin–Ullah (2024) demonstrated that GRE contributes to a long-term reduction in environmental pollution in Pakistan. Bhat et al. (2022) investigated the relationship between climate change, economic growth, and energy consumption in G20 countries, considering the influence of green energy. The authors revealed negative and significant elasticity in renewable energy, indicating that increased renewable energy consumption will enhance environmental quality.

Razzaq et al. (2023) investigated the impact of energy transition and environmental governance using renewable energy investments and human development, finding that environmental regulation has a significant positive effect on GRE. Wei et al. (2023) examined the effects of renewable energy consumption, green economic growth, green technology, green trade, and inward financial flow on environmental quality in the world's leading green future economies. The study demonstrated a bidirectional relationship between GRE and green technologies that contribute to a cleaner and more sustainable environment. Zhao et al. (2023) analysed the potential impact of GRE on CO_2 emissions in China, determining that it has initial positive outcomes, with a significantly negative effect on CO_2 emissions. Sun et al. (2022) found that CO_2 emissions decrease by 0.262% due to positive shocks in green technology, while negative shocks increase emissions by 0.104%. Wei et al. (2024) explore the impact of financial technology, natural resources, green finance, and GRE on environmental sustainability in Brazil, Russia, India, China, and South Africa (BRICS countries), demonstrating that green finance and GRE serve as key mechanisms for enhancing environmental sustainability. Lin–Ullah (2024) demonstrated that GRE reduces long-term environmental contamination in the long run in BRICS countries. Jiang et al. (2024) found that investing in environmental protection and cleaner energy research and development (R&D) has a significant impact on reducing carbon emissions. Zahra et al. (2025) examined how GRE, green technological innovations, agricultural eco-efficiency, and trade openness contribute to carbon neutrality in the three countries (China, USA, India) with the highest carbon emissions. The authors demonstrated a significant U-shaped relationship between carbon emissions and GRE and green technological innovation.

Several studies have examined the economic growth–environment relationship in the CEE countries. For example, Marinaş et al. (2018) explored the relationship between economic growth and renewable energy consumption in 10 European Union member states. Dong et al. (2022) illustrated a nonlinear relationship between renewable energy and carbon emissions efficiency (CaEE) in optimizing the energy transition pathway. The findings revealed that while renewable energy development enhances CaEE, a significant threshold effect exists, indicating that the impact varies depending on specific conditions and renewable energy adoption levels. Pata et al. (2023) found that renewable energy enhances short- and long-term LCF, whereas globalization and economic growth negatively affect LCF over the long term. Jin et al. (2024) examined the effects of renewable energy, energy efficiency, nuclear energy R&D, and financial globalization on LCF. The findings revealed that green energy and energy efficiency R&D contribute to LCF by improving ecological quality. Their findings indicated a shift toward a new energy paradigm in the short term, while analysed factors moved toward equilibrium in the long term. Dilanchiev et al. (2024) analysed the relationship between green finance, financial openness, and environmental quality, revealing that CO_2 emissions in the CEE countries are still increasing, and financial openness is a significant contributor to rising emissions. However, the study also showed that green finance implementation counteracts the negative environmental effects of financial openness by reducing its impact on CO_2 emissions. These results emphasize the importance of integrating sustainable financial practices to mitigate environmental degradation in financially open economies. Mengxuan et al. (2024) demonstrated a causal link between technological innovation and energy efficiency wherein energy efficiency is directly influenced by the rate at which innovations are adopted.

In summary, previous studies have primarily focused on the relationship between GRE and environmental quality, with findings largely limited to the CEE countries and environmental and economic implications. While existing research has predominantly examined the impact of GRE on CO_2 emissions, few studies have systematically explored its connection to LCF (an example: Balsalobre-Lorente et al. 2025). Furthermore, recent studies have shifted from analysing the long-term effects of GRE on LCF to investigating cost-effective energy transition strategies (e.g. Duran−Saqib 2024, Harvey 2020, Pang et al. 2024). To address this gap, our study systematically examines the quantile-frequency relationships in the CEE countries.

Methodology

This section describes the methodological framework employed in the study, which is uses two principal techniques – the QQR and the spectral (frequency-domain) Granger causality test. These approaches are employed to capture nonlinear asymmetric relationships and dynamic causal interactions between GRE and LCF. A detailed explanation and justification of these methods are provided below.

Quantile-on-quantile regression

Sim–Zhou (2015) introduced the QQR approach as an extension of quantile regression, designed to assess how the quantiles of an independent variable affect the corresponding quantiles of a dependent variable. This method integrates nonparametric and QQR techniques, offering a more detailed analysis of their relationship across different distribution levels.

The QQR model is particularly suitable for this study because it estimates asymmetric and heterogeneous influences that conventional linear or quantile regressions cannot detect (Özkan−Destek 2025). In the context of the CEE countries, the effect of GRE on LCF is unlikely to be uniform. Economies at different stages of development, or those experiencing varying levels of environmental stress are expected to respond differently to GRE policies. QQR accommodates these heterogeneous responses by exploring how specific quantiles of GRE influence corresponding quantiles of LCF (Sim−Zhou 2015, Özkan−Destek 2025).

The following equation is the nonparametric QQR model:

$$LCF_t = \gamma^{\sigma}(GRE_t) + \mu_t^{\sigma} , \tag{1}$$

where GRE_t represents GRE at time t, LCF_t denotes environmental quality at time t, σ is the σ^{th} quantile of the GRE, and the quantile error term μ_t^{σ} has a conditional σ^{th} quantile that is equal to zero. γ^{σ} is the unidentified function because we do not have previous knowledge of the nexus across the markets under consideration.

Selecting the appropriate bandwidth is crucial in a nonparametric analysis as it directly influences the smoothness of the estimates. A larger bandwidth increases bias, while a smaller bandwidth leads to greater variance in the estimates. Striking the right balance between bias and variance is essential for accurate estimation. This study applies bandwidths of h = 0.05h = 0.05h = 0.05 (Sim–Zhou 2015) due to bandwidth constraints.

Spectral Granger causality test with the frequency-domain approach

To complement the QQR findings, we employ the spectral Granger causality test developed by Breitung–Candelon (2006) to examine causal links between GRE and LCF in the frequency domain. Unlike traditional Granger causality tests, which solely operate in the time domain, the spectral approach decomposes causal associations into different frequency bands to identify short-, medium-, and long-term interactions between variables.

This technique has two key advantages. First, it provides greater flexibility in modelling the persistence of causal effects, distinguishing between transient and enduring connections (Mutascu 2023, Kassi et al. 2024). Second, it considers seasonal fluctuations and cyclical behaviours in economic–environmental systems; an essential consideration for the CEE countries, where policy impacts may manifest differently over time horizons (Ullah et al. 2024).

The integration of QQR and spectral causality enables a multidimensional understanding of the GRE–LCF relationship. Rooted in the time domain, the QQR model identifies distributional asymmetries and nonlinear impacts across quantiles of the time series. In contrast, the spectral causality test, grounded in the frequency domain, examines temporal dynamics by distinguishing between causal influences over short-, medium-, and long-term horizons. In doing so, these techniques provide a more comprehensive analysis than traditional mean-based or time-domain-only models, revealing cross-sectional heterogeneity and temporal persistence in the interplay between green growth and environmental quality.

Data

Our data span 1991–2022 for selected CEE countries, with the choice of countries and timeframe constrained by data availability. This study uses quarterly data to examine the relationship between green growth and the LCF. We measure GRE as production-based CO_2 emissions in percentage, and the data are sourced from the Organization for Economic Co-operation and Development. LCF data are obtained from the Global Footprint Network database.

Annual data limitations restrict the feasibility of conducting this type of analysis, which requires high-frequency data, preferably at a quarterly level. To increase the number of observations, we converted annual data to a quarterly frequency using the quadratic match-sum method referencing Hung (2022). All variables were subjected to log transformation to achieve distributional normalization and minimize the effect of outliers, thereby improving model readiness.

Table 1

Descriptive statistics

Variables	Mean	Median	Maximum	Minimum	SD	Skewness	Kurtosis	Jarque–Bera
Hungary								
LCF	1.576931	1.576759	1.893909	1.333287	0.141095	0.056329	2.043812	3.553449**
GRE	0.172380	0.073242	0.697180	−0.02318	0.203828	1.175660	3.200041	21.34675***
Romania								
LCF	1.330354	1.322222	1.626984	0.944123	0.127961	0.386636	3.758592	4.498069
GRE	0.266776	0.264754	0.898430	−0.04531	0.228873	0.657725	2.904799	6.667969***
Czech Republic								
LCF	2.088009	2.069643	2.498696	1.868802	0.135913	0.752132	3.673385	10.41233*
GRE	0.672918	0.644589	1.936467	−0.04505	0.460529	0.830520	3.415191	11.23719
Poland								
LCF	1.618490	1.610345	1.732568	1.533842	0.053178	0.323144	2.103527	4.681848*
GRE	0.908333	1.052668	2.464844	−0.03255	0.633279	0.337426	2.319449	3.521201**
Croatia								
LCF	1.546654	1.551356	1.785427	1.247488	0.094995	−0.26532	4.613594	11.06019**
GRE	0.152173	0.096875	0.604158	−0.02318	0.151786	1.001460	3.591341	16.71859**

Note: *, **, and *** denote the significance at 10%, 5%, and 1% levels, respectively.

Table 1 presents the descriptive statistics for all study indicators, measured in natural logarithm. Average values indicate that LCF has a higher mean than GRE across the selected economies, with Czechia and Poland exhibiting the highest scores. Additionally, standard deviation (SD) values suggest no substantial deviations from the mean, implying that the data points are closely aligned with the average. Kurtosis and skewness results confirm that both variables in the selected countries deviate from a normal distribution. Moreover, the Jarque–Bera test is statistically significant for all variables, rejecting the null hypothesis of normality. This finding supports the application of nonlinear econometric methods for our analysis.

We employ a nonlinear quantile unit root test to assess the variables' stationarity and stationarity properties. The results of this test are presented in Table 2, which includes the persistence parameter coefficient and t-statistics for all-time series. The results confirm that all examined indicators exhibit nonstationary behaviour at the level series. Moreover, the persistence parameter coefficient remains close to zero across all quantiles in each country, further confirming the presence of nonstationary characteristics at the level series.

Table 2

Quantile autoregression unit root analysis

τ	LCF		GRE		LCF		GRE	
	$\hat{\alpha}$	t-statistic	$\hat{\alpha}$	t-statistic	$\hat{\alpha}$	t-statistic	$\hat{\alpha}$	t-statistic
	Hungary				Romania			
0.05	−2.8550	2.8245	−2.6568	0.8335	−3.0174	6.5043	−2.8633	−1.1627
0.10	−3.1417	−0.4440	−2.4874	−0.2005	−3.3952	−1.1875	−2.8712	1.6078
0.15	−3.2967	−0.3548	−2.6267	−2.4913	−3.2523	−0.8318	−3.0783	1.1029
0.20	−3.3850	−0.3967	−2.6160	−3.4916	−3.4100	−0.5796	−3.1749	0.5038
0.25	−3.4100	−0.5328	−2.6277	−6.2859	−3.4100	−0.6765	−3.1782	0.0403
0.30	−3.4100	−0.7952	−2.6773	−7.4750	−3.4100	−1.5533	−3.4100	−0.4469
0.35	−3.4100	−0.8411	−2.7626	−8.4982	−3.4100	−1.4433	−3.3700	−0.4647
0.40	−3.4100	−1.0667	−2.7674	−4.1930	−3.4100	−1.4229	−3.4100	−0.6842
0.45	−3.4100	−1.4058	−3.1820	−5.7226	−3.4100	−1.2112	−3.4100	−0.3101
0.50	−3.4100	−2.1309	−3.3604	−9.4232	−3.4100	−1.1514	−3.4100	−0.4790
0.55	−3.4100	−1.6767	−3.2684	−7.8695	−3.4100	−1.3698	−3.4100	−0.7436
0.60	−3.4100	−1.2073	−3.2480	−6.8099	−3.4100	−0.8748	−3.4100	−0.8617
0.65	−3.4100	−0.7630	−3.2929	−8.2805	−3.4100	−0.8736	−3.4100	−3.2227
0.70	−3.4100	−0.9398	−3.2767	−8.3447	−3.4100	−0.7847	−3.4100	−4.9439
0.75	−3.4100	−1.1637	−3.1252	−10.5036	−3.4100	−1.1481	−3.3736	−4.2274
0.80	−3.4100	−1.5325	−3.1434	−14.7485	−3.4100	−2.5199	−3.0433	−5.0604
0.85	−3.4100	−0.6892	−3.1301	−17.8386	−3.3187	−2.2025	−3.4100	−4.9216
0.90	−3.2267	−0.7416	−2.6571	−31.8993	−3.2690	−1.6096	−2.9054	−5.2708
0.95	−2.7828	2.1650	−2.3100	7.2413	−2.7441	1.7811	−3.2359	3.3207
	Poland				Croatia			
0.05	−2.5277	−1.8022	−3.3013	−3.3218	−2.3100	−2.1384	−2.3231	−4.3470
0.10	−2.8021	0.0796	−2.9318	0.8081	−3.1782	−2.5274	−3.0226	0.5632
0.15	−3.3089	−0.2707	−2.9294	0.6354	−3.4100	−2.6439	−3.0084	0.3566
0.20	−3.2451	−0.4491	−3.3490	0.3823	−3.4100	−3.7396	−3.1028	−0.5004
0.25	−3.4100	−0.7655	−3.3496	0.3478	−3.4100	−3.5627	−3.1933	−0.5422
0.30	−3.4100	−0.8784	−3.4100	0.2978	−3.4100	−3.7660	−3.3729	−0.4853
0.35	−3.4100	−0.5708	−3.4100	−0.4028	−3.4100	−3.6343	−3.4100	−0.5214
0.40	−3.4100	−0.8636	−3.4100	−1.7528	−3.4100	−3.2463	−3.4100	−0.8422
0.45	−3.4100	−1.1156	−3.4100	−1.5106	−3.4100	−3.6556	−3.4100	−3.2128
0.50	−3.4100	−1.1635	−3.4100	−1.4033	−3.4100	−3.3206	−3.4100	−3.1825
0.55	−3.4100	−1.4793	−3.4100	−1.4091	−3.4100	−2.7779	−3.4100	−3.9187
0.60	−3.4100	−1.3786	−3.4100	−1.6248	−3.4100	−2.7727	−3.4100	−3.5484
0.65	−3.4100	−1.4635	−3.3916	−1.4916	−3.4100	−2.0889	−3.4100	−4.3996
0.70	−3.4100	−1.7531	−3.2839	−3.1228	−3.4100	−2.0747	−3.3718	−4.9114
0.75	−3.4100	−1.1862	−2.9914	−4.8392	−3.4100	−1.6333	−3.3405	−5.4174
0.80	−3.4100	−0.6415	−2.6646	−4.2349	−3.4100	−0.7074	−3.4100	−6.1824
0.85	−3.4100	0.2960	−2.4225	−5.8824	−3.1130	−0.7962	−3.4100	−3.2124
0.90	−3.4100	−1.1976	−2.5923	−6.5056	−3.1843	0.6082	−2.9682	−3.3721
0.95	−3.3294	−0.6467	−2.3100	3.8890	−3.0945	−2.7727	−2.8446	3.6297

(Table continues on the next page.)

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τ	LCF		GRE	
	$\widehat{\alpha}$	t-statistic	$\widehat{\alpha}$	t-statistic
	Czech Republic			
0.05	−2.9689	2.7112	−3.0464	−3.3574
0.10	−3.1883	−1.2898	−3.2099	0.3392
0.15	−3.2346	−0.7127	−3.2243	0.2035
0.20	−3.4100	−0.4710	−3.3417	0.4952
0.25	−3.4100	−0.5050	−3.4100	−0.8395
0.30	−3.4100	−0.6220	−3.4100	−0.6046
0.35	−3.4100	−1.1221	−3.4100	−0.7987
0.40	−3.4100	−1.3177	−3.4100	−0.8445
0.45	−3.4100	−1.6171	−3.4100	−0.8318
0.50	−3.4100	−2.3967	−3.4100	−1.0301
0.55	−3.4100	−3.2251	−3.4100	−1.6192
0.60	−3.4100	−3.7952	−3.4100	−0.8967
0.65	−3.4100	−3.5152	−3.4100	−2.6015
0.70	−3.4100	−4.0394	−3.3450	−2.8644
0.75	−3.4100	−3.7018	−3.0496	−2.4307
0.80	−3.4100	−2.3870	−2.8506	−2.6617
0.85	−3.2620	−0.8507	−2.7723	−4.3766
0.90	−3.3294	−0.7152	−2.7543	−3.7857
0.95	−3.2704	3.5397	−2.3818	3.6837

Note: this table presents point estimates and t-statistics at the 5% significance level.

Table 3

Quantile cointegration test

τ	β	γ	β	γ	β	γ	β	γ
	Hungary		Romania		Poland		Croatia	
0.05	0.0088	2.0945	0.1071	21.6288	2.6486	1.0607***	0.3481	1.2558
0.10	0.1503	14.3143	0.0414	9.1128	3.5484	1.8604	0.6544	1.7768
0.15	0.2095	10.5447	0.2315	11.9292	3.9352	5.7394	0.8446	2.0250
0.20	0.3532	9.7991	0.2349	11.4114	2.7776	2.1811	1.0472	2.2311
0.25	0.2398	5.3662	0.3416	10.7031	5.2813	2.6877	1.0402	0.8517***
0.30	0.1738	0.6493***	0.7837	9.8760	5.0672	2.9417	0.8290	3.1145
0.35	0.1342	2.7165	0.8200	9.6901	4.4741	3.1918	0.8815	3.9901
0.40	0.0874	4.5891	0.7622	7.1938	5.1581	3.5474	0.8670	3.5554
0.45	0.1641	5.0222	0.8880	7.0786	4.3899	3.9033	1.0076	0.9153***
0.50	0.3977	2.2028	0.8236	6.1083	4.0996	4.1287	0.7653	0.5895***
0.55	0.6171	1.9921	0.8326	5.2974	4.4325	4.2950	0.6751	1.2438
0.60	0.6087	3.1857	0.8959	4.9670	3.3158	4.7162	0.7765	0.8856***
0.65	0.9010	2.5759	0.6597	0.7870***	2.9951	5.3524	0.8426	0.7212***
0.70	1.1193	2.2448	0.8748	3.0867	2.1714	6.1033	0.9398	2.4742
0.75	1.0860	3.0481	0.9750	3.0893	2.5814	7.1026	0.9902	2.0401
0.80	0.7395	1.7702	1.1532	3.1430	2.6361	8.5349	1.0387	1.0814***
0.85	0.5170	1.6932	1.2246	2.3026	0.4534	12.7443	1.4049	2.6383
0.90	0.7875	1.4359	1.6698	2.2657	−1.5736	10.2616	1.6118	2.5141
0.95	1.0257	1.1933***	2.1073	2.3660	−7.4527	12.6477	1.2672	4.4168

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τ	β	γ
	Czech Republic	
0.05	−0.5151	2.1473
0.10	−0.5786	1.9320
0.15	0.1330	2.2972
0.20	0.4671	1.8760
0.25	0.8810	3.2870
0.30	0.8916	1.0089***
0.35	0.4992	1.9564
0.40	0.4291	1.5994
0.45	0.3284	3.2021
0.50	−0.1688	3.7405
0.55	−0.1298	2.6425
0.60	−0.1869	2.0868
0.65	−0.2679	1.3493
0.70	−0.0036	2.2211
0.75	−0.0472	2.3622
0.80	−1.0010	4.6120
0.85	−1.4533	5.3303
0.90	−1.4477	0.6887***
0.95	−3.4636	19.7370

Note: *** denotes a 1% significance level.

Table 3 presents the estimated cointegrating coefficients (β and γ) of the quantile cointegrating model proposed by Troster et al. (2018). The results reveal that the estimated coefficients between LCF and GRE are positive but statistically insignificant at the 1% level across all quantiles. However, the cointegration coefficients between these two variables are significant at the 1% level for certain quantiles. Overall, Table 3 demonstrates a nonlinear cointegrating relationship between LCF and GRE in the CEE countries.

Empirical results

Quantile-on-quantile regression

After establishing a long-term cointegrating interaction between LCF and GRE, we employ QQR to examine the impact of GRE on LCF in the CEE countries from 1991 to 2022. The slope coefficients obtained from the QQR are illustrated using three-dimensional graphs. Figure 1a)–e) illustrates the slope coefficient estimates, $\beta1(\theta, \tau)$, which capture the effect of the τth quantile of the independent variable on the θth quantile of the dependent variable at varying θ and τ values for the selected countries. The figures present a surface plot that illustrates the dependency structure between LCF and GRE. These illustrations provide an in-depth analysis of the dependency dynamics across 19 quantiles, demonstrating how these relationships fluctuate under various economic conditions.

We begin by examining the impact of GRE on LCF in Hungary, as shown in Figure 1a). The results indicate that all GRE quantiles have a significant negative influence on most LCF quantiles [0.05–0.85]. This indicates that as the GRE ratio rises, LCF responds negatively. However, GRE positively impacts higher LCF quantiles [0.9–0.95]. Overall, the findings reveal a negative relationship between the two variables across most quantiles, implying that GRE significantly contributes to environmental quality in Hungary. These results are partially consistent with the studies conducted by Hao et al. (2021) on G7 countries and Saleem et al. (2022) on Asian nations, which explored the nexus between GRE and LCF.

Figure 1b) illustrates the influence of GRE on LCF in Poland. The slope coefficient ranges from −5.049 to 7.245, indicating a significant negative relationship between the middle to lower quantiles of LCF and all GRE quantiles. These findings indicate that GRE is likely to decrease in response to a rise in LCF. In contrast, the impact of GRE on LCF is significantly positive for all GRE quantiles and higher LCF quantiles. Overall, the findings reveal a strong influence of GRE on LCF, which partially aligns with Li et al. (2022) and Abid et al. (2022), which demonstrated a negative relationship between the two variables.

The influence of GRE on LCF in Figure 1c) exhibits positive and negative effects for Croatia. The findings indicate a significant negative impact within the region encompassing all GRE quantiles [0.1–0.95] in relation to low and middle LCF quantiles [0.1–0.8]. Conversely, the effect of GRE on LCF remains negative for both variables' remaining quantile. Negative GRE has a higher impact on LCF than the positive relationship, which aligns with the findings of Sun et al. (2022) and Lin–Ullah (2024).

In case of the Czech Republic, the coefficient in Figure 1d) ranges from −9.911 to 13.2, indicating that the asymmetric impact is strong and heterogeneous. A strong negative correlation between LCF and GRE is developed in regions that consolidate low to medium LCF quantiles [0.05–0.65] with whole GRE quantiles. This demonstrates a strong inverse correlation, revealing that GRE significantly decreases LCF in the Czech Republic from the lower-mid to the highest LCF levels. Furthermore, a combination of strong and weak positive associations between LCF and GRE is observed in segments connecting middle to high LCF quantiles [0.7–0.95] with the full range of GRE quantiles. The dominance of a strong negative relationship between LCF and GRE in the Czech Republic was also demonstrated by Dong et al. (2022).

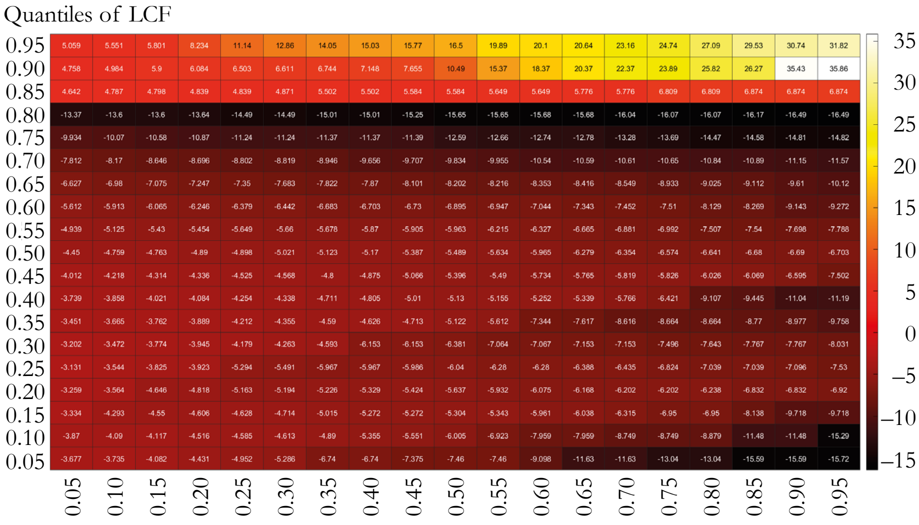
In Romania, a strong negative GRE–LCF relationship is identified in regions where moderately lower to upper-mid LCF quantiles [0.05–0.65] align with the full range of GRE quantiles in Figure 1e). This distinctly negative and robust correlation indicates that GRE significantly reduces LCF at medium-low to moderately high LCF levels. Conversely, a strong positive interaction is observed between GRE and LCF in areas linking medium to high LCF quantiles [0.7–0.95] with the full spectrum of GRE quantiles. This demonstrates that GRE substantially enhances LCF in Romania at medium to higher levels.

Overall, the QQR models reveal that GRE has its strongest negative impact on LCF in low and middle quantiles, whereas it has a positive effect in the higher LCF quantiles across all GRE quantiles in the CEE countries.

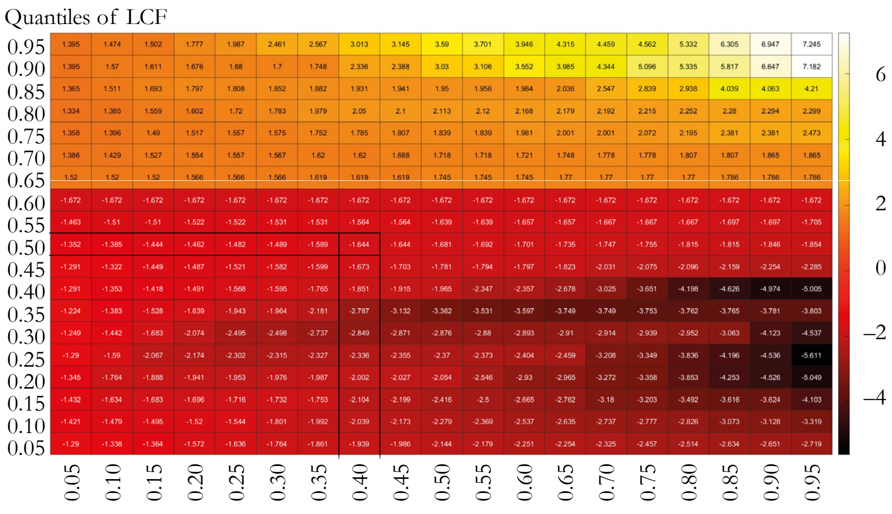
Figure 1

Effect of green growth on load capacity factor

a) Hungary



b) Poland



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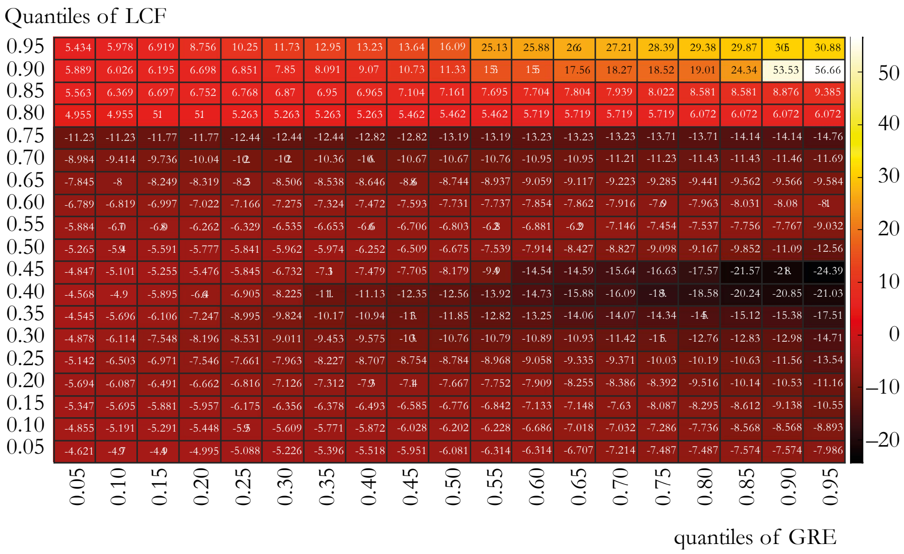
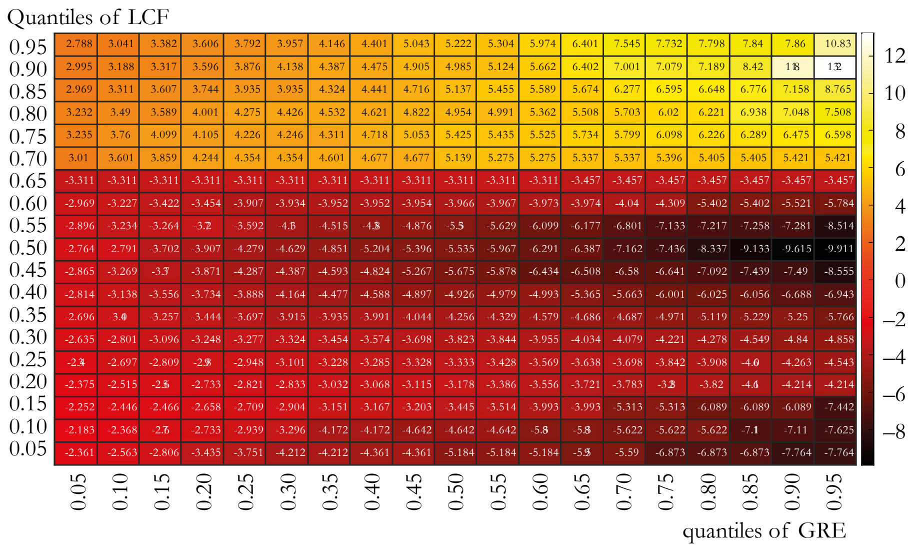
c) Croatia



d) Czech Republic



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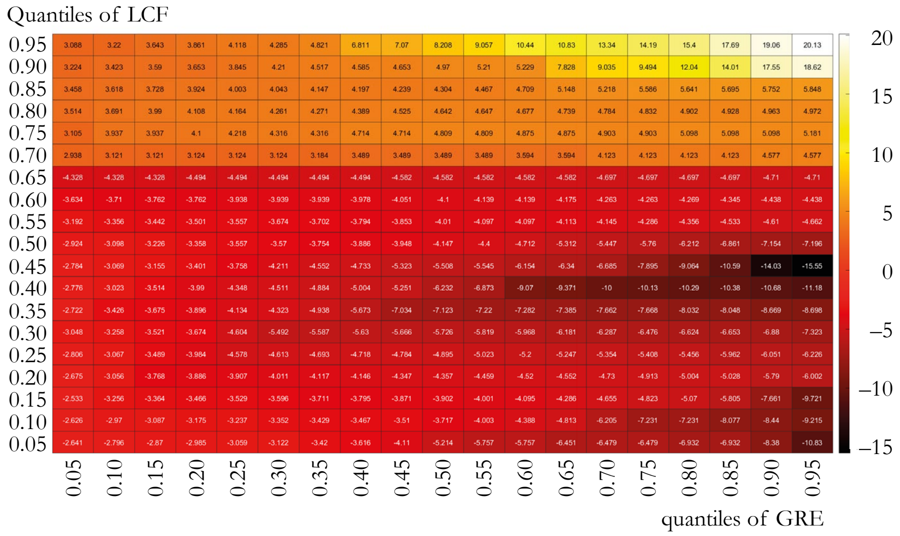
e) **Romania**



Breitung–Candelon frequency domain causality

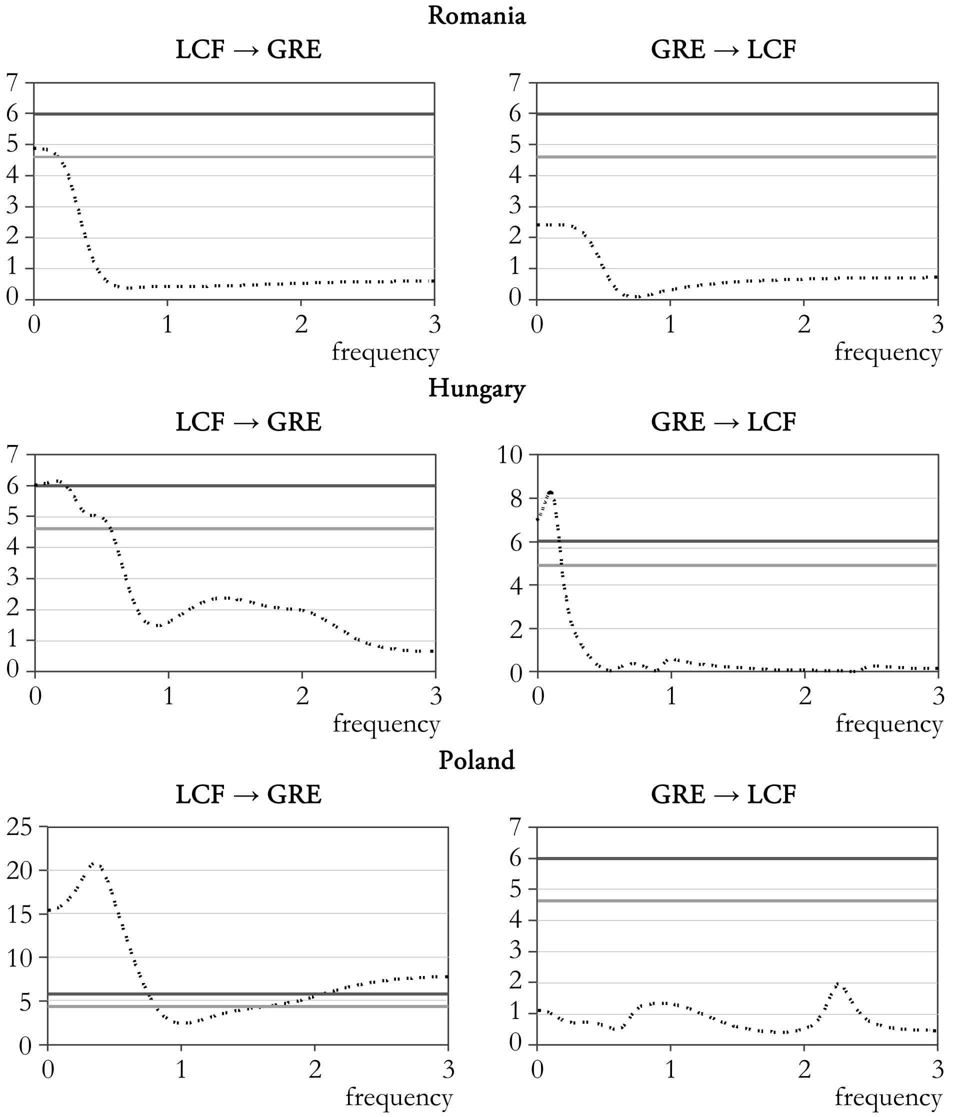
To examine short-, medium-, and long-term causal relationships among variables, we employ the frequency domain causality approach developed by Breitung–Candelon (2006). This method can effectively identify and characterize causal linkages between variables. Specifically, the test uses three frequency bands to assess causal relationships across different investment horizons. The null hypothesis, which suggests no Granger causality between independent and dependent variables, may be rejected at frequency 1 for the long term, frequency 2 for the medium term, and frequency 3 for the short term. The dark grey and light grey horizontal lines in Figure 2 represent 5% and 10% critical values, respectively. If the black dotted line surpasses the grey (light or dark) horizontal lines, it indicates that the F-statistic exceeds its critical value, rejecting the null hypothesis of no causal relationship between the two variables.

The causal associations between GRE and LCF in the CEE countries in Figure 2 reveal that the null hypothesis is rejected at a 5% significance level in the short- and medium-term in Romania. However, in the long term, a causal effect runs from LCF to GRE at a 10% significance level. Similarly, in Hungary, the findings indicate that the null hypothesis is rejected in the short- and medium-term at a 5% significance level. Nevertheless, in the long term, the null hypothesis is not rejected at either the 5% or 10% significance level. Notably, a one-way relationship runs from LCF to GRE across different timescales in Poland.

In Croatia, the results demonstrate that the null hypothesis of no causality between the two variables is rejected in the medium-term; however, a unidirectional relationship runs from LCF to GRE in the short- and long-term. Finally, in the Czech Republic, LCF causes GRE in short-term business cycles, while GRE Granger-causes LCF in long-term business cycles at a 5% significance level. These findings align with Dogan et al. (2022), Saleem et al. (2022), and Abid et al. (2022). Based on these results, government officials and policymakers in these countries should consider these variables when formulating GRE policies, as changes in these factors will influence LCF.

Figure 2

Spectral Granger causality test



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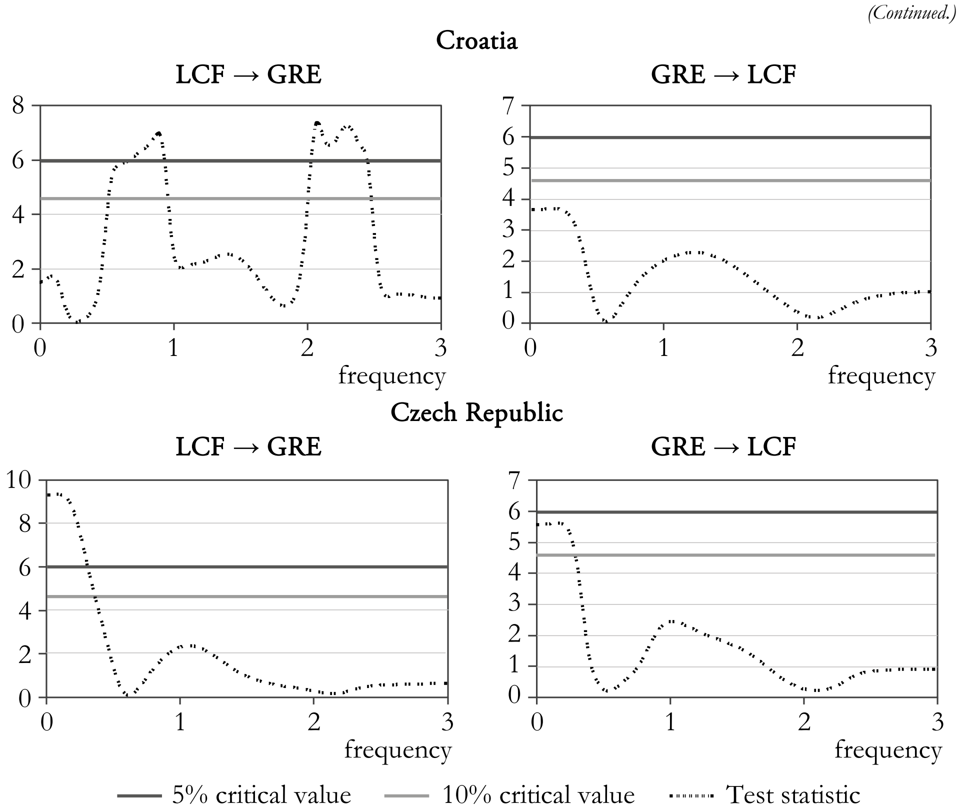

Discussion

This study employs QQR and spectral Granger causality techniques to examine the asymmetric association between GRE and LCF in CEE countries. The results demonstrate a transition in the relationship between the variables from negative to positive correlations across different quantiles. Specifically, GRE has a positive effect in higher LCF quantiles, indicating that increased GRE has a dramatic positive impact on environmental quality.

At the initial stages of development, increasing GRE is often accompanied by greater financial allocations to green investments in energy generation, transmission, and distribution systems (Raihan et al. 2025). Such investments expand renewable energy capacity by integrating wind, solar, and hydropower resources, contributing to long-term LCF improvements (Caglar et al. 2024). Additionally, higher GRE scores typically enhance technological progress and the adoption of innovative energy systems that foster energy efficiency and resource management (Abid et al. 2022). Economic growth also boosts policy innovation and institutional frameworks that prioritize sustainable development, reinforcing environmental resilience (Razzaq et al.

2023). These outcomes align with previous studies. For example, Li et al. (2022) revealed that GRE helped the MINT countries reduce CO_2 emissions, and Bhat et al. (2022) demonstrated a positive influence of GRE on environmental quality across G20 economies. In contrast, other studies, e.g., Razzaq et al. (2023) and Wei et al. (2023), have documented that the environmental outcomes of GRE are not uniformly positive, highlighting the presence of transitional trade-offs and country-specific heterogeneity.

Our results also reveal a negative interaction between GRE and LCF at lower quantiles, indicating that increases in GRE may temporarily reduce LCF in economies with weaker environmental capacity. The observed decline is likely attributable to the resource-intensive phase of the green transition, during which investments in renewable infrastructure, eco-industrial zones, and sustainable transportation systems necessitate a considerable use of land, water, and raw materials. While such efforts are vital for reducing carbon intensity and promoting long-term ecological sustainability, they might initially strain natural ecosystems through land-use competition, resource depletion, and/or waste generation. This result aligns with Pata et al. (2023) and Jin et al. (2024), who demonstrated that renewable energy development, while beneficial in the long term, can initially create short-term pressure on ecological systems.

Notably, the sample period of this study encompasses two major global shocks – the 2008–2009 financial crisis and the Covid-19 pandemic – which significantly influenced the dynamics between economic activity and environmental issues. During both crises, CEE countries experienced significant contractions in industrial production and energy consumption, resulting in temporary improvements in environmental indicators (Jin et al. 2024). Notably, post-crisis recoveries reignited economic and energy demand, which could explain some of the short-term fluctuations and asymmetric effects observed in our QQR analysis. Although the models do not explicitly control these events, the quantile-based approach effectively captures the nonlinear impacts across different states of environmental quality.

Furthermore, we do not divide the dataset into different crisis (2008 global financial crisis or the Covid-19 outbreak) and non-crisis periods. The primary reason is the structure of our data, which is annual and covers a somewhat short time span for each CEE country. If the sample was divided, the number of observations would become too small for the QQR model to operate properly because this technique requires a reasonably large sample to capture interactions across different quantiles. This difficulty is popular in empirical studies using annual data, and earlier research applying QQR and Granger causality test frameworks (Arain et al. 2020, Haseeb et al. 2021, Hassan et al. 2021) that also estimated full samples rather than separating crisis intervals. As a result, our analysis cannot explicitly isolate the impact of individual global shocks. We acknowledge this as a limitation of the study, and note that our results should be interpreted with the understanding that any crisis-related effects might only appear indirectly through patterns observed at extreme quantiles.

Overall, the findings confirm and extend related literature by demonstrating that the GRE–LCF nexus is asymmetric, time-varying, and sensitive to external shocks. Aligning with previous results, the results confirm that GRE improves environmental quality when economies achieve sufficient institutional and technological capacity. However, in early transition phases or under crisis conditions, the adjustment process can entail temporary trade-offs between ecological protection and economic expansion. These insights emphasize the importance of adaptive green policies that strike a balance between short-term economic resilience and long-term environmental sustainability.

Conclusion

This study examines the asymmetric relationship between GRE and LCF in the CEE countries. While the existing literature has predominantly investigated the effects of GRE on greenhouse gas and CO_2 emissions, this study shifts the focus to its impact on enhancing the LCF, considering quantiles and periods. We also investigate this issue by adopting LCF as an alternative and distinct proxy for ecological deterioration. Examining the CEE countries, we employ data spanning 1991–2020, we apply QQR and spectral Granger causality techniques to estimate the complicated interactions. The results demonstrate that GRE has a nonlinear impact on LCF in the countries analysed.

The QQR findings reveal that GRE has a decreasing impact at lower and middle LCF quantiles and all quantiles of GRE in all countries; however, GRE has an increasing impact on LCF at higher quantiles for all selected economies. The analysis also uncovers significant asymmetry in the interrelationships across quantiles in response to similar market regimes.

The spectral Granger causality demonstrates the causal association between the two variables. A bidirectional relationship is evident between GRE and LCF in Hungary and Czech in the long term, while the no feedback Granger from GRE to LCF is statistically significant in the short-term for the remaining countries. In addition, one-way causality running from LCF to GRE is found in different frequencies for Croatia and Poland. These estimates reveal that GRE contributes to environmental benefits; therefore, robust policies are needed to foster green investment and cultivate an environment that attracts foreign innovations to the CEE countries. This sophisticated understanding should guide policymaking in the CEE economies to ensure a balance between economic growth, environmental conservation, technological advancement, and energy security. A comprehensive perspective is essential to effectively address these challenges and develop robust, sustainable energy solutions.

Increased GRE within the CEE economies will drive higher in energy infrastructure investment, e.g., power plant construction, transmission networks, and grid modernization. Improved infrastructure enhances energy generation and distribution efficiency and reliability, strengthening LCF. Furthermore, higher GRE levels will support increased R&D spending, driving technological advancements in energy generation and storage. These advancements can improve the efficiency and stability of renewable energy sources, increasing LCF. Additionally, governments should prioritize investments in renewable and clean energy options such as solar, wind, and hydroelectric power. Policies like subsidies, tax incentives, rewards, and public–private partnerships can further promote the adoption of renewable energy technologies.

While this study provides valuable insights into the asymmetric relationship between GRE and LCF in the CEE countries, we acknowledge three limitations. First, the analysis relies on aggregate data, which may obscure country-specific institutional, technological, and policy differences that influence the relationship between GRE and environmental quality. Future research could employ panel quantile or spatial econometric approaches to capture cross-country heterogeneity and spatial spillovers more effectively. Second, this study primarily focuses on GRE and LCF, without explicitly considering other environmental indicators such as EF, biodiversity loss, and/or material consumption, which may provide a more comprehensive assessment of environmental sustainability. Incorporating these indicators into future models would enhance the robustness of the findings. Finally, as noted above, while the QQR and spectral causality models can effectively capture asymmetric and dynamic correlations, they cannot explicitly accommodate structural breaks induced by major shocks such as the 2008–2009 financial crisis and the Covid-19 pandemic. Therefore, future studies could employ regime-switching or time-varying parameter models to evaluate how global crises alter the direction and magnitude of the GRE–LCF relationship.

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