ASSESSING THE IMPACT OF GREEN FINANCE AND THE DIGITAL ECONOMY ON ENERGY TRANSITION: A MULTI-QUANTILE ANALYSIS OF E7 COUNTRIES' PROGRESS TOWARDS SDGS 7, 9, 13 AND COP28

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Abstract. The global transition to sustainable energy systems is crucial for achieving sustainable development goals and addressing the challenges of climate change, while aligning with the COP28 goals. In this context, the roles of Green Finance (GRF) and the Digital Economy (DTE) have gained increasing importance, especially in emerging seven economies (E7) countries. However, the synergistic impact of these two factors on Energy Transition (ENT) has been underexplored in the literature. This study investigates the combined effects of GRF and DTE on ENT in the E7 nations, with the objective of identifying pathways to accelerate sustainable energy transitions and meet COP28 climate objectives. Using annual data (2000-2023) and applying the Moment Quantile Regression (MMQR) method, we analyze the relationship between GRF, DTE, and ENT across different quantiles. Our findings reveal that GRF significantly enhances the energy transition process, while digital technologies play a vital role in increasing the efficiency and reach of energy systems. Notably, we observe a synergistic effect between GRF and DTE, where GRF moderates the impact of DTE on ENT, particularly in countries with higher levels of financial and technological development. Building on these findings, we propose critical policy interventions to accelerate the energy transition, driving impactful change toward a sustainable and resilient energy future.
Keywords: *climate change, digital technologies, emerging economies, moment quantile regression, sustainable development goals*

Introduction

Climate change represents a profound menace to the sustainability of ecosystems and human health. Specifically, climate change has exacerbated and prolonged severe weather conditions, such as droughts, floods, and storms. These events have increased agricultural problems and negatively impacted infrastructure and the economy (Qin et al., 2022; Chisti et al., 2023). Among the leading culprits of climate change is the burning of carbon-based fuels, which results in elevated carbon emissions (Nordhaus, 2019). According to IEA's 2021 report, three quarters of greenhouse gas emissions (GHGs) come from the energy industry, which are projected to reach 22 billion tons by 2050, resulting in an increase of approximately 2.1°C in global temperature if no action is taken. Accordingly, the 28th United Nations Climate Change Conference (COP28), held in Dubai in December 2023, established an agreement to phase out the conventional fuels from the energy system. Population growth and industrial expansion

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are driving energy demand upwards. Given the limited availability of fossil fuels, nations are increasingly required to develop alternative energy resources that are sustainable and limitless (Li al., 2023a). To this end, it has become a necessity to expedite the conversion to clean energy and foster sustainability. Sustainable Development Goals (SDGs) 7 further underscore the necessity of switching to renewable energy, which focuses on ensuring reliable and cheap energy for everyone. This goal is indispensable for fostering economic growth, improving health outcomes, and promoting social equity, particularly in developing and emerging economies. The energy transition (ENT) is crucial to SDG 7's success, as it involves shifting from carbon-intensive energy sources to clean, renewable, and sustainable alternatives (Shahbaz et al., 2022). The ENT offers a viable option for combating climate change while encouraging social and economic sustainability. A key advantage is that alternative forms of energy release relatively less or no carbon dioxide and other contaminants, therefore having minimal environmental impact (Ullah et al., 2023; Habiba et al., 2025). Additionally, it is capable of bolstering energy security while minimizing the necessity for energy imports. Hence, it is essential to examine how to accelerate ENT.

Given the transition toward carbon neutrality and the importance of addressing climate change, scholarly research is focusing on the significance of the digital economy (DTE) for the energy sector. (Shahbaz et al., 2022; Xie et al., 2024). Digitization has changed many sectors, including business models, customer connections, and economic outcomes (Shaju, 2023). Many sectors, including energy, greatly benefit from digital technologies, particularly artificial intelligence (AI), machine learning, and the Internet of Things (IoT). Digital technologies have been widely recognized for their use in analyzing data, making intelligent decisions, and exchanging knowledge as a powerful tool for advancing the transition to renewable energy and reducing energy consumption (Wang et al., 2022a; Xin et al., 2023; Huang and Lin, 2024). Hence, by integrating conventional and digital energy companies, energy efficiency can be significantly improved. Besides integrating energy and digital technologies, information technology can facilitate the creation of new energy ecosystems, decrease the cost of production, create new models for cooperation, optimize resource allocation, and facilitate the transition to renewable energy resources through the provision of accurate digital data and the establishment of a reliable online network (Nambisan et al., 2017; Yi et al., 2024). In the context of digitalization, the extractive industries become more aware of natural resource exploitation and increase their productivity. Additionally, in the context of the global sustainability agenda, SDG 9 calls for resilient infrastructure, sustainable industrialization, and innovation. Within this framework, the digital economy (DTE) is central to advancing technological solutions that enhance energy system efficiency, cut emissions, and support the adoption of renewable energy (Agyapong, 2021; Feng et al., 2024). It follows that the DTE has a substantial role to play in renewable energy advancement. Thus, it is imperative to analyze this association.

A review of empirical studies demonstrates that several researchers have analyzed technological innovation's impact on green energy based on simple measures such as total patents (Geng and Ji, 2016; Ulucak, 2021; Habiba et al., 2022). Additionally, several studies have examined how information and communication technologies (ICT) affect energy usage and green energy transformation (Zhang, 2020; Bano et al., 2022; Yu et al., 2023), but the results have been inconclusive. Among them, Lange et al. (2020) indicate that ICT services consume more energy. Further, Murshed et al. (2020) suggest that ICT

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development does not expedite the transition to green energy. In contrast, Zhao et al. (2021) demonstrate a significant positive correlation between ICT development and energy efficiency, arguing that digital technologies, such as AI and big data, can be utilized to optimize and upgrade industrial processes, thereby reducing energy consumption and increasing production efficiency. Moreover, several studies investigated ICT's impact on carbon emissions (Bastida et al., 2019; Charfeddine and Kahia, 2021; Khan et al., 2022). Even with these efforts, there is still little empirical evidence linking renewable energy to the DTE, especially in emerging seven (E7) countries. E7 countries account for a large proportion of world energy consumption and GHGs. In light of global warming, population growth, and urbanization, it is crucial for these countries to develop sustainable energy sources. Furthermore, previous studies have largely focused on assessing technology based on simple parameters such as ICT. ICT does not represent the entire DTE, but rather a segment of it. ICT value added can merely indicate the level of development of the ICT sector within a specific nation or region. A single indicator cannot adequately capture the developmental traits of DTE. Hence, this study considers four aspects of DTE, including digital social effects, social support, infrastructure, and digital trade (Shahbaz et al., 2022).

Funding is the biggest obstacle to a successful green transition. The conventional financial market faces environmental challenges, such as overcapacity and heavy investment in environmentally damaging sectors. Unlike conventional finance, green finance (GRF), which promotes the sustainability of society and the economy by protecting the environment and human needs, is receiving increasing attention as a means to promote economic and social sustainability (Bhatnagar and Sharma, 2022; Meng and Hao, 2024). The primary objective of this initiative is to promote investments in environmentally friendly companies and prevent funds from being allocated to polluting companies (An et al., 2021). Typically, GRF focuses on making substantial investments and funding environmentally friendly projects (Zhang et al., 2022). Additionally, GRF is crucial for effective resource allocation, the management of environmental risks, and the provision of guidance in the area of green investments (Lee et al., 2024a). Green financial institutions are instrumental in the progression of renewable energy initiatives, providing crucial financial support that dismantles monetary obstacles and expedites both the advancement and proliferation of renewable energy technologies. Concurrently, risk management instruments such as insurance and financial derivatives mitigate the risks associated with renewable energy initiatives, thereby enhancing the confidence of investors. To summarize GRF is essential for transforming the energy sector and establishing a new energy infrastructure (Wang et al., 2022b; Yu et al., 2022). In addition to SDG 7 and SDG 9, SDG 13 calls for urgent action to combat climate change and its impacts, emphasizing the reduction of global greenhouse gas emissions. The energy transition, supported by green finance (GRF) and digital technologies (DTE), is one of the most effective ways to achieve SDG 13. This transition not only mitigates climate change by shifting to renewable energy but also enhances the resilience of energy systems, reduces carbon emissions, and supports climate adaptation efforts.

Given the importance of GRF, this paper explores how GRF affects ENT, focusing particularly on E7 economies. GRF serves as a pivotal force in fostering the interplay between the DTE and ENT, channeling investments into digital innovations that bolster energy efficiency, advance sustainable business paradigms, and support policy implementation. The synergistic interaction expedites the worldwide ENT, thereby advancing the fulfillment of climate objectives and fostering the growth of a sustainable

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economy (Tan et al., 2024). A further benefit of investing in digital infrastructure is that governments and organizations will be able to monitor progress towards achieving energy transition goals, ensuring compliance, and adjusting policies accordingly. In order to maintain the momentum of the ENT, digital oversight is essential (Huang and Ren, 2024). Overall, the majority of scholars have concentrated on the influence of DTE (Shahbaz et al., 2022; Wang et al., 2022) and GRF (Du et al., 2023; Hafner et al., 2021; Jawadi et al., 2024) on the green transition. However, these studies primarily address their direct effects without examining their combined effects on ENT, nor do they incorporate these core variables within the same research design. *Figure 1* illustrates the evolving relationship between GRF, DTE, and ENT for the E7 countries over time. There is a clear positive correlation between these factors, demonstrating how digital technologies and GRF are contributing to the acceleration of energy ENT in these countries. Furthermore, *Figure 2* illustrates the performance of E7 countries in terms of these factors. Thus, the purpose of this paper is to fill the void by analyzing the impact of GRF and the DTE on ENT, as well as their synergistic effects on ENT in the E7 economies.

There are several reasons why this study selected E7 countries. The E7 countries, which include Indonesia, Mexico, Brazil, China, India, Russia, and Turkey, contribute significantly to global energy consumption. Their combined energy consumption is greater than 40% of global consumption. Considering the significant energy consumption of the E7 countries, it is clear that they are key players in global energy dynamics, and that their participation in a sustainable ENT is necessary. Their transition to renewable energy will contribute significantly to achieving global climate goals. Furthermore, it is essential to conduct comprehensive research on E7 economies, as these have the potential to surpass established markets. Therefore, a thorough analysis of E7 economies is necessary for formulating recommendations and policies.

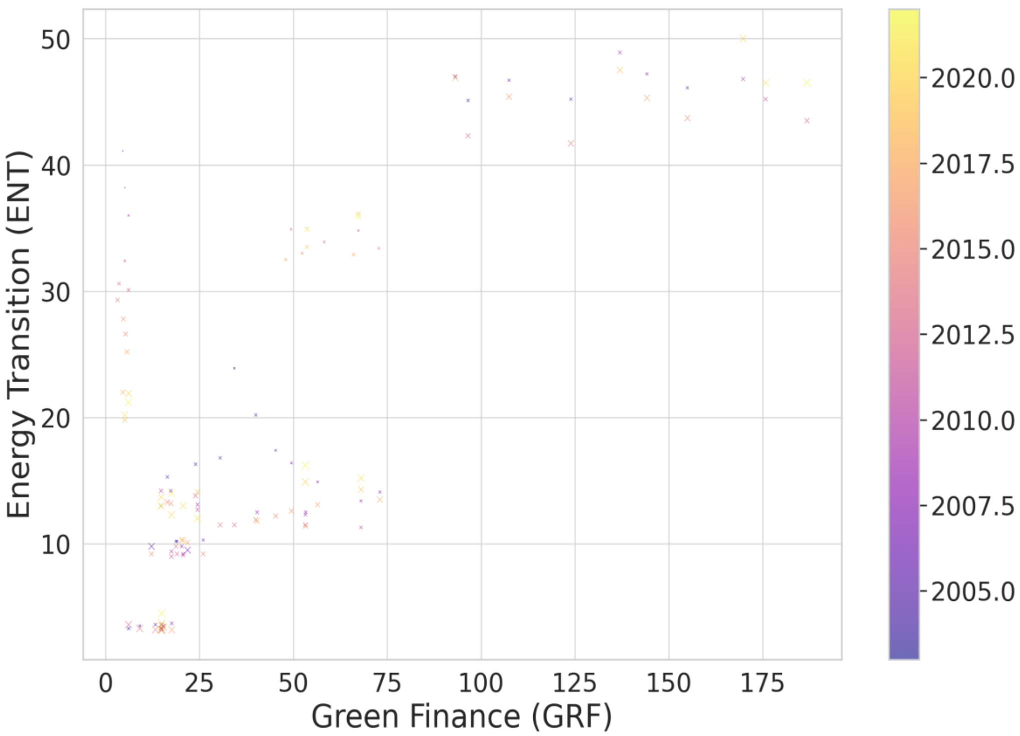

Figure 1. *A graph showing the relationship between GRF, DTE, and ENT for the E7 countries over time*

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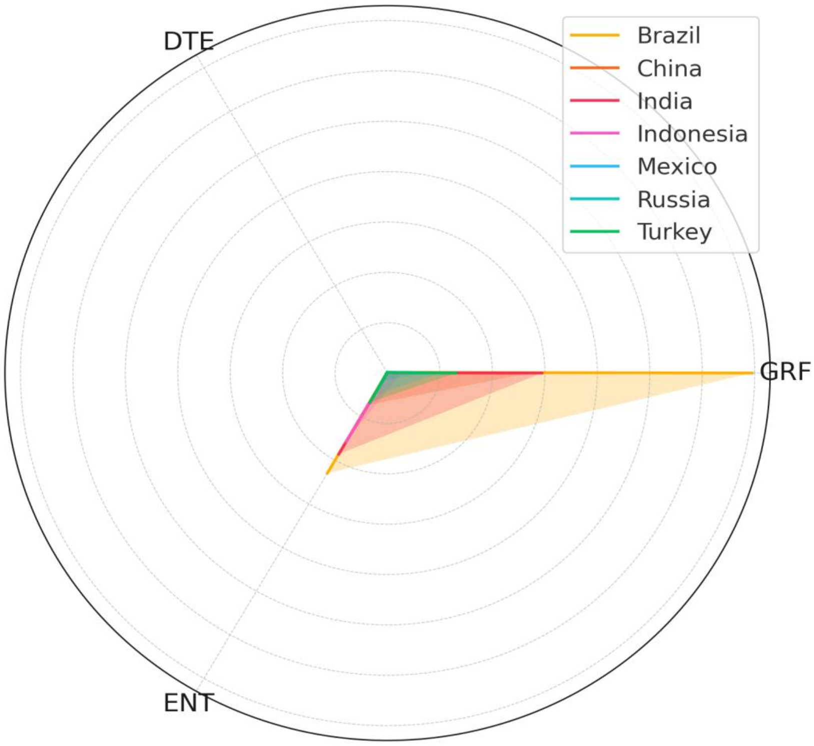

Figure 2. *A comparison of the relative performance of GRF, DTE, and ENT across E7 countries*

This study makes the following contributions to the literature: First, this research represents the first comprehensive analysis of the interconnections between GRF, DTE, and ENT in the context of the E7 countries, contributing to the advancement of ecological modernization, innovation diffusion, and energy transition theories. Second, this study differs from previous studies that have predominantly focused on traditional finance in accelerating the transition to renewable energy, focusing instead on GRF. The research provides policymakers with valuable insights into the mechanisms underpinning energy system transformation by identifying GRF as a pivotal catalyst that directly contributes to the achievement of SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action). Third, this study provides a distinctive evaluation of the digital economy's impact on the energy transition within the E7 economies. In light of the swift advancement of emerging digital technologies, the study's results are crucial for policymakers tasked with formulating forward-thinking strategies that leverage digital infrastructure to support the clean energy transition, in alignment with SDG 9 (Industry, Innovation, and Infrastructure). Third, this study uses a novel digital economy index, meticulously constructed from ten sub-components, which encompass key parameters such as digital infrastructure, the social impacts of digitalization, digital trade, and digital support. In order to ensure that the findings of this study are comprehensive and practical, this index provides a robust and nuanced measure of the digital economy's role in facilitating energy transition. Finally, this study advances the methodology by employing the Moment Quantile Regression (MMQR) method, which allows for a nuanced analysis of the heterogeneous and non-linear effects of GRF, DTE, and their interaction across different quantiles of energy transitions. This approach overcomes the limitations of

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traditional regression models by providing a more robust and granular perspective on how the variables interact under varying economic conditions and energy transition stages. Taking advantage of this methodology, the study provides actionable insight into how policies can be tailored to countries at different stages of digital and financial development.

The remainder of the study is organized as follows. An overview of prior empirical studies and theoretical frameworks is provided in the "Literature Review" section. The "Data and Methodology" section outlines the econometric methods and variables employed in the analysis. The key empirical findings are discussed in the "Results and Discussion" section. Finally, the "Conclusion and Recommendations" section presents a summary of the conclusions and suggestions for future research.

Theoretical underpinnings and literature review

Energy transition

As the world strives to become carbon neutral and keep global warming below 1.5°C, shifting to greener and more renewable resources is a major concern (Khan et al., 2021; Zou et al., 2024). An important actor in achieving these targets is the energy sector (González and Rendon, 2022). Following the discovery of fire, humankind has experienced two energy transitions and is undergoing a third ENT. The first ENT was characterized by the ascendancy of coal over firewood as the main form of energy, a shift facilitated by technological advancements, particularly the steam engine. In the subsequent ENT, coal was replaced by oil and natural gas as the primary fuel due to the development and adoption of combustion engines. The world is undergoing a third ENT, shifting from carbon-based energy to green, low-carbon, safe, and efficient green smart energy (Solomon and Krishna, 2011; Zou et al., 2024). In the aftermath of the 1970s global oil crisis, several nations implemented ENT policies toward the use of alternative energy sources (Huang and Liu, 2021). Furthermore, transitioning to sustainable energy is imperative for fostering a sustainable society, as it harmonizes economic growth with environmental protection. Consequently, it creates eco-friendly jobs, reduces energy usage, and promotes human health by reducing greenhouse gas emissions (Rehman et al., 2022). Additionally, transitioning to renewable energy helps conserve natural resources and biodiversity, which have been negatively impacted by fossil fuel extraction and consumption (Radulescu et al., 2024).

Numerous studies indicate that gradual technological progress and remedial technologies are not enough to counter excessive energy consumption patterns that result in biodiversity loss, the depletion of natural resources, and environmental degradation. Thus, we need to undertake a massive, revolutionary shift toward a low-carbon energy system (Köhler et al., 2019). In a book published by the German Institute of Applied Ecology titled "An energy revolution that is possible without oil and uranium," researchers asserted that economic growth could be achieved without significant consumption of energy by transitioning to renewable energy sources and enhancing energy efficiency (Krause et al., 1980). According to Khan et al. (2021), transitioning to green energy, including the adoption of cleaner, modern sources of energy and abandoning conventional energy, contributes significantly to economic development in the long-term. They emphasize that the establishment of a carbon-neutral and environmentally friendly society is inherently linked with the process of ENT. Yang et al. (2024) suggests that ENT will diverge from conventional development paradigms that

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focus primarily on economic benefits and neglect environmental and social elements. Instead of focusing solely on economic gains, this approach will contribute to sustainable development by achieving synergistic advantages in social, economic, and environmental contexts.

Green finance-energy transition

The Energy Ladder Theory, as proposed by Hosier and Dowd (1987), suggests that as households or societies attain greater wealth, they transition from using traditional, inefficient energy sources to more efficient, greener alternatives. In light of this theory, we can understand the fundamentals of ENT, which involves the transformation from fossil fuels to clean energy and improving energy efficiency (Lee et al., 2024a). Developing and implementing ENT projects requires adequate financial support. GRF, a concept derived from climate finance as introduced by Salazar (1998), holds that financial development should facilitate social development by balancing environmental sustainability with economic growth. GRF and ENT have been the subject of many studies since then. A study by Chishti et al. (2023) indicates that GRF contributes greatly to the ENT process by providing sufficient funding for initiatives related to energy conservation and green energy. Madaleno et al. (2022) underscored the importance of providing substantial green financing for clean energy projects.

As per existing theories, financial institutions are expected to utilize its resources responsibly in order to protect the environment, expand industrial infrastructure, and stimulate the economy. Financial development is closely intertwined with the process of ENT via multiple channels, the most evident of which is the technology innovation effect. GRF facilitates energy sector reform by fostering green technology (Polzin and Sanders, 2020). Several studies on ENT point out that substantial financial support and significant investments in green technology innovation are essential for transitioning to renewable energy sources (Gebreegziabher et al., 2012; Hötte, 2020; Pradhan and Ghosh, 2022). Additionally, the findings of these studies underscore the necessity of investing in sustainable technologies as the most effective approach to accelerating the global renewable energy transition (Chen and Lin, 2020; Wang and Lee, 2023; Lee et al., 2024b). A study by Xu et al. (2022) indicates that low-carbon technological innovation can facilitate ENT by reducing fuel consumption and increasing energy efficiency. Based on the effect of capital support, Brunnschweiler (2010) posits that a robust financial sector can efficiently mobilize private funds to finance renewable energy. Conversely, inefficiencies within the financial sector are likely to impede this process. Consequently, it appears that the ENT has been largely driven by financial development. For instance, Le et al. (2020) conducted a study across 55 countries with varying economic levels and concluded that well-developed financial sectors contributed to promoting renewable energy conversion. Similarly, Anton and Nucu (2020) examined 28 EU countries and found that a robust EU banking system facilitates lower-cost financing. This financial advantage enhances capital accumulation and fosters technological innovation within the renewable energy sector, primarily by providing more immediate liquidity. In addition, well-developed bonds and stocks facilitate business investment and risk management in renewable energy projects. For the period 1971-2015, Eren et al. (2019) found that an expansion of financial resources increased investments in sustainable energy projects in India. Based on a study conducted by Ji and Zhang (2019), financial institutions had a substantial influence on the energy structure of China between 1992 and 2013. Using data from G7 countries from 2000 to 2020, Liu et al. (2023) demonstrated that a thriving

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financial sector facilitates the long-term transition to clean energy and a sustainable energy economy.

Research discourse on GRF and ENT is relatively recent. Following recent studies, Du et al. (2023) advocates that GRF systems facilitate energy sector restructuring by offering financial support to industries that employ green methods of production, while concurrently restricting financial support to fossil fuel-intensive industries. As a result, efficiently operating markets can enhance the impact of green financial development on advancing the ENT and diminish the necessity for fiscal subsidies to support China's energy sector transformation. The study by Hou et al. (2023) shows that GRF has the potential to establish diverse channels of financing for ENT, thereby accelerating its growth. Wang et al. (2022) contend that green bond financing promotes the transition to renewable energy sources by reducing climate change risks. According to Meng and Hao (2024), GRF can reduce capital costs for renewable energy projects, improving their competitiveness compared to conventional sources of energy. For the UK, Hafner et al. (2021) confirms that inadequate green financing is a major obstacle to ENT. As noted by Zhao et al. (2024), climate finance significantly contributes to the acceleration of ENT. Climate finance provides essential financial resources necessary for scaling up and deploying green projects, addressing the initial investment costs associated with these technologies.

Digital economy-energy transition

Modern society is heavily dependent on digital technologies across various sectors, as they constitute fundamental components of modern infrastructure (Omri and Kahia, 2024). The correlation between DTE and ENT can be elucidated through the lens of ecological modernization theory, which suggests that technological innovation facilitates the simultaneous achievement of accelerated economic growth while maintaining environmental sustainability (Dryzek et al., 2020). It is argued from this theoretical perspective that digital technologies can assist in mitigating environmental problems, and as such can serve as a framework for studying the impact of DTE on the ENT process (Huber, 2000). In several ways, DTE impacts the ENT. Digital technologies, such as smart grids, improve the reliability, efficiency, and sustainability of energy resources, thereby facilitating the transition to renewable and low-carbon energy. The utilization of these technologies optimizes the utilization of renewable energy, minimizes energy loss, and improves demand response management. In addition to this, the DTE promotes the adoption of decentralized energy systems, which encompass residential batteries and solar panels, as well as other forms of decentralized energy. This shift reduces dependence on traditional fuel sources and fosters more sustainable, localized power systems (Geels, 2011).

This is consistent with the theory of diffusion of innovation as articulated by (Yi et al., 2024), who argue that the proliferation and adoption of technologies are pivotal. The DTE acts as an engine to spur innovation by expediting diffusion of energy-efficient technologies. Digital technologies, including IoT, AI, and blockchain, facilitate the swift adoption of clean energy solutions by lowering costs, enhancing efficiency, and integrating these technologies into existing infrastructures. For instance, AI can optimize renewable energy production, while blockchain can enable decentralized energy trading. Core components of the DTE, namely cloud computing, big data, AI, and the mobile internet, are crucial to this process. Consequently, the expansion of the DTE may foster a more robust platform for the exchange of information and a greater influence on

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knowledge diffusion. For example, technology like AI and machine learning is vital to forecasting energy demand, optimizing renewable energies, and managing renewable energy storage. Therefore, the integration of a DTE is essential to the transition to renewable energy.

In terms of empirical evidence concerning DTE and ENT, researchers contend green energy is positively linked to DTE. For example, research carried out by Hwang (2023) based on panel data from 18 Latin American countries indicated that DTE contributes to energy efficiency enhancements and accelerated adoption of renewable energy sources, thus having a positive effect towards a transition to renewable energy. A similar conclusion was reached by Wang et al. (2022c), who assessed the correlation between the DTE and ENT based on a sample of 72 economies between 2010 and 2019, demonstrating that the DTE enhances economic justice and facilitates ENT. Using data spanning the period 2003-2019, Shahbaz et al. (2022) studied the effect of DTE on ENT in 72 countries. Researchers found that DTE influenced ENT positively. Further, the researchers found that the impact of DTE on ENT differed significantly between countries (developed countries are more likely to benefit from DTE than developing countries). Hou and Ye (2024) confirmed the positive nature of this relationship by emphasizing the significance of DTE in China’s ENT. To ensure sustainable energy consumption, a strong digital environment is necessary.

In most existing studies, the ICT industry has been used as a measure of the DTE to assess its impacts on energy, energy efficiency, and the environment. Using an empirical approach, Zhao et al. (2022) investigated how ICT development relates to energy efficiency in emerging Asian countries and reported that increased energy efficiency is associated with a rise in ICT development. It is endorsed by Tzeremes et al. (2023) that ICT is a significant choice in the development of ENT and resolving environmental problems. Similarly, Lee et al. (2022) examined the nexus between renewable energy and ICT, and found that ICT promotes innovation in this area. For South Asian economies, Murshed (2020) empirically examined ICT trade’s impact on green ENT, and revealed that it contributes to improved green energy consumption, reduced energy intensity, and improved environmental quality. Furthermore, by integrating digital technology with conventional financial practices, conventional financial operations are transcended in terms of both time and space. By leveraging modern digital technologies like blockchain, AI, and big data, the efficiency of financial service processes is significantly enhanced. In addition to improving financial services accessibility and efficiency, this technological synergy minimizes financing frictions resulting from market incompleteness, resulting in a reduction in costs and an increase in efficiency of financing activities for businesses (Li and Zhou, 2024). In support of these arguments, Li et al. (2023b) determined that the low-carbon energy transition is significantly impacted by the use of digital finance. Conversely, Lange et al. (2020) examined how digitalization could affect energy demand, and concluded that the demand for energy increases as the digital sector grows. A similar conclusion is reached by Arshad et al. (2020), stating that ICT products and applications use excessive energy and have a progressive effect on the environment.

Research gap

Despite the increasing recognition of the role of the GRF and the DTE in the facilitation of ENT, their combined impact has remained largely unexplored, especially within emerging economies. Existing studies primarily examine the GRF and DTE as

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independent factors, analyzing their individual contributions to sustainable energy systems. However, the critical interaction between these two factors and how they complement each other to accelerate the energy transition has been largely overlooked. This gap is particularly significant for E7 countries, which, despite being major contributors to global energy consumption and carbon emissions, have been underrepresented in the literature. Given their pivotal role in global energy dynamics, understanding the interplay between GRF and DTE in these nations is essential for driving a more rapid and effective energy transition. Furthermore, much of the research on the digital economy focuses predominantly on ICT, often neglecting the broader, more comprehensive scope of digital innovations that are reshaping energy systems. Critical aspects such as digital trade, infrastructure, and the social impacts of digitalization are frequently overlooked, even though they are integral to enhancing energy efficiency and supporting the transition to renewable energy. This research addresses these gaps by exploring the synergistic relationship between GRF and DTE in driving energy transition in E7 countries. It proposes a novel framework to assess their combined effects, offering vital insights for policymakers striving to meet SDGs 7, 9, 13, while aligning with the climate objectives outlined in COP28.

Data and methodology

Model construction, variables, and data sources

On the basis of the empirical models of (Akberdina et al., 2024; Habiba et al., 2023; Khan et al., 2021), this study aims to investigate the dynamic effects of GRF and DTE on ENT in E7 economies using the following empirical models.

$$ENT_{it} = \alpha_0 + \alpha_1 GRF_{it} + \alpha_2 DTE_{it} + \alpha_3 GDP_{it} + \alpha_4 FDI_{it} + \alpha_5 URB_{it} + \varepsilon_{it} \quad \text{(Eq.1)}$$

Model 1 assesses the independent effects of GRF and DTE on ENT, while controlling for GDP, FDI, and URB. This serves as the baseline specification. Model 2 extends model 1 by including an interaction term between GRF and DTE. This interaction term allows us to test whether the effect of green finance on energy transition is moderated or amplified by digital economy development, highlighting any potential synergistic impacts.

$$ENT_{it} = \alpha_0 + \alpha_1 GRF_{it} + \alpha_2 DTE_{it} + \alpha_3 (GRF * DTE)_{it} + \alpha_4 GDP_{it} + \alpha_5 FDI_{it} + \alpha_6 URB_{it} + \varepsilon_{it} \quad \text{(Eq.2)}$$

where ENTit signifies the energy transition. The terms GRFit and DTEit refer to green finance and digital economy, respectively. GDPit, FDIit, and URBit are control variables that represent economic development, foreign direct investment, and urbanization, respectively. (GRF*DTE) it is the interaction term between green finance and the digital economy. α1- α6 indicate the parameters for estimation. The term i represents the countries and t represents the time frame. $^{\varepsilon}$it represents the error term. The dimensional effects of the variables are neutralized by taking the logarithmic form of each variable.

The data for the E-7 countries (Russia, India, Brazil, China, Turkey, Mexico, and Indonesia) is taken from 2003 to 2022. The analysis period coincides with the availability of data on all variables. In this study, ENT is captured in terms of renewable energy's share of total energy consumption, which serves as a metric for measuring the

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transformation of energy sources. This method offers a direct way to assess the performance of a country on the consumption side of ENT (Shahbaz et al., 2022). Considering the intent of the energy transition to reduce reliance on fossil fuels and increase the use of renewable energy, the percentage of renewable energy in total energy consumption shows the effective transition from a high- to low-carbon energy consumption structure. Data on ENT came from the World Bank database.

This study focuses on GRF as the key independent variable. An investment fund dedicated to renewable energy was used as a proxy to measure GRF, in accordance with Chin et al. (2024) and Jawadi et al. (2025). We obtained the GRF dataset from the International Renewable Energy Agency. DTE is another key independent variable in this study. The digital economy in various countries has been gauged by a few scholars recently. To date, the DTE lacks commonly accepted metrics for tracking its growth and a standardized framework for its evaluation. Consequently, we have constructed an index of the DTE on the basis of the work of Pan, et al. (2022), and Huang et al. (2024). As the index is formulated using the entropy method, it encompasses four critical perspectives: digital trade, digital infrastructure, digital social support, and digital social impact. There are various sub-components within each of the four categories included in this index. Data for the E-participation index was obtained from the United Nations E-Government Survey. This dataset provides information on e-participation initiatives such as online voting and e-consultations across different countries. The data used was from the most recent 2022 edition of the survey. The Online Service Index data was also sourced from the United Nations E-Government Survey, which tracks the availability and quality of online government services. The data from the 2022 version was used for this study. An overview of indicators and data sources can be found in *Table 1*. *Figure 3* breaks down each category and its components.

For the control variables, we focus on three variables that are associated with energy transition. The first variable is economic growth, measured by GDP per capita. Increasing economic wealth has become a key factor contributing to the increase in energy consumption. It is also a factor contributing to the energy transition dilemma, since it could facilitate the transfer of technology towards cleaner energy sources (Huang, 2022). Another variable to consider is FDI, which promotes clean energy consumption by spurring investment in clean energy markets. On the other hand, FDI stimulates industrial growth, which counteracts the move toward renewable energy (Horvey and Odei-Mensah, 2024). This means that FDI has a significant impact on the energy transition; however, its exact impact is unknown. Additionally, urbanization, measured by the proportion of urban residents in total, is also included as a control variable. As a result of urbanization, industrial structure, technical level, and energy efficiency improved, thereby decreasing dependency on energy (Yang et al., 2016). Data for all control variables is drawn from the World Development Indicators (World Bank, 2022). *Table 2* shows descriptive statistics. To assess the distributional properties of the variables, we applied the Jarque-Bera test. The Jarque-Bera values test for normality; higher values suggest greater deviation from the normal distribution. The Jarque-Bera statistic is a goodness-of-fit measure that tests whether sample data have the skewness and kurtosis matching a normal distribution. A higher Jarque-Bera value indicates greater deviation from normality. The results, presented in *Table 2*, suggest that some variables deviate significantly from normality, thus justifying the use of non-parametric and distributionally robust methods such as MMQR in our analysis. In *Table 3*, a correlation matrix is presented. *Figure 4* shows box charts.

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***Table 1.** Description of the sub-indices and sources of data for the digital economy index*

Sub-indices	Description	Units	Data sources	Data source links
Digital trade	Goods imports related to ICT	Percentage of all goods imported	World Bank (WB)	https://data.worldbank.org/indicator
	Goods exports related to ICT	Percentage of all goods exported	WB	https://data.worldbank.org/indicator
Social impact	E-participation index	Proportion of the population	UN	https://publicadministration.un.org/egovkb/
	Online service index	Proportion of the population	UN	https://publicadministration.un.org/egovkb/
	Individuals using the internet	Proportion of the population	ITU	https://www.itu.int/en/ITU-D/Statistics/Pages/default.aspx
Social support	Value added per capita by the service sector	USD per person	WB	https://data.worldbank.org/indicator
Digital infrastructure	Telecommunication infrastructure index	Based on 100 people	ITU	https://www.itu.int/en/ITU-D/Statistics/Pages/default.aspx
	Fixed-telephone subscriptions	Based on 100 people	ITU	https://www.itu.int/en/ITU-D/Statistics/Pages/default.aspx
	Fixed-broadband subscriptions		UN	https://publicadministration.un.org/egovkb/
	Mobile-cellular subscriptions	Based on 100 people	ITU	https://www.itu.int/en/ITU-D/Statistics/Pages/default.aspx

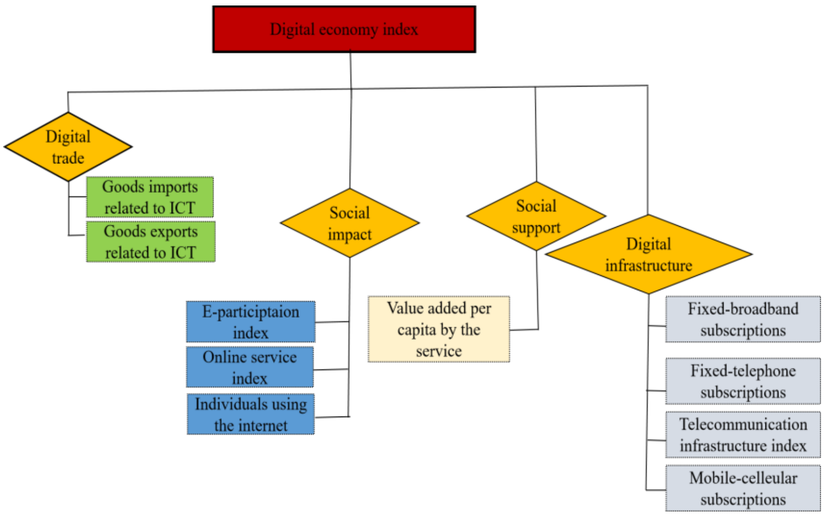


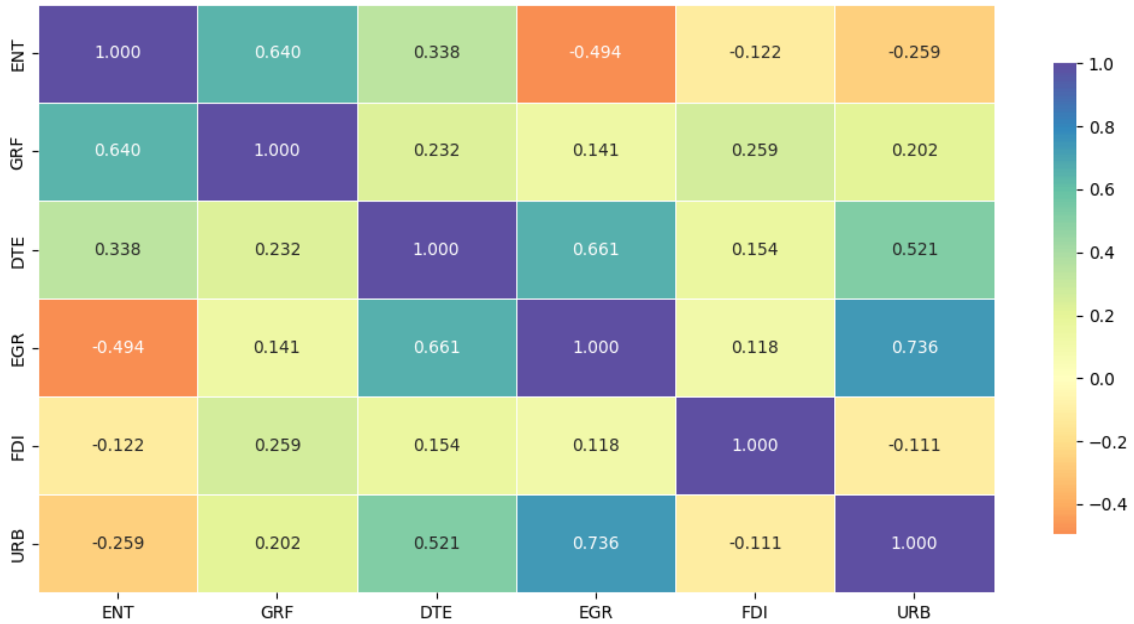
***Figure 3.** Digital economy components*

***Table 2.** Descriptive statistics*

Parameters	Mean	St. Dev	Max.	Min.	Jarque-Bera
ENT	2.806	0.846	3.912	1.163	22.523[a]
GRF	3.318	1.049	5.229	1.173	11.457[a]
DTE	0.261	0.209	0.774	-0.031	61.672[a]
EGR	8.597	0.841	9.676	6.299	17.853[a]
FDI	24.155	1.071	26.564	21.255	49.095[a]
URB	4.104	0.328	4.472	3.352	25.361[a]

Descriptive statistics of key variables in E7 countries (2003–2022). The letter a refers to 1% significance. ENT – Energy Transition; GRF – Green Finance; DTE – Digital Economy; GDP – Gross Domestic Product; FDI – Foreign Direct Investment; URB – Urbanization

Table 3. *Correlation matrix heat map. Correlation matrix of model variables in E7 economies (2003–2022)*



	ENT	GRF	DTE	EGR	FDI	URB
ENT	1.000	0.640	0.338	-0.494	-0.122	-0.259
GRF	0.640	1.000	0.232	0.141	0.259	0.202
DTE	0.338	0.232	1.000	0.661	0.154	0.521
EGR	-0.494	0.141	0.661	1.000	0.118	0.736
FDI	-0.122	0.259	0.154	0.118	1.000	-0.111
URB	-0.259	0.202	0.521	0.736	-0.111	1.000

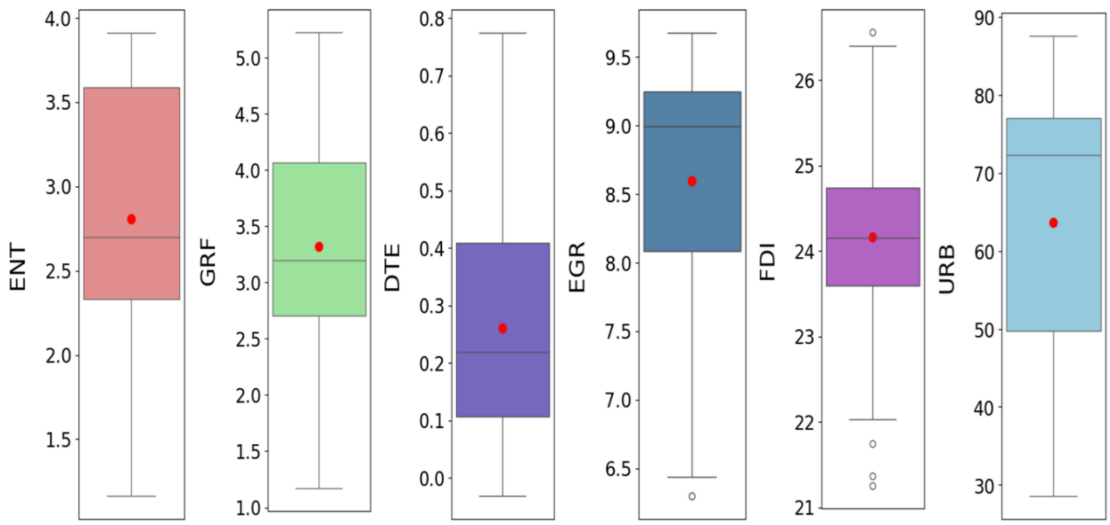


Figure 4. *Boxplots*

Estimation approach

An econometric analysis follows a series of steps to accomplish research objectives, as depicted in *Figure 5*.

Cross-sectional dependence (CSD) test

It is important to assess the CSD in the panel data before conducting a formal analysis. In today's globalized world, every country's actions affect, connect with, and influence one another. Consequently, CSD is often evident in panel data. In panel data analysis,

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CSD verification is therefore essential to obtain accurate and impartial estimates. In order to accomplish this, we used the CSD test developed by Pesaran (2004). The test consists of the following components:

$$\mathrm{CSD} = \sqrt{\frac{2T}{N(N-1)}}\left(\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\hat{p}_{ij}\right)$$

Here, N signifies the size of the sample, T represents the period, and P_{ij} represents the pair-wise correlation coefficient. Based on this test, the null hypothesis is that CSD does not exist.

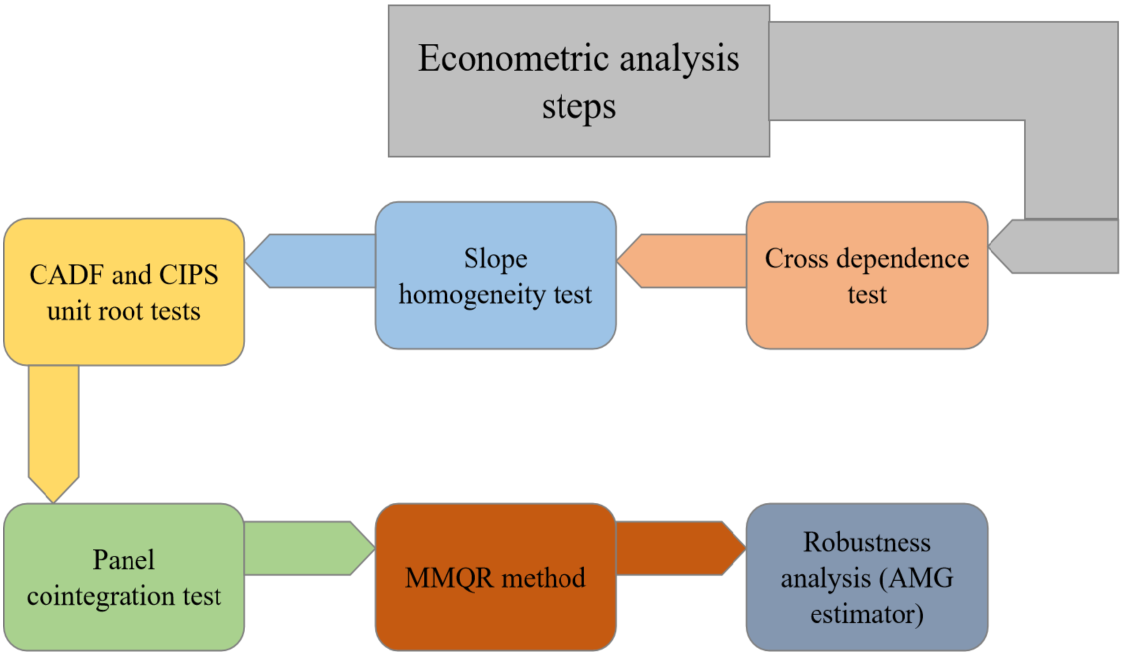

Figure 5. *The econometric analysis algorithm*

Slope homogeneity (SH) test

After conducting the CSD test, we evaluated the homogeneity of the coefficient slopes. A slope homogeneity assumption could lead to biased cointegration outcomes and produce unreliable panel estimates if slope parameters vary. For this analysis, the authors employed the slope homogeneity test described by Pesaran and Yamagata (2008). Test statistics are represented by the following equations:

$$\widetilde{\Delta_{SH}} = (N)^{\frac{1}{2}}(2K)^{-\frac{1}{2}}\left(\frac{1}{N}\tilde{S} - K\right)$$

$$\tilde{\Delta}_{ASH} = (N)^{\frac{1}{2}}\left(\frac{2K(T-K-1)}{T+1}\right)^{-\frac{1}{2}}\left(\frac{1}{N}\tilde{S} - 2K\right)$$

Here, delta tilde is expressed as $\widetilde{\Delta_{SH}}$ and adjusted delta tilde is represented as $\tilde{\Delta}_{ASH}$. Statistically significant values will reject homogeneity of slope coefficients as the null hypothesis.

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Unit root tests

Afterward, second-generation unit root CIPS and CADF tests by Pesaran (2007) were applied to assess the stationarity characteristics of variables. This approach was chosen to overcome some of the restrictions associated with the first-generation unit root tests as well as to address issues related to CSD and heterogeneity. CADF test statistics consist of the following components:

$$\Delta Y_{it} = \theta_i + Y_{it-1} + \theta_i \bar{X}_{t-1} + \sum_{I=0}^{p} \theta_{iI} \Delta \bar{Y}_{t-1} + \sum_{I=1}^{p} \theta_{iI} \Delta Y_{t-1} + \varepsilon_{it}$$

where $\bar{Y}_{t-1}$ is an indicator of lagged variables. Below are statistics about the CIPS test:

$$\widehat{CIPS} = \frac{1}{N} \sum_{i=1}^{n} CADF_i$$

Panel cointegration test

A long-term equilibrium relationship among parameters was investigated using the error correction model (ECM)-based cointegration algorithm described by Westerlund (2007). Since this strategy has the advantage of producing consistent results even with heterogeneity and CSD, it is more advantageous than previous methods for cointegration. In this test, there are four panels of statistics; two are group statistics (G_t, G_a) and two are panel statistics (P_t, P_a) that can be summarized as follows:

$$G_t = \frac{1}{N} \sum_{i-1}^{N} \frac{\acute{a}_i}{SE(\acute{a}_i)}$$

$$G_a = \frac{1}{N} \sum_{i-1}^{N} \frac{T\acute{a}_i}{\acute{a}_i(1)}$$

$$P_t = \frac{\acute{a}}{SE(\acute{a})}$$

$$P_a = T\acute{a}$$

MMQR method

In this study, we used the Method of Moment Quantile Regression (MMQR) suggested by Machado and Silva (2019) to investigate the long-term relationships between green finance, the digital economy, economic growth, FDI, urbanization, and energy transition. An approach such as this is particularly useful when there are non-uniform distributions of data. The MMQR method is capable of capturing non-linear and heterogeneous effects, as well as estimating the correlation between predictors and different quantiles of the dependent variable. It has distinct advantages over non-linear techniques, such as NARDL, which tend to capture symmetric relationships effectively or need to be transformed to account for asymmetry. Based on these facts, MMQR is more robust and reliable, particularly when producing non-linear and heterogeneous effects, and is more robust against outliers, endogeneity, and heterogeneity. The following is an illustration of the MMQR regression in mathematical terms:

$$Y_{it} = \dot{\alpha}_i + \ddot{X}_{it}\emptyset + \left(\dot{Y}_i + \varrho \check{Z}_{it}\psi\right)\ddot{U}_{it}$$

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For the purposes of strengthening the validity of MMQR findings, a robustness analysis was performed using the Augmented Mean Group (AMG) estimate proposed by Bond and Eberhardt (2013). The MMQR estimator yields credible results, however, alternative estimation methods, such as AMG, enhance the robustness of the analysis. In choosing AMG over other methods, we are driven by its robustness in the presence of heterogeneity, non-stationarity, and CSD.

Results and discussion

Proceeding to the findings, the results of the CSD analysis are presented in *Table 4*. On the basis of the p-values, there is strong evidence to reject the null hypothesis that no CSD exists in the variables ENT, GRF, DTE, GDP, FDI, and URB. Based on these results, CSD appears to be present in the examined series. As a next step, *Table 5* provides results of the slope homogeneity test. The p-values indicate that the null hypothesis of a homogeneous slope is rejected. In this manner, the slope coefficients are heterogeneous across cross-sections. This suggests that heterogeneous panel methods are appropriate for estimation.

Table 4. *CSD test outcomes*

Variables	Pesaran CSD	P-values
ENT	5.143[a]	0.000
GRF	4.247[a]	0.000
DTE	11.113[a]	0.000
EGR	11.565[a]	0.000
FDI	2.969[a]	0.000
URB	2.912[a]	0.000

Results of cross-sectional dependence test for E7 countries (2003–2022). The letter a refers to1% significance. ENT – Energy Transition; GRF – Green Finance; DTE – Digital Economy; GDP – Gross Domestic Product; FDI – Foreign Direct Investment; URB – Urbanization

Table 5. *Slope homogeneity outcomes*

	Statistics	P-value
$\widetilde{\Delta_{SH}}$	4.868[a]	0.000
$\tilde{\Delta}_{ASH}$	6.510[a]	0.000

Results of slope homogeneity test for E7 countries (2003–2022). The letter a refers to 1% significance

Following that, CIPS and CADF tests were conducted to determine if there are unit roots in the series. *Table 6* displays the results of both tests. There is no rejection of the null hypothesis of non-stationarity for all series at the level. In both tests, there is a rejection of the null hypothesis at the first difference for all series. In other words, ENT, GRF, DTE, GDP, FDI, and URB follow the order I (1). As a further analysis, the cointegration relationship between ENT and the explanatory variables was examined employing Westerlund's (2007) cointegration method. The results in *Table 7* indicate that both statistics, including panel statistics (Pt Pa) and group statistics (Gt Ga) are statistically significant at 1% and 5%, underscoring the cointegration of ENT, GRF, DTE, GDP, FDI, and URB over the studied period.

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Table 6. *Unit root test outcomes*

Variables	CIPS		CADF	
	1(0)	1(1)	1(0)	1(1)
ENT	-1.628	-5471[a]	-0.752	-2.626[b]
GRF	-4.431[a]	---	-3.708[a]	---
DTE	-1.493	-4.618[a]	-1.890	-2.788[a]
EGR	-1.641	-5.313[a]	-1.749	-2.725[a]
FDI	-2.738	-4.792[a]	-1.643	-3.435
URB	-2.168	-6.237[a]	-1.104	-2.464[a]

Panel unit root test results (CIPS and CADF) for E7 countries (2003–2022). The letters a and b indicate significance of 1% and 5%, respectively. ENT – Energy Transition; GRF – Green Finance; DTE – Digital Economy; GDP – Gross Domestic Product; FDI – Foreign Direct Investment; URB – Urbanization

Table 7. *Cointegration test outcomes*

	G_t	G_a	P_t	P_a
Value	-3.091[b]	-10.640[a]	-3.805[b]	-8.264[a]
Z-value	4.614	5.897	2.199	3.971

Westerlund cointegration test results for E7 countries (2003–2022). The letters a and b indicate significance of 1% and 5%, respectively. ENT – Energy Transition; GRF – Green Finance; DTE – Digital Economy; GDP – Gross Domestic Product; FDI – Foreign Direct Investment; URB – Urbanization

To derive the main estimates, our investigation employed the MMQR technique to deal with the non-normal data distribution and heterogeneous attributes of the ENT and its regressors. A summary of the results of this method is presented in *Table 8*. As for the impact of GRF on ENT, the results of model (1) in *Table 8* indicate that GRF positively impacts ENT, which differs considerably across estimated quantiles. To be more specific, a 1% increase in GRF accelerates ENT by 0.135% to 0.932%. It is interesting to note that the positive impact of GRF shows an increasing trend from quantiles 1 to 9. We can infer that GRF promotes ENT in E7 countries. This finding aligns with the findings of Hou et al. (2023) for 53 countries, Du et al. (2023) for China, and Meng and Hao (2024) for the regional comprehensive economic partnership region. The justification for this positive impact can be attributed to several key factors. For example, GRF reduces financing costs for clean energy projects by offering lower-interest loans and green bonds, which are more affordable than conventional forms of financing. In this way, renewable technologies, like wind and solar power, are developed and scaled more quickly, leading to an acceleration of the ENT (Zhao et al., 2021). Additionally, the adoption of policies that promote green finance, such as subsidies, tax incentives, and carbon pricing mechanisms, is a powerful tool in encouraging private investment in green technologies. By establishing such supportive policies, a conducive investment environment can be created, thereby enhancing private sector engagement in clean energy projects (Karpf and Mandel, 2022). Further, as increasing capital is allocated to the green sector, economies of scale drive down renewable energy technologies' production costs, enhancing their competitiveness relative to conventional energy sources. Additionally, escalating awareness of climate risks and environmental issues exerts pressure on businesses and investors to prioritize sustainability. Thus, GRF, whether in the form of an organization

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or as an integral part of the financial system, is crucial to the attainment of sustained long-term economic growth.

Table 8. *MMQR regression outcomes (Model 1)*

Variables	Loca.	Scale	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]
GRF	0.493[a] (0.161)	0.797[a] (0.088)	0.135[b] (0.055)	0.186[a] (0.065)	0.248[b] (0.129)	0.424[a] (0.145)	0.493[a] (0.161)	0.554[a] (0.152)	0.780[a] (0.176)	0.951[a] (0.105)	0.932[a] (0.069)
DTE	0.137[b] (0.056)	0.159[c] (0.150)	0.003 (0.098)	0.048 (0.101)	0.045 (0.040)	0.057 (0.069)	0.137[b] (0.056)	0.141[b] (0.079)	0.146[b] (0.081)	0.157[b] (0.086)	0.162[a] (0.114)
EGR	-0.865[b] (0.329)	-0.986[b] (0.372)	-0.423[b] (0.207)	-0.325[c] (0.180)	-0.415[b] (0.193)	-0.644[a] (0.229)	-0.865[b] (0.329)	-1.088[a] (0.348)	-1.181[a] (0.215)	-1.276[a] (0.169)	-1.409[a] (0.310)
FDI	0.154[c] (0.084)	0.334[b] (0.128)	-0.088 (0.066)	-0.067 (0.095)	0.081 (0.121)	0.117 (0.119)	0.154[c] (0.084)	0.185[a] (0.053)	0.202[a] (0.067)	0.142[b] (0.064)	0.246[a] (0.110)
URB	0.817 (0.577)	1.936[a] (0.688)	0.155 (0.539)	-0.103 (0.306)	-0.005 (0.339)	0.390 (0.379)	0.817 (0.577)	1.290[c] (0.730)	2.169[a] (0.661)	2.277[a] (0.339)	2.091[a] (0.427)
Constant	7.634[a] (2.321)	-7.115 (4.720)	5.552[c] (3.420)	6.741[a] (2.445)	8.617[a] (2.896)	8.475[a] (2.482)	7.634[a] (2.321)	7.356[a] (2.632)	3.690 (2.884)	1.435 (3.288)	-1.563 (3.25)

MMQR estimation results for energy transition drivers in E7 countries (Model 1, 2003–2022). The letters a, b, and c indicate significance of 1%, 5%, and 10%, respectively. ENT – Energy Transition; GRF – Green Finance; DTE – Digital Economy; GDP – Gross Domestic Product; FDI – Foreign Direct Investment; URB – Urbanization

Model (1) further illustrates the DTE results. The estimated coefficients reveal that the effects of the DTE on ENT are heterogeneous. The coefficients of the DTE exhibit both insignificance and significance across quantiles. Specifically, from quantiles 1 to 4, the estimated coefficients are positive but statistically insignificant. Conversely, from quantiles 5 to 9, there is a positive correlation and statistical significance. As the DTE grows by 1%, the ENT increases from 0.137% to 0.162% across quantiles 5 to 9. This suggests that lower levels of the DTE do not contribute to the energy transition, whereas higher levels do. This finding is consistent with that of Murshed (2020) for South Asian nations, Shahbaz et al. (2022) for 72 economies, and Hou and Ye (2024) for China. A possible explanation for this is as follows: As digital technologies are increasingly integrated into energy systems, including the IoT, AI, and big data analytics, significant opportunities exist for enhancing energy efficiency, optimizing the utilization of renewable energy, and improving grid management. For instance, smart grids powered by digital solutions can better align energy supply with demand, minimize energy loss, and integrate intermittent renewable energies (Hossain et al., 2020). By doing so, a smooth transition from carbon-based to renewable energy can be achieved. Furthermore, digitization contributes to innovation by reducing costs and expanding renewable energy access. In a study by Brock et al. (2021), more efficient investment in clean energy projects can be facilitated by the digitalization of energy markets, which can lower transaction costs, increase transparency, and foster a faster shift to low-carbon energy. Hence, based on our analysis, it appears that the DTE has positive direct impacts, however, these impacts are only visible at higher quantiles as the DTE grows.

A study by Akberdina et al. (2024) contends that the DTE has not only transformed the financial landscape, but has also augmented the efficacy and scope of green financing initiatives, particularly in facilitating global and cross-border investments in projects that support sustainability. This expansion has expedited the ENT and opened up new financial opportunities for addressing environmental issues. Given this, the study explores the role of the DTE in driving the ENT by examining its moderating effect on GRF. The estimates presented in *Table 9* and model 2 indicate that the interaction coefficients

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between GRF and the DTE have a positive, growing impact on the ENT. Similarly to the earlier finding, the combined effects of GRF and the DTE are significant from quantiles 4 to 9, indicating that the combined effects on the ENT start modestly but become more significant over time. In other words, as both factors gain more traction and influence in the energy sector, their synergies will result in more significant progress toward sustainable energy. Li et al. (2024) corroborate this assertion, asserting that blockchains and other digital instruments enhance the security of financial transactions, thus improving the reliability and credibility of green financing. Therefore, by integrating digital technologies, we are able to increase participation in GRF, optimize resource allocation, and ultimately improve the greenness of the projects financed with green finance, facilitating a smooth transition to a low-carbon economy.

Table 9. *MMQR regression outcomes (Model 2)*

Variables	Loca.	Scale	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]
GRF	0.702[a] (0.257)	1.458[a] (1.170)	0.328[a] (0.103)	0.326[c] (0.186)	0.405[a] (0.149)	0.605[a] (0.198)	0.702[a] (0.257)	0.851[a] (0.304)	1.110[a] (0.353)	1.351[a] (0.177)	1.494[a] (1.165)
DTE	0.142[b] (0.043)	0.090 (0.110)	0.120 (0.075)	0.110 (0.070)	0.087 (0.102)	0.146[b] (0.184)	0.142[b] (0.043)	0.174[a] (0.124)	0.176[a] (0.096)	O.177[a] (0.060)	0.192[a] (0.081)
GRF*DTE	0.024[a] (0.008)	0.027[c] (0.014)	0.007 (0.006)	0.003 (0.006)	0.009 (0.007)	0.022[a] (0.007)	0.024[a] (0.008)	0.023[a] (0.008)	0.025[a] (0.009)	0.026[a] (0.007)	0.029[b] (0.013)
EGR	-0.743[b] (0.333)	-0.909[b] (0.361)	-0.370 (0.282)	-0.303 (0.254)	-0.309 (0.256)	-0.611[c] (0.337)	-0.743[b] (0.333)	-0.883[b] (0.336)	-0.916[a] (0.247)	-1.140[a] (0.217)	-1.097[a] (0.225)
FDI	0.017 (0.143)	0.418[a] (0.124)	-0.165 (0.101)	-0.119 (0.078)	-0.094 (0.088)	-0.101 (0.129)	0.017 (0.143)	0.185[b] (0.083)	0.215[a] (0.073)	0.195[a] (0.065)	0.169[b] (0.072)
URB	0.224 (0.753)	2.661[a] (1.009)	-0.459 (0.815)	-0.281 (0.563)	-0.458 (0.625)	0.014 (0.789)	0.224 (0.753)	0.549 (0.804)	0.785 (0.679)	1.458[b] (0.604)	1.670[b] (0.594)
Constant	12.035[a] (1.762)	-4.361 (5.134)	8.421[a] (2.966)	7.424[a] (2.680)	10.843[a] (2.644)	11.937[a] (2.171)	12.035[a] (1.762)	10.937[a] (2.301)	9.638[a] (2.794)	8.845[b] (4.106)	4.932 (4.190)

MMQR estimation results with interaction of green finance and digital economy (Model 2, 2003–2022). The letters a, b, and c indicate significance of 1%, 5%, and 10%, respectively. ENT – Energy Transition; GRF – Green Finance; DTE – Digital Economy; GDP – Gross Domestic Product; FDI – Foreign Direct Investment; URB – Urbanization

As for the control variables, the findings indicate a negative correlation between economic growth and ENT. With increasing quantiles, the coefficients become increasingly negative and larger in magnitude. A major reason for this is the fact that as the economy expanded, energy consumption increased, especially in industries that consume a large amount of energy, such as transportation, manufacturing, and construction. As energy demand increases, coal provides much of the energy, stifling efforts to decarbonize the sector. According to Yang et al. (2024), higher income levels correspond to increased economic activity. As a result, increased economic activity necessitates increased energy consumption. It is therefore necessary to develop more robust policy measures aimed at achieving a truly sustainable energy future, including incentives for energy efficiency and a faster shift away from fossil fuels. The findings regarding FDI reveal a heterogeneous impact on the ENT, which differs across quantiles. Lower quantiles show negative coefficients for FDI, which are statistically insignificant. However, the coefficients become statistically significant at higher quantiles, specifically from 5 to 9. This indicates that as foreign investment potentially shifts towards more sustainable or efficient industries, such as renewable energy or green technologies, the positive effect of FDI becomes more pronounced, especially at higher quantiles. Therefore, to ensure that FDI contributes to long-term economic and environmental goals, policymakers should encourage foreign investment in green technologies or industries that support sustainability. Estimates of

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urbanization yield similar results, with significant and positive coefficients observed only in quantiles 6 to 9. This positive effect underscores the enhanced capacity of cities to implement clean energy solutions and advocate for policy changes that facilitate the transition away from fossil fuel dependence. Urbanization mitigates energy insecurity, increases energy availability and improves energy efficiency (Zhao et al., 2022). *Figures 6* and *7* show plots of MMQR estimates.

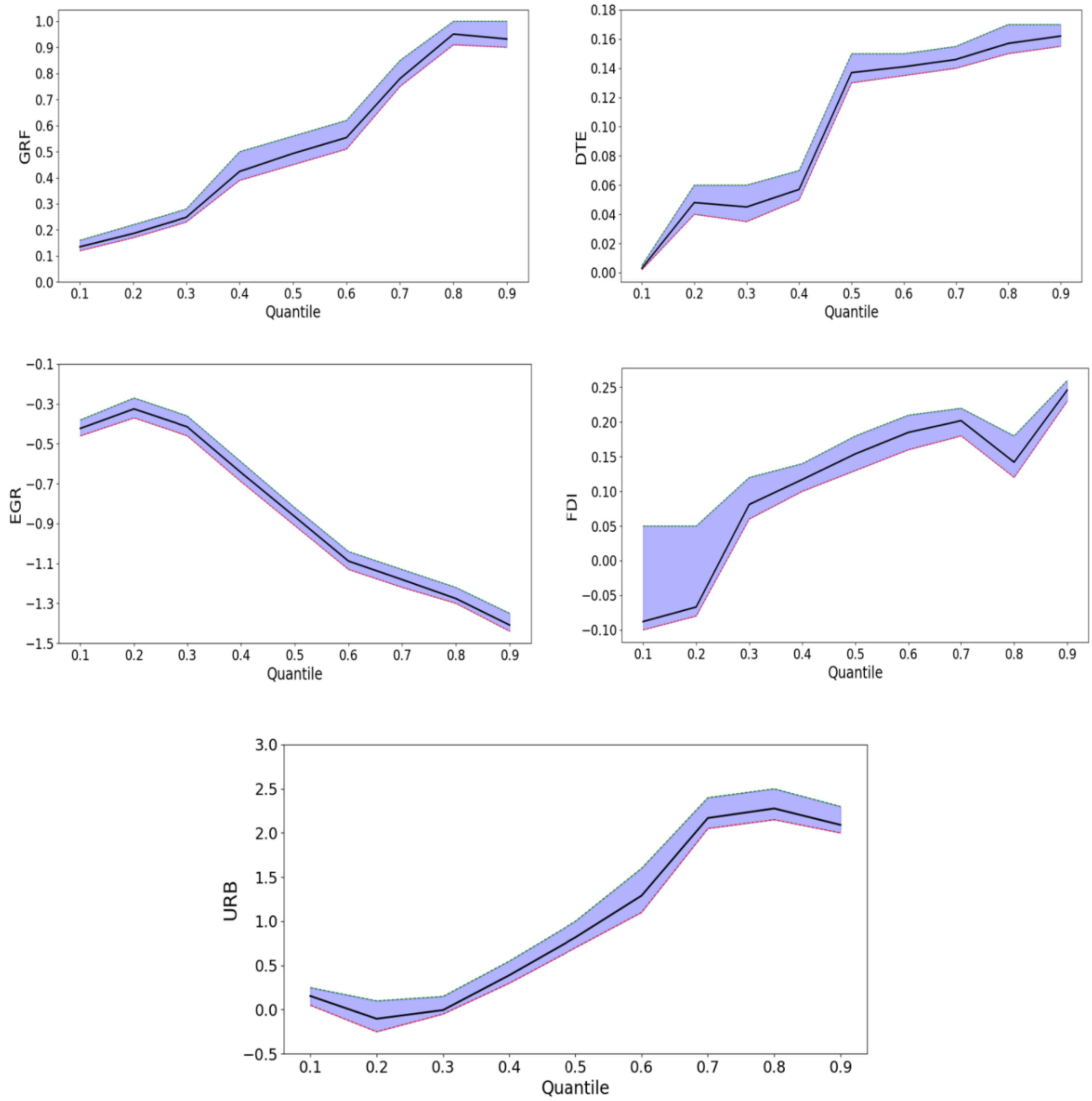

Figure 6. *MMQR estimates plots (model 1)*

Implications for SDG and COP28 commitments

The findings of this study offer meaningful insights into the collective progress of E7 countries toward the Sustainable Development Goals (SDGs) and COP28 commitments. Specifically, the significant and positive effects of green finance and digital economy indicators on the energy transition index across higher quantiles suggest that improvements in these areas are crucial drivers of progress. This aligns with the

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objectives of SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation, and Infrastructure), and SDG 13 (Climate Action), which emphasize clean energy deployment, innovation, and climate resilience. Although the results are derived from a panel model and are not country-specific, they reveal common trends and policy-relevant relationships that are broadly applicable across the E7 group. The results underscore the importance of coordinated investments in green and digital finance to enhance renewable energy use and achieve emission reduction goals, supporting the broader targets set forth in COP28. These insights can inform regional policy frameworks that promote sustainable energy transitions in emerging economies.

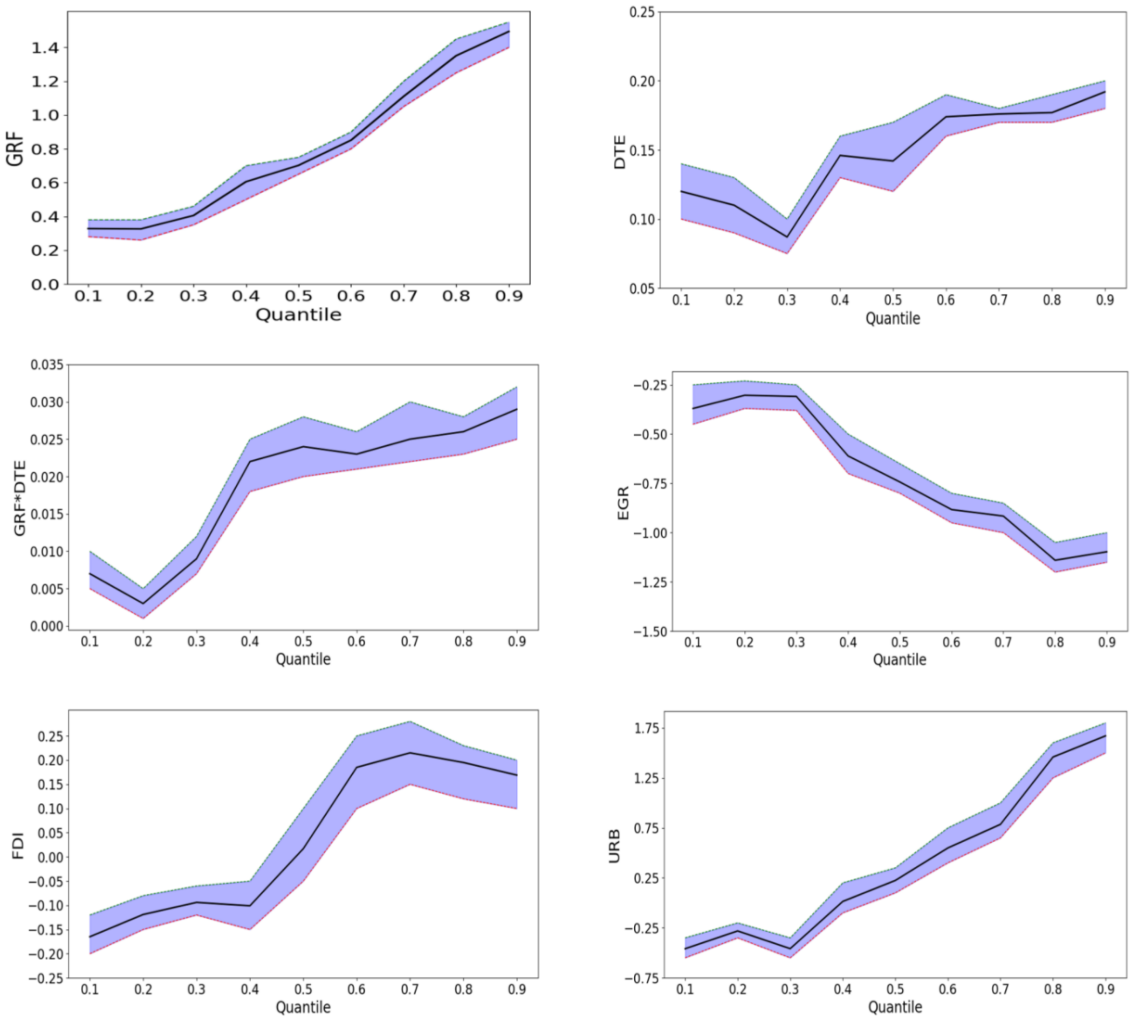

Figure 7. *MMQR estimates plots (Model 2)*

Robustness analysis

To assess the robustness of MMQR results, we also employed the AMG method. A summary of the results for models 1 and 2 can be found in *Table 10*. GRF has a positive effect on energy transition, with a 1% increase in GRF increasing ENT by 0.433% (model 1) and 0.521% (model 2). The DTE also exerts a favorable impact on ENT, increasing by 1% contributes to an increase in ENT by 0.239% (model 1), and by 0.274% (model 2). Additionally, the combined effect of GRF and the DTE positively influences

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energy transition, revealing that a 1% increase in the interaction term (GRF*DGE) corresponds to a 0.067% augmentation in ENT (model 2).

Table 10. *Robustness analysis*

Variables	Model [1]	Model [2]
	Coefficients	Coefficients
GRF	0.433[a]	0.521[a]
DTE	0.239[b]	0.274[b]
GRF*DTE	---	0.067[a]
EGR	-0.230[a]	-0.257[a]
FDI	0.038[c]	0.045[b]
URB	1.619[a]	1.491[a]
Constant	3.168[a]	3.041[a]

AMG estimation results for robustness check (E7 countries, 2003–2022). The letters a, b, and c indicate significance of 1%, 5%, and 10%, respectively. ENT – Energy Transition; GRF – Green Finance; DTE – Digital Economy; GDP – Gross Domestic Product; FDI – Foreign Direct Investment; URB – Urbanization

Conclusion and policy implications

We are currently experiencing severe weather extremes due to global warming, putting both ecosystems and human health at risk. By shifting to renewable energy, ENT serves as a vital strategy for reducing carbon emissions and alleviating global warming. It constitutes a fundamental component of SDG 7 and is pivotal to reaching net zero emissions by 2050, as underscored at COP27 and COP28. In order to accomplish this, significant effort and resources are required. A digital economy could facilitate green financing for ENT, but this assertion lacks empirical evidence, particularly for E7 nations. Therefore, we examine the synergy and heterogeneity of GRF and the DTE in relation to ENT. To do so, this study uses the MMQR technique to estimate results for selected E7 nations between 2003 and 2022. Following are some of the significant conclusions reached. First, GRF appears to have a positive effect on the ENT. Consequently, GRF is essential to the transition to renewable energy sources. Second, there is also a significant positive impact of the DTE on ENT, but this effect is only noticeable at higher quantiles from 0.5 to 0.9. It is noteworthy that this effect shows an increasing trend. Third, it has been shown that GRF contributes to the DTE-ENT nexus, which suggests that the synergy between GRF and the DTE can accelerate ENT.

A number of implications can be drawn from the findings of this study. First, to support the transition from a carbon-based economy, policymakers should focus on developing climate-friendly financial instruments, like green bonds, which can provide the capital required to transform large-scale energy systems. The establishment of a clear and consistent regulatory framework for green finance is crucial to reducing uncertainty and encouraging long-term investment in such initiatives. The government could also develop public-private partnerships to drive renewable energy projects by combining public funding with private sector innovation. Incorporating green finance into national energy policies can significantly contribute to equitably sharing the benefits of energy transition, particularly in regions that are underfunded or underserved.

Second, given the profound impact of DTE on higher levels, the study recommends that policymakers should promote digital infrastructure and innovation, since digital

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technologies can contribute to an accelerated energy transition. A significant area of focus may involve the incorporation of smart grids, energy management systems, and data analytics into national energy strategies to enhance energy distribution and consumption efficiency. By providing incentives for energy companies to adopt advanced technologies, such as AI and blockchain, governments can also increase the efficiency and transparency of renewable energy markets. Moreover, we should prioritize digital education and skill development programs to ensure that the workforce is prepared for a digitally driven energy sector.

Third, given that a developed green financial system is necessary for the advancement of the digital economy, For large-scale renewable energy projects to be financed, governments should establish partnerships between the public and private sectors that utilize both green finance capital and technological advances resulting from the digital economy. Moreover, policies should be formulated to encourage collaboration among energy providers, financial institutions, and tech companies, creating an environment conducive to scaling up digital solutions in conjunction with green investments. Moreover, it is imperative that both digital technologies and green finance are subject to regulation to guarantee their accessibility across all economic sectors, particularly in underdeveloped or emerging markets. A supportive environment for accelerating renewable energy deployment could be created through the implementation of these policy steps.

This work is constrained by certain limitations, which offers scope for further investigation. In this study, renewable energy sources (solar, wind, and geothermal) are not included due to lack of data. Further research could be conducted to determine how GRF and DTE affect various renewable energy categories. Additionally, an analysis of this relationship with respect to a particular country would be valuable. Ultimately, these efforts will contribute to a deeper understanding of climate change issues and a more specialized approach to policy formulation.

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