frontiers | Frontiers in Energy Research

TYPE Original Research
PUBLISHED 21 July 2023
DOI 10.3389/fenrg.2023.1197030

EDITED BY
Xiaohang Ren,
Central South University, China

REVIEWED BY
Mucahit Aydin,
Sakarya University, Türkiye
Najabat Ali,
Hamdard University Islamabad, Pakistan

*CORRESPONDENCE
Ying Chen,
✉ 2021225025119@stu.scu.edu.cn

RECEIVED 30 March 2023
ACCEPTED 06 July 2023
PUBLISHED 21 July 2023

CITATION
Chen Y, Chen Y, Zhang L and Li Z (2023), Revealing the role of renewable energy consumption and digitalization in energy-related greenhouse gas emissions—Evidence from the G7.
Front. Energy Res. 11:1197030.
doi: 10.3389/fenrg.2023.1197030

Revealing the role of renewable energy consumption and digitalization in energy-related greenhouse gas emissions—Evidence from the G7

Yuze Chen, Ying Chen*, Liuyue Zhang and Zhi Li

Business School, Sichuan University, Chengdu, China

The massive consumption of energy promotes rapid economic growth, but it also unavoidably results in a large amount of greenhouse gas emissions, which seriously hinders society's green and low-carbon development. This paper aims to explore the real impact of renewable energy and digitalization on greenhouse gas emissions from an energy-related perspective using advanced panel econometrics methods based on G7 panel data for 1990–2020. Economic growth and energy efficiency are also considered as control variables. Due to the nonlinear properties of panel data, the moment quantile regression approach is utilized in this research. The findings show that slope heterogeneity is widespread, section-dependent, and has a long-term equilibrium relationship. In addition, digitalization, renewable energy, and energy efficiency can reduce energy-related greenhouse gas emissions and ease environmental pressures. Economic expansion, on the other hand, remains an important positive driver for energy-related greenhouse gas emissions. The results of this study are robust and the causal relationships between variables are tested. Based on the conclusion presented above, this study advises the G7 economies to expand investments in renewable energy and digitalization to promote energy system transformation and pave the road for global decarbonization objectives to be met.

KEYWORDS

greenhouse gas emissions, renewable energy, digitalization, energy efficiency, economic growth

1 Introduction

Energy is a critical physical underpinning for economic progress. Energy consumption has increased due to economic expansion, however the increased use of nonrenewable energy sources endangers ecosystems (Adebayo and Rjoub, 2022). The amount of greenhouse gas emissions in the atmosphere has increased dramatically in recent years, causing a slew of natural disasters such as global warming, droughts, and iceberg melting that represent a severe threat to human civilization (Li et al., 2023a). According to the research "*CO2 Emissions in 2022*", despite the fact that the growth of global GHG emissions in 2022 was less than expected, non-renewable energy sources continued to account for a large share of GHG emissions, and many fossil fuel businesses were even reaping record profits (IEA, 2023). Furthermore, the growth in CO2 intensity of energy usage, a substantial contributor to greenhouse gas emissions, is increasing at a quicker rate than the previous 10-year average, which is clearly out of step with the global emission reduction objective (Kirikkaleli et al., 2023). As previously stated, greater attention should be paid to the issue of energy-related greenhouse gas emissions, and more in-depth research on this topic is urgently needed to overcome this conflict and achieve low-carbon development.

The G7 countries accounted for 23.2% of global greenhouse gas emissions in 2020, with fossil fuels accounting for 75% of those emissions, according to the research (Dale, 2021). When the G7 nations signed the Paris Climate Agreement in 2015, they promised to establishing a green, low-carbon society, reducing environmental strains, and achieving sustainable development. G7 members have created policies to modify energy consumption, boost renewable energy consumption while decreasing use of fossil fuels, and promote digitalization to support the transition of energy systems to energy efficiency and low-carbon. These tactics are meant to help the agreement's aims be met more effectively (Voumik et al., 2023). The G7 countries continue to enjoy a significant advantage in terms of renewable energy consumption and digitalization, but this does not change the reality that the G7 countries remain large producers of greenhouse gas emissions. As a result, the G7 nations' transition to renewable energy and progress of the energy system through digitalization is slow, and there is still a long way to go before meeting the greenhouse gas emission reduction target (Lei et al., 2022). Therefore, investigating energy-related greenhouse gas emissions in the G7 is essential to meeting the global decarbonization goals.

Several factors, such as energy efficiency and economic growth, have been proven to have an impact on energy-related greenhouse gas emissions (Mirza et al., 2022; Wang et al., 2023a; Gyamerah and Gil-Alana, 2023). However, research on the influence of renewable energy and digitalization on energy-related greenhouse gas emissions is lacking. Renewable energy is regarded as a critical measure for reducing greenhouse gas emissions, protecting ecosystems, and ensuring electricity supply (Xu and Ullah, 2023). Few studies have linked renewable energy to energy-related greenhouse gas emissions in the past, and greater emphasis has been made to the influence of renewable energy on greenhouse gases in recent years. Simultaneously, digitalization, as a virtual approach to complete energy transformation, can increase company resource use, cut energy consumption, and even offer low-carbon financing to enterprises (Wu et al., 2023). Digitalization is also an important aspect in promoting green enterprise transformation and improving green performance (Zhao et al., 2023). Existing studies focus on improving digitalization at the corporate level while neglecting its impact on a country's or economy's total energy system and green development. Although some studies have demonstrated that digitalization can reduce greenhouse gas emissions due to dematerialization effects, further empirical research is needed to evaluate whether it has a major impact on energy-related greenhouse gas emissions. As a result, the following objectives are sought by this essay. The influence of renewable energy on energy-related greenhouse gas emissions is first investigated. Second, evaluate the effect of digitalization on energy-related greenhouse gas emissions. Finally, investigate the effects of energy efficiency and economic growth on greenhouse gas emissions related to energy. To accomplish the research objectives, the study utilizes ENGHG as energy-related greenhouse gas emissions, REC as renewable energy consumption, DIGT as Digitalization, ENERF as energy efficiency, GDP as economic growth.

The inspiration for this research arises from the G7 countries' increasing emissions of energy-related greenhouse gases and the absence of relevant studies to examine the influencing elements of energy-related greenhouse gas emissions. The G7 should be a global leader in decreasing energy emissions, but their growing reliance on chemical fuels has resulted in large emissions of hazardous gases, which have had a severe impact on the global environment. This work has significant implications for worldwide environmental protection. It is critical to emphasize that the G7 study adds to the body of knowledge about the factors that influence energy-related greenhouse gas emissions. Investing in renewable energy and supporting digitalization can help to cut greenhouse gas emissions and enhance environmental quality. The empirical evaluation results are also confirmed. Thus, this study yields novel findings for environmental protection and sustainable development, particularly in G7 economies.

The main contribution of this article is the following three points. The study firstly investigates the influence of renewable energy use and digitalization on energy-related greenhouse gas emissions in G7 economies from 1990 to 2020. Previously, Ahmadi and Frikha (2022) investigated the role of environmental innovation and renewable energy consumption in international trade and discovered novel conclusions. However, digitalization is a novel issue that has not been explored in terms of its impact on energy-related gas emissions. A few studies (Alina-Petronela et al., 2023; Li et al., 2023b; Deshuai et al., 2022) integrate digitalization with renewable energy consumption in non-G7 economies. Therefore, this paper presents new empirical evidence for G7 countries' greenhouse gas emission reductions and energy transformation. Second, the literature on energy-related greenhouse gas emissions and renewable energy consumption is limited. This study examines the actual influence of renewable energy consumption on gas emissions from an energy standpoint, adding to the existing mainstream literature. Third, a thorough empirical examination of the influence of digitalization on energy-related greenhouse gas emissions is carried out. This paper also provides the first simultaneous causal analysis of renewable energy consumption, digitalization, and energy efficiency, as well as energy-related emissions in G7 economies. As a result, this work adds to the current empirical literature in a novel and useful way.

The remainder of the manuscript is organized as follows. The second section examines relevant literature for research analysis. Section 3 contains information on the research's data, model, and methods. Section 4 discusses the findings and comments, while Section 5 discusses the conclusions and policy implications.

2 Literature review

Understanding the nexus between the variables under research is documented in this manuscript section.

2.1 Impact of renewable energy consumption and digitalization on energy-related emissions

REC and DIGT are important factors that influence ENGHG emissions. Several authors have investigated this link and discovered diverse results. There are numerous studies in the existing literature on the relationship between renewable energy consumption and ENGHG emissions that demonstrate that REC has a significant influence on decreasing carbon emissions. Qing et al. (2023) studied the relationship between renewable energy and energy-related emissions using moment quantile regression and discovered that they are interrelated and that renewable energy has a favorable influence. Leng and Zhang (2023) thought that renewable energy may help to reduce carbon emissions while also assisting in the restructuring of the global energy system. Zhang and Zhang (2022) examined renewable energy and ENGHG emissions and discovered that using renewable energy significantly lowered ENGHG emissions in the region. Anser et al. (2021) investigated the impact of renewable energy consumption on BRICS countries and discovered that renewable energy has the potential to considerably cut ENGHG emissions. However, empirical studies from Lei et al. (2022) reveal that the positive shock of renewable energy consumption has a large negative influence on ENGHG emissions, whereas the negative shock of renewable energy consumption leads to an increase in ENGHG emissions in the long run. As a result, it is important to note that the effect of renewable energy consumption on ENGHG emissions may be unclear. The majority of mainstream research concludes that renewable energy consumption has a beneficial environmental impact (Ren et al., 2023a; Yuan et al., 2022; Abbas et al., 2022; Sharma et al., 2021; Mohsin et al., 2021; Hu et al., 2021; Hussain et al., 2021). Furthermore, the following body of work explores the connection between REC and ENGHG emissions (Borzuei et al., 2022; Chien et al., 2022). For causality analysis, Mohsin et al. (2021) showed causal associations in their research.

The influence of digitalization on ENGHG emissions is determined by the national level of digitalization. Huang and Zhang (2023) recently explored the relationship between digitalization, global value chain placement, and carbon emissions. The empirical findings indicated that technological advancements in digitalization can boost low-carbon growth. Digitalization has greatly lowered regional ENGHG emissions, and this effect will be long-lasting (Ma and Wu, 2023). The empirical findings of (Zhang et al., 2023b) demonstrated that digitalization may stimulate energy storage technology innovation and coordinate energy systems, hence lowering carbon emissions. Kuzior et al. (2022) examined the effect of digitalization on ENGHG emissions using EU member states as an example. The empirical findings of Dong et al. (2022) demonstrated that digitalization reduces the intensity of emissions; Ma et al. (2022) predicted that the Chinese economy's digitalization may achieve the carbon-neutrality objective, and empirical results showed that digitalization can limit energy emissions to minimize carbon dioxide production. Chen (2022) evaluated the long-term and significant relationship between digitalization and ENGHG emissions. By lowering energy consumption and increasing the structure and efficiency of energy systems, digitalization can assist accomplish the Sustainable Development Goals (Ali et al., 2023; Ren et al., 2023b; Xu et al., 2022a; Mondejar et al., 2021).

2.2 Nexus between energy efficiency, economic growth, and energy-related emissions

Energy efficiency is critical in reducing CO2 emissions and managing the environment. Li et al. (2022a) researched the impact of energy efficiency and green innovation on ENGHG emissions in China between 1991 and 2019. The empirical analysis found that increasing energy efficiency and green innovation reduces emissions, whereas decreasing energy efficiency and green innovation increases China's CO2 emissions in the long run. Qing et al. (2023) examined the significance of energy efficiency in reducing ENGHG emissions in BRICS countries. Calvillo (2023) evaluated the influence of five different energy system models on energy efficiency and gas emissions, and the empirical results demonstrate that energy system selection is significant in enhancing energy efficiency and, as a result, lowering gas emissions. Mirza et al. (2022) checked the impact of energy efficiency on energy emissions in developing nations. According to the research, energy efficiency is a substantial factor to lowering energy emissions. Tu et al. (2022) evaluated energy efficiency and CO2 emissions connected to energy in RCEP economies. The discovery reveals that energy efficiency can be used as a corrective action to dramatically cut emissions and increase environmental sustainability. Furthermore, the following publications support the favorable impact of environmental innovation on ENGHG emissions (Wang et al., 2023b; Ali et al., 2022; Sattar, 2022; Bao et al., 2022; Mahapatra and Irfan, 2021).

There are plenty of studies in the literature that suggest that economic growth exerts a significant impact on ENGHG emissions (Ren et al., 2022; Wen et al., 2022; Kartal et al., 2023; Kirikkaleli et al., 2023). Su et al. (2023) observed that the effect of economic expansion on ENGHG emissions revealed EKC features. Liu and Ma (2023) demonstrated the link between green economic growth and ENGHG emissions in Belt and Road member nations. Chen et al. (2023) investigated the influence of economic growth on emissions reduction in China's power system, and the empirical findings imply that long-term economic measures to minimize greenhouse gas emissions should be implemented. Chen (2022) evaluated the relationship between CO2 emissions and French economic development from 1975 to 2019. Economic expansion increases CO2 emissions, according to empirical evidence. Obobisa et al. (2022) analyzed the long-term impact of institutional quality and economic growth on CO2 emissions in 25 African nations between 2000 and 2018. According to the findings, economic growth and institutional quality have a favorable effect on CO2 emissions. Other research has demonstrated a positive relationship between ENGHG emissions and GDP (Xu et al., 2022b; Sun et al., 2022). The implication is that GDP will increase, reducing environmental sustainability. The empirical conclusion of Mujtaba et al. (2022) implies that economic expansion suppresses environmental quality in OECD nations; the NARDL model estimates that each 1% rise in economic growth reduces ENGHG emissions by 0.4%. Methodology.

3 Theoretical framework and methodology

3.1 Theoretical framework and model construction

The impact of renewable energy consumption (REC), digitalization (DIGT), energy efficiency (ENERF), and economic growth (GDP) on energy-related greenhouse gas emissions (ENGHG) is discussed in this section. Policymakers around the world have adopted a range of strategies to reduce greenhouse gas emissions, including expanding renewable energy consumption (Xu and Ullah, 2023). Renewable energy development is a critical method for achieving carbon neutrality and mitigating climate change (Tang et al., 2023). Countries must raise the amount of renewable energy, adapt the energy structure, and discover more suitable energy sources to reduce greenhouse gas emissions and enhance environmental quality (Zhang et al., 2023a). In other words, renewable energy is critical for environmental protection, combating climate change, and attaining long-term economic and social growth. Based on the preceding explanation, this analysis assumes that the negative impact of REC on ENGHG is: $\delta_1 = \frac{ENGHG_{it}}{REC_{it}} < 0$. Another important element influencing energy-related greenhouse gas emissions is digitalization (Wu et al., 2023). Digitalization is expected to reduce greenhouse gas emissions. Through the "dematerialization effect," or the movement of the economy from the provision of physical products to the provision of services, digitalization decreases energy-related greenhouse gas emissions (Ozcan and Apergis, 2018; Chen, 2022). Digitalization may maximize the usage of clean energy, capture these energy sources at peak supply periods, and determine the optimum way to store energy, all of which contribute to lower energy consumption and, as a result, lower energy-related greenhouse gas emissions (Wei et al., 2023). Digitalization also contributes to the growth of green innovation by providing technological assistance for firms' green transformation (Li et al., 2022b). Furthermore, digitalization has the potential to transform the economy toward a lighter, more energy-efficient structure, which is critical for long-term sustainability. Based on the foregoing, this analysis assumes that the negative impact of DIGT on ENGHG is as follows: $\delta_2 = \frac{ENGHG_{it}}{DIGT_{it}} < 0$. As technology advances, every economy strives to utilize less energy to get the most out of it. Energy efficiency can lower CO2 emissions and pollution levels immediately (Lei et al., 2022). The combustion of fossil fuels produces a considerable amount of greenhouse gases, and energy efficiency may significantly reduce greenhouse gas emissions both directly from the combustion or use of fossil fuels and indirectly from electricity production (Zhang et al., 2023a). Because these studies indicate that ENERF can lower ENGHG, the following assumptions are made in this study: $\delta_3 = \frac{ENGHG_{it}}{ENERF_{it}} < 0$. Economic growth leads to the expansion of the scale of product production and waste disposal, leading to a large amount of energy consumption, resulting in a large amount of greenhouse gas emissions (Adebayo and Rjoub, 2022; Xue et al., 2022). Rapid economic expansion, in particular, necessitates the use of huge amounts of nonrenewable energy to power conventional industrial sectors and hence raise income levels. Increased wealth encourages industrial product sector output, which increases energy consumption, resulting in high volumes of greenhouse gas emissions (Cheng et al., 2019; Liu et al., 2021). Based on the preceding explanation, this analysis assumes that GDP has the following positive influence on ENGHG: $\delta_4 = \frac{ENGHG_{it}}{GDP_{it}} > 0$.

Five variables are chosen based on the theoretical framework and research aims. Energy-related greenhouse gas (ENGHG) emissions were the dependent variable. Renewable energy consumption (REC) and digitalization (DIGT) are, on the other hand, critical factors. In addition, two control variables were added: energy efficiency (ENERF) and economic development (GDP). Since the combined impact of renewable energy use and digitalization on energy-related greenhouse emissions is still unknown, this study tends to explore the true association between them in the Group of Seven (G7) economies, including United States, United Kingdom, France, Germany, Japan, Italy and Canada. This study covers the period of the last three decades, ranging from 1990 to 2020. Following the literature (Zheng et al., 2023) and (Lei et al., 2022), this study constructes the following general model:

$$ENGHG_{it} = f(REC_{it}, DIGT_{it}, ENERF_{it}, GDP_{it}) \tag{1}$$

For the empirical estimations, the model can be given below:

$$ENGHG_{it} = \gamma_0 + \delta_1 REC_{it} + \delta_3 DIGT_{it} + \delta_2 ENERF_{it} + \delta_4 GDP_{it} + \varepsilon_{it} \tag{2}$$

where γ_0 is the intercept, δ_1, δ_2, δ_3 and δ_4 are the intercept of each explanatory variable, and ε_{it} indicates the model's random error. Besides, i and t in the subscript reveals the cross-section and time period, respectively. The data for all these variables are extracted from various sources, which include OECD[1] and the World Bank[2]. While the importance of other developed or emerging economies in the environment cannot be overlooked, the G7 must take the necessary steps to address the pressing challenges at hand as the global leader in sustainable development and energy policy.

3.2 Description of data and normality check

Initially, this research summarizes the data using descriptive statistics such as mean, median and range. Additionally, the study also evaluated the standard deviation of the data to measure the overall volatility of each data set. Further, this research investigates the regularity of each variable. Specifically, skewness and kurtosis are estimated to understand if the data have a regular distribution. In this sense, the current study calculates skewness and Kurtosis against critical values of 1 and 3, respectively. This research additionally uses the Jarque and Bera (1987) normalcy test, which assumes skewness

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[1] Data for ENGHG and DIGT [Individuals using the Internet (% of population)] are obtained from the OECD (2022) website, available at: https://stats.oecd.org/

[2] Data for GDP (constant US dollars 2015), REC (% of total final energy consumption), and ENERF [GDP per unit of energy use (constant 2017 PPP $ per kg of oil equivalent)] from the World Development Indicators of the World Bank (2022), available at: https://databank.worldbank.org/source/world-development-indicators#

and excess Kurtosis to be equivalent to zero. The statistics of may be calculated using the following equation:

$$JB = \frac{N}{6}\left(S^2 + \frac{(K-3)^2}{4}\right) \tag{3}$$

3.3 Slope heterogeneity and cross-section dependence

Since this study focuses on panel data, panel data techniques are appropriate to use. This research examines panel data properties including Slope heterogeneity and Cross-section Dependence. These two panel data issues are considered crucial and if not solved, the results will be biased and inaccurate (Wei et al., 2022). Considering the G7 countries are all sophisticated economies, it is critical to determine whether they have any similarities. Using the slope coefficient homogeneity test devised by Pesaran and Yamagata (2008) is better, since it produces both the standard slope coefficient homogeneity and the adjusted slope coefficient homogeneity, as follows:

$$\Delta_{SCH} = (N)^{1/2}(2k)^{-1/2}\left(\frac{1}{N}\acute{S} - K\right) \tag{4}$$

$$\Delta_{ASCH} = (N)^{1/2}\left(\frac{2K(T-K-1)}{T+1}\right)^{-1/2}\left(\frac{1}{N}\acute{S} - K\right) \tag{5}$$

where Δ_{SCH} defines the slope coefficient homogeneity and Δ_{ASCH} specifies the adjusted slope coefficient homogeneity.

Under the influence of economic globalization, activities such as foreign trade, capital flows, and technology transfer potentially increase a country's dependence on other economies, as well as the dependence of other economies or regions on it. Yet, ignoring *PCD* may lead to erroneous and misleading study findings (Campello et al., 2019). In this study, Pesaran (2004) 's *PCD* test is employed to assess cross-section dependency across the G7 countries, which takes independent cross-sections as the null hypothesis, stated as:

$$CD_{Test} = \sqrt{\frac{2T}{N(N-1)}\sum_{i=1}^{N-1}\sum_{k=1+i}^{N} T_{ik}} \tag{6}$$

3.4 Unit root testing

Due to the possible commonality of the panel data, this study uses a unit root estimator to address SCH and PCD issues. In particular, this study employs the Pesaran's (2007) cross-sectional IPS (CIPS) test. Pesaran (2006) skillfully constructed a factor model to analysis the cross-sectional dependence of unexplained cross-sectional averages; Pesaran (2007) managed to modify the Augmented Dickey-Fuller regression by combining the average and first differed cross-section lags. This methodology produces cross-sectional dependence even though the panels are unbalanced (T > N or N > T). The basic CIPS equation is as follows:

$$CIPS = N^{-1}\sum_{i=1}^{N} CADF_i \tag{7}$$

The CIPS test assumes the existence of a unit root in the time series.

3.5 Cointegration

This study uses the error correction framework of Westerlund (2007) to assess the long-run equilibrium relationship between the variables under consideration. This test is designed to provide accurate estimates despite the cross-sectional dependence and slope fluctuations. Since it considers both group mean statistics, *i.e.*, $G_\tau = \frac{1}{N}\sum_{i=1}^{N}\frac{\alpha_i}{S.E\alpha_i}$ and $G_a = \frac{1}{N}\sum_{i=1}^{N}\frac{T\alpha_i}{\alpha_i(1)}$, and the panel statistics, *i.e.*, $P_\tau = \frac{\alpha}{S.E(\alpha)}$ and $P_a = T.\alpha$.

3.6 Method pf moment quantile regression (MMQR)

As the estimation results verify the cointegration between the variables, the study considers the non-normality, which leads to a new estimation method, i.e., Method of Moments Quantile Regression (MMQR) (Koenker and Bassett, 1978). Quantile regression works well when the dataset's distribution is asymmetrical or follows the properties of non-normal distribution (Shahzad et al., 2023). Machado and Santos Silva (2019) designed the MMQR technique for assessing the dispersion of quantile estimates (Sarkodie and Strezov, 2019), which is a solution to the problem of non-normality. Equation **8** provides the conditional quantile location-scale variant $Q_y(\tau|R)$ as follows:

$$Y_{it} = \alpha_i + \beta R_{it} + (\gamma_i + \rho Z_{it})\mu_{it} \tag{8}$$

Here, the probability representation $p(\gamma_i + \rho Z_{it} > 0)$ is equal to one, whereas α, β, γ, and ρ indicate the coefficients to estimate. The subscript "i" presents the fixed effect for $i = 1, 2, \ldots, n$.In addition, R is a component of the k-vector, denoted by Z, and the symbol "l" indicates a distinctive variation.

$$Z_1 = Z_l(R), l = 1, 2, \ldots, k \tag{9}$$

where R_{it} is distributed symmetrically and independently for the total fixed i and t time, which is orthogonal to both i and t (Machado and Santos Silva, 2019). Therefore, the outer reserves and external components are both stabilized. Following the context, the constructed model may be modified as follows:

$$Q_y(\tau R_{it}) = (\alpha_i + \gamma_i q(\tau)) + \beta R_{it} + \rho Z_{it} q(\tau) \tag{10}$$

where R_{it} captures explanatory variables such as REC, ENERF, DIGT, and GDP in logarithmic form. In addition, R_{it} reveals the quantile dissemination of the predictor variables (Y_{it}), which is ENGHG emissions in this study, which also replies on the quantile's position. Furthermore, $[-\alpha_i(\tau) \equiv \alpha_i + \gamma_i q(\tau)]$ is a scalar coefficient that demonstrates the stable influence of τ quantiles on i. In contrast, the influence of each quantile does not influence the intercept. Due to the separate temporal structure of variables, various impacts are vulnerable to modification. Lastly, $q(\tau)$ symbolizes the $\tau - th$ quantiles' sample, which are $Q^{0.25}$, $Q^{0.50}$, $Q^{0.75}$, and $Q^{0.90}$ in this research. This study uses the quantile equation as follows:

$$min_q \sum_i \sum_t \theta_\tau(R_{it} - (\gamma_i + \rho Z_{it})q) \tag{11}$$

where $\theta_\tau(A) = (\tau - 1)AI\{A \leq 0\} + TAI\{A > 0\}$, denotes the check function.

As robustness estimation, this work used Bootstrap Quantile Regression (BSQR) technique after obtaining empirical data for each variable by MMQR. The BSQR method is a gap technique for analyzing confidence intervals and statistical significance, which uses algorithmic capabilities to estimate the sample distribution of the evaluation model. The BSQR method has the merit of obtaining quantifiable information, which avoids asymptotically normal sample distribution restrictions. The BSQR approach could offer more efficient estimation and empirical results (Markus and Groenen, 1998).

3.7 Causality

Due to the lack of causality between the dependent and explanatory variables in the above method, even the presence of an unbalanced panel (T is not equal to N) will not provide an optimal and accurate estimate. This study uses the panel Granger causality test developed by Dumitrescu and Hurlin (2012), which is more powerful and deals well with the panel data including cross-section dependency and slope variability (Banday and Aneja, 2020).

4 Results and discussion

4.1 Pre-estimation diagnostics

To begin with, this study performed a descriptive diagnosis of the statistics including mean, median, maximum and minimum values. The means and medians of all variables in this study are positive, indicating that these variables have increased over time. The standard deviation of variables illustrates the volatility of the data and the extent to which they deviate from the mean position. Kurtosis and skewness can reflect the symmetry and peakedness of the data distribution. According to Table 1, it can be seen that DIGT, REC and ENERF show a skewed negative distribution, and ENGHG emissions and GDP show a skewed normal distribution. In this study, the non-normality of the data distribution was verified using the Jarque Bera method, and the probability statistics showed significant results, leading to the rejection of the original hypothesis and the conclusion that all variables are asymmetrically distributed.

4.2 Heterogeneity and cross-sectional dependence

Since this study deals with panel data from seven developed countries and spans the period 1990–2020, it is necessary to perform slope homogeneity and cross-sectional dependence tests before panel data analysis. The estimation results of these checks are presented in Tables 2, 3. According to the empirical result in Table 2, the empirical result in Table 2 indicates that SCH and ASCH statistics are significant at the 1% level of significance, thus rejecting the original hypothesis of homogeneity. According to the empirical result of PCD in Table 3, all variables are statistically significant at the 1% level of significance, thereby rejecting the null hypothesis and concluding that all variables in G7 countries are interrelated and cross-dependent.

TABLE 1 **Descriptive statistics and normality check.**

	ENGHG	ENERF	REC	GDP	DIGT
Mean	5.912288	0.973963	0.845016	12.47180	1.287627
Median	5.766890	0.980833	0.885926	12.40000	1.779600
Maximum	6.799500	1.218130	1.355834	13.30050	1.984530
Minimum	5.481930	0.625786	−0.215908	11.97020	−1.75586
Std. Dev	0.385423	0.156941	0.374385	0.328408	0.922636
Skewness	1.317022	−0.521112	−0.719397	1.095840	−1.514446
Kurtosis	3.589487	2.463776	3.159050	3.555002	4.206638
Jarque-Bera	65.87473	12.42114	18.94613	46.21637	96.11437
Probability	0.000000	0.002008	0.000077	0.000000	0.000000

TABLE 2 **Slope heterogeneity.**

Slope heterogeneity test	Statistics
$\tilde{\Delta}$	17.111[a]
$\tilde{\Delta}^{\text{Adjusted}}$	18.684[a]

Significance level is denoted by.
[a] For 1%.
[b] For 5%.
[c] For 10%.

TABLE 3 **Cross-sectional dependence.**

Cross-sectional dependence	
ENGHG 9.803[a]	ENERF 23.523[a]
REC 19.984[a]	GDP 23.456[a]
DIGT 25.323[a]	

Significance level is denoted by.
[a] For 1%.
[b] For 5%.
[c] For 10%.

4.3 Unit root analysis and cointegration tests

In this study, the CIPS unit root test of Pesaran (2007) was used. Table 4 provides the stationary results of unit root analysis. The test result reveals that REC, DIGT, and ENERF are significant, but ENGHG emissions and GDP are not significant, which indicates the existence of unit roots for these two variables. In addition, by testing the first-order difference data for these two non-stationary variables, this verifies their stationary and permits this research to investigate the long-term relationship.

The results of the unit root test indicate that all variables are stationary, so the existence of a long-run cointegration relationship between them needs to be examined. The Westerlund ECM Cointegration Test is employed in this study. The empirical result from Table 5 reveals that there is no cointegration in the

TABLE 4 Unit root testing.

Variables	Intercept and trend	
	I (0)	I (1)
ENGHG	−2.515	−5.415^{a}
ENERF	−3.102^{a}	-
REC	−3.026^{b}	-
GDP	−1.904	−4.201^{a}
DIGT	−3.037^{b}	-

Significance level is denoted by.

[a] For 1%.

[b] For 5%.

[c] For 10%.

I (0) is for level, and I (1) is for the first.

TABLE 5 Cointegration testing.

Variable	Value	*Z*-value	*p*-value
G_t	−2.682	−1.808	0.035^{b}
G_a	−10.474	−0.221	0.413
P_t	−6.116	−1.451	0.073^{c}
P_a	−8.024	−0.691	0.245

Significance level is denoted by.

[a] For 1%.

[b] For 5%.

[c] For 10%.

original hypothesis. The significant *p*-values demonstrate a long-term correlation between the variables, indicating that ENERF, REC, GDP, and DIGT are cointegrated with ENGHG emissions.

4.4 Method of moments quantile regression

The above empirical findings indicate that long term relationships exist between the variables explored, therefore, this study attempts to explore their effects on ENGHG emissions. The non-normality of the information leads to the choice of a new approach, i.e., MMQR for empirical results. The primary results are provided in Table 6. First, energy efficiency is significantly and negatively correlated with ENGHG emissions in all quartiles, which suggests that in the G7, improving energy efficiency can reduce ENGHG emissions. The variable finding is consistent with (Li et al., 2022a; Lei et al., 2022; Mirza et al., 2022). Next, the coefficients of all quartiles of economic growth are negative, indicating a significant negative correlation between GDP and ENGHG emissions. The negative impact of economic growth is consistent with (Iqbal et al., 2022; Obobisa et al., 2022; Sufyanullah et al., 2022; Xue et al., 2022). This means that economic growth will largely aggravate environmental pollution. Further, renewable energy consumption is significant in the first and second quartiles and the coefficients are all negative, which indicates that increased REC could lower ENGHG emissions. The estimated results are in line with the existing studies of (Apergis et al., 2023; Mukhtarov et al., 2023). Finally, all coefficients of the digitalization are also negative, which demonstrates a negative correlation between DIGT and ENGHG emissions. The result is consistent with (Ke et al., 2022; Ma and Wu, 2023). This suggests that the advancement of digitalization allows for a reduction in ENGHG emissions while also improving environmental quality. Figure 1 depicts the trend graphs between all variables in the moment quantile regression and energy-related greenhouse gas emissions.

TABLE 6 Primary results-MMQR.

Variable	Location	Scale	Quantiles			
			$Q_{0.25}$	$Q_{0.50}$	$Q_{0.75}$	$Q_{0.90}$
ENERF	−0.864^{a}	0.152^{a}	−0.991^{a}	−0.800^{a}	−0.704^{a}	−0.652^{a}
	[0.062]	[0.037]	[0.071]	[0.065]	[0.070]	[0.101]
REC	−0.060^{a}	0.039^{a}	−0.093^{a}	−0.043^{c}	−0.018	−0.005
	[0.023]	[0.014]	[0.025]	[0.024]	[0.027]	[0.034]
DIGT	−0.020^{c}	−0.004	−0.018	−0.022^{c}	−0.024^{c}	−0.025^{c}
	[0.011]	[0.007]	[0.012]	[0.011]	[0.013]	[0.015]
GDP	1.039^{a}	−0.045^{a}	1.077^{a}	1.020^{a}	0.992^{a}	0.976^{a}
	[0.016]	[0.010]	[0.019]	[0.017]	[0.019]	[0.027]
Constant	−6.127^{a}	0.454^{a}	−6.508^{a}	−5.935^{a}	−5.647^{a}	−5.493^{a}
	[0.229]	[0.138]	[0.253]	[0.245]	[0.282]	[0.345]

Here, ENGHG, is the dependent variable. Significance level is denoted by.

[a] For 1%.

[b] For 5%.

[c] For 10%.

4.5 Robustness check—BSQR

This study used Bootstrap Quantile regression to assess the model's robustness, and the results indicate that the model utilized in this study is stable and dependable. Significant robustness analysis results are presented in Table 7, especially at the ($Q_{0.75}$) and ($Q_{0.90}$) quartiles. The trend of all variable coefficients in Bootstrap Quantile regression is plotted in Figure 2.

4.6 Causality analysis

Since moment quantile regression is unable to reveal the causal relationship between variables, this study employs the Dumitrescu and Hurlin's (2012) panel Grander causality test, and estimated results are shown in Table 8. The variable pairs ENERF≠ENGHG, ENGHG≠ENERF; REC≠ENGHG, ENGHG≠REC; GDP≠ENGHG, ENGHG≠GDP are significant. However, no significant causal relationship was found between DIGT and ENGHG emissions. For the assessment of causal relationships between variables in line with the literature (Anser et al., 2021; Eskander and Istiak, 2021; Lei et al., 2022; Tufail et al., 2022; Mukhtarov et al., 2023; Zheng et al., 2023).

4.7 Empirics discussion

The empirical econometric results above illustrate a long-term relationship between four variables in G7 advanced countries:

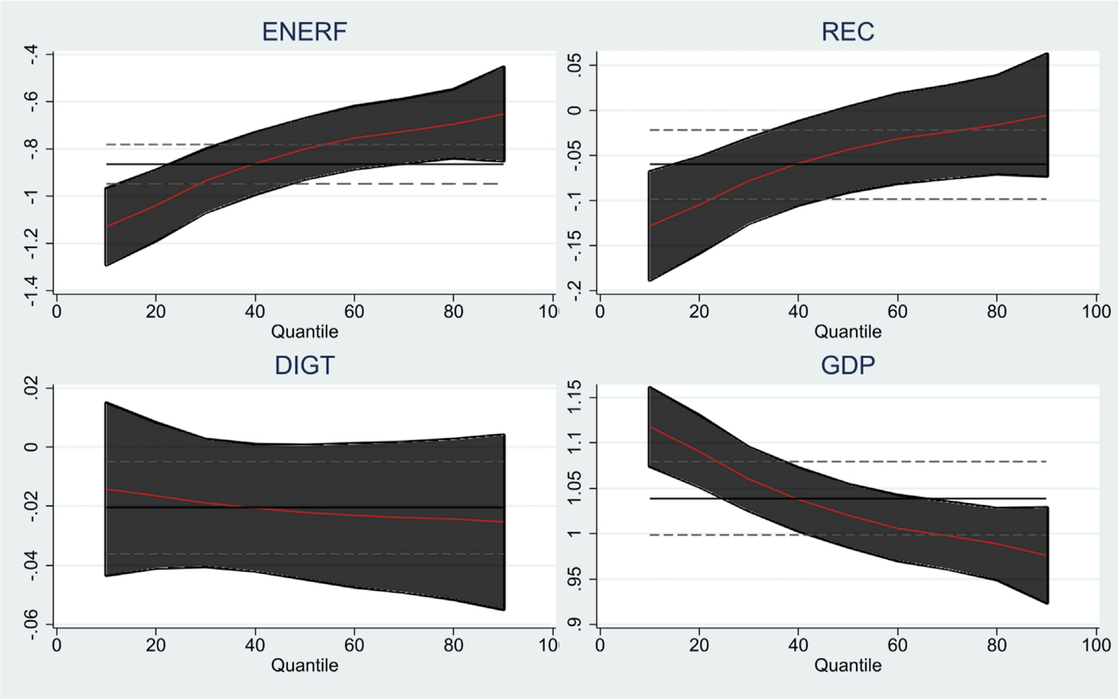

FIGURE 1
Graphical depiction of MMQR Quantiles.

TABLE 7 **Robustness results-BSQR.**

Variable	Quantiles			
	$Q_{0.25}$	$Q_{0.50}$	$Q_{0.75}$	$Q_{0.90}$
ENERF	−1.191^{a}	−0.784^{a}	−0.763^{a}	−0.792^{a}
REC	−0.093^{b}	0.017	−0.058^{a}	−0.080^{a}
DIGT	0.008	−0.031^{a}	−0.016^{a}	−0.010^{a}
GDP	1.069^{a}	1.058^{a}	0.994^{a}	0.969^{a}
Constant	−6.258^{a}	−6.462^{a}	−5.598^{a}	−5.235^{a}

Here, ENGHG, is the dependent variable. Significance level is denoted by.
[a] For 1%.
[b] For 5%.
[c] For 10%.

energy efficiency (ENERF), renewable energy consumption (REC), digitalization (DIGT), and economic development (GDP). Empirical results reveal that REC has a negative influence on ENGHG of G7 economies, which is consistent with (Xiong et al., 2022; Zhang and Zhang, 2022). These two studies, conducted in BRICS and Belt and Road nations, looked at the detrimental impact of renewable energy on energy-related greenhouse gas emissions. These studies give actual evidence of renewable energy's negative influence on greenhouse gas emissions in various economies. The essence of renewable energy's negative impact on energy-related greenhouse gas emissions is a shift in energy mix. Renewable energy, as an alternative to traditional fossil fuels, can have a low carbon footprint or minimize greenhouse gas emissions and other chemical pollutants in the manufacturing process. According to the findings of Lei et al. (2022)'s survey on renewable energy in China, renewable energy has some benefits over traditional fossil fuels in terms of energy supply diversification and environmental sustainability. However, renewable energy confronts several challenges, including expensive construction and development costs, challenging storage, and a long payback period. Sanchez et al. (2022) illustrated this in their investigation of alternative energy choices. Therefore, finding acceptable alternative energy sources, boosting renewable energy conversion efficiency, and lowering investment prices are critical ways to minimize greenhouse gas emissions from energy sources.

DIGT, on the other hand, has a negative influence on ENGHG, as evidenced by Alina-Petronela et al. (2023)'s European nation survey. The results of our research suggest that digitisation reduces energy-related greenhouse gas emissions. Previously, the OECD (2010) estimated that digitalization would expand the manufacturing scale of information and communication technology, resulting in increased energy consumption and greenhouse gas emissions. However, current empirical studies on digitalization indicate that this viewpoint is certainly no longer prevalent. Digitalization is considered as a blessing for lowering greenhouse gas emissions (Chen, 2022). Digitalization promotes national energy system transformation, increases clean energy efficiency, decreases energy consumption in the economic system, and reduces energy-related greenhouse gas emissions. ENERF had a detrimental influence on ENGHG as well. Mirza et al. (2022) and JinRu and Qamruzzaman (2022) also corroborated this conclusion. These studies indicate that increasing energy efficiency may save the country money while also lowering energy-related greenhouse gas emissions. Empirical results reveal that GDP boosts ENGHG emission, which is consistent

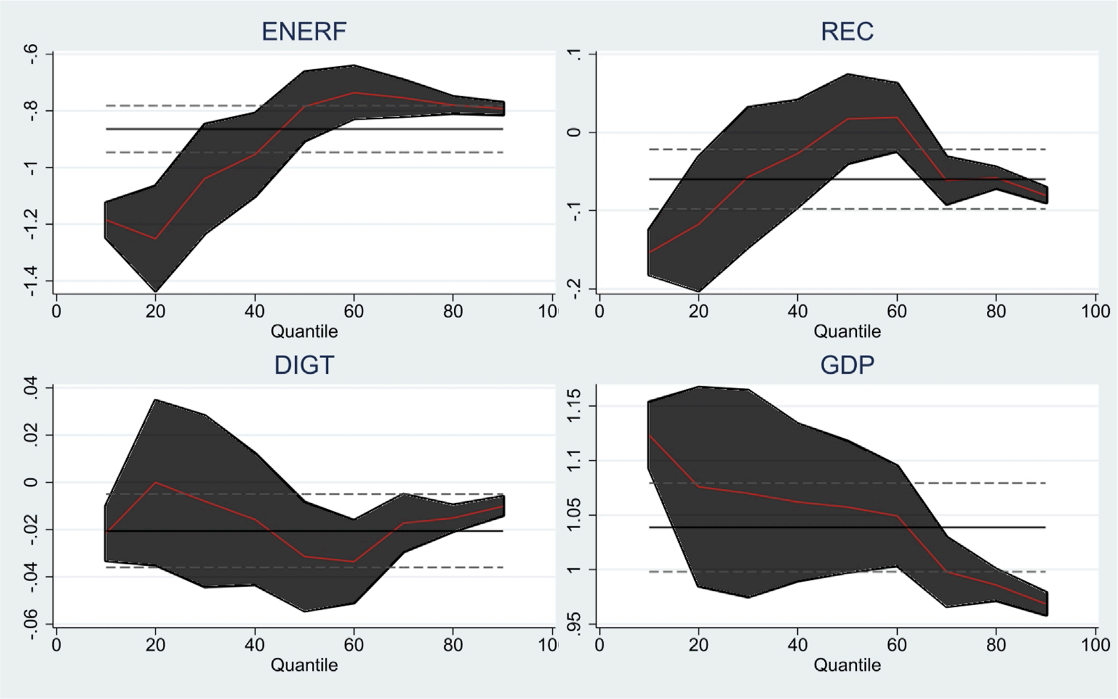

FIGURE 2
Graphical depiction of the coefficients—BSQR.

TABLE 8 Panel causality test.

H_0	Wald$_{\text{stats}}$	$\overline{Z}_{\text{stats}}$	*p*-value
ENERF≠ENGHG	3.37702[a]	3.74241	2.E-04
ENGHG≠ENERF	3.91679[a]	4.62184	4.E-06
REC≠ENGHG	6.90453[a]	9.48960	0.0000
ENGHG≠REC	3.85634[a]	4.52336	6.E-06
DIGT≠ENGHG	1.71552	1.03543	0.3005
ENGHG≠DIGT	1.29473	0.34984	0.7265
GDP≠ENGHG	5.40511[a]	7.04668	2.E-12
ENGHG≠GDP	2.19319[c]	1.81367	0.0697

Significance level is denoted by.
[a]For 1%.
[b]For 5%.
[c]For 10%.

with (Gyamerah and Gil-Alana, 2023; Yahyaoui, 2023). Economic development is still heavily reliant on nonrenewable resources, resulting in significant greenhouse gas emissions.

In conclusion, investigating the link between energy efficiency, renewable energy consumption, digitalization, and economic growth, as well as energy-related greenhouse gas emissions in the G7, is critical for balancing economic and environmental progress. Many industries rely on energy inputs to grow, which increases greenhouse gas emissions and environmental pressures. Consumption of renewable energy and digitalization necessitate large investment expenditures that middle-income or rising nations may be unable to finance. Improvements in energy efficiency may result from technology breakthroughs, investment in R&D expenses, and other causes, but no immediate advantages should be expected. Large-scale energy efficiency gains take time, and ineffective energy efficiency switching can stymie national economic development. Storage and other issues hinder green progress when it comes to adopting and integrating renewable energy sources. In this context, the empirical outcomes of this study may give a path for academics, politicians, and regulators to take appropriate action in order to achieve low-carbon development.

5 Conclusion and policy implication

5.1 Conclusion

The research investigated the influence of renewable energy consumption, digitalization, energy efficiency, and economic growth on energy-related greenhouse gas emissions in the G7 economies objectively. The simultaneous evaluation of these factors in G7 economies was unique. Despite substantial research, their relevance to energy-related greenhouse gas emissions has received little attention. As a result, this research investigated the genuine impact of renewable energy consumption and digitalization on energy-related greenhouse gas emissions. Advanced econometric tools were employed in this work to analyze in depth the factors influencing energy-related greenhouse gas emissions. On the one hand, empirical studies suggested that promoting renewable energy may reduce reliance on fossil fuels, achieve carbon neutrality and ameliorate climate change, and promote green and low-carbon growth. By facilitating energy system transition and improving energy sector structure, digitalization can help to reduce energy-related greenhouse gas emissions. On the other hand, economic development and energy efficiency are major elements in reducing emissions and improving the environment. The estimated results are consistent with the existing mainstream literature. Overall, our research uncovered novel connections between renewable energy use, digitalization, energy efficiency, and energy-related greenhouse gas emissions. This discovery has the potential to significantly improve environmental quality and achieve sustainable development.

5.2 Policy implications

Based on the findings of the empirical research, this paper suggests some policy recommendations that may assist governments and policymakers in developing and implementing effective policies to reduce energy emissions. Renewable energy consumption should be encouraged in developed countries, and government incentives and aid should be offered to sectors transitioning to clean energy. Simultaneously, investment and government spending in energy technology must be expanded, prompting policymakers to place a greater emphasis on energy-related technical innovation. A higher degree of digitalization will reduce environmental impact; consequently, the development of smart technology in the digital sphere should be supported. Furthermore, for global environmental sustainability, economic development in industrialized economies must minimize reliance on nonrenewable energy sources.

5.3 Limitations and future research direction

This study primarily looks at the influence of these elements in G7 nations; nevertheless, the impact may be significant in other economies throughout the world, particularly in terms of digitalization. Future studies might look into the impact of digitalization in different economies. In addition, the larger data set can improve the comprehensiveness of the study model, which future researchers can accomplish.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

YuC: contributed to developing the idea, software, analysis, overall writeup and estimations of the results. YiC: Proofread, review. LZ: estimations, preparing draft. ZL: review. All authors contributed to the article and approved the submitted version.

Acknowledgments

The authors would like to acknowledge the support from the program “Research and application of key technologies of new generation enterprise digital platform” (No. 0050205502322).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher’s note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenrg.2023.1197030/full#supplementary-material

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