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Determinants of carbon emissions cycles in the G7 countries

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ABSTRACT

This paper investigates the relationships between economic growth, energy consumption, exports, tourism, geopolitical risk, and carbon dioxide (hereafter cited as “CO_2”) emissions in Group of Seven (hereafter cited as “G7”) countries from 1990 to 2021. Cross-sectional correlation tests, unit root tests, cointegration analysis, regression analysis, panel data estimation, and Granger causality tests are performed. The empirical results show that energy consumption and geopolitical risk negatively affect environmental quality. In addition, globalization exacerbates the problem of ecological degradation. At the same time, the increase in export levels and emerging tourism development are conducive to reducing CO_2 emissions. It is recommended that policymakers pay attention to the role of the digital economy and technological innovation in shaping the energy consumption patterns, carbon emissions, and geopolitical risks in G7 countries, encourage digital transformation, use technological innovation in energy efficiency to drive economic growth, use the digital economy to promote sustainable tourism, decouple it from high carbon emissions, challenge the traditional Environmental Kuznets Curve (hereafter cited as “EKC”) framework, and jointly promote dual sustainable development of the economy and environment.

1. Introduction

In recent years, global climate change has aroused widespread concern. According to the sixth assessment report of the Intergovernmental Panel on Climate Change (hereafter cited as “IPCC”), since the last half of the 19th Century (1850–1900), the global average surface temperature has risen by about 1 °C, and in the next 20 years, the global temperature rise is expected to reach or exceed 1.5 °C. At the same time, the IPCC report shows that carbon dioxide remains the main driving factor of climate change. The concentration of carbon dioxide in the atmosphere is at the highest level in at least 2 million years. The impact of global warming on the climate system, sea level, Arctic sea ice, permafrost, mountain glaciers, and polar ice sheets will be irreversible on a time scale of hundreds to thousands of years in the future (Blunden and Boyer, 2022). Climate change has aroused widespread concern because the ever-increasing change in the environment threatens many aspects of society including politics, the economy, the ecosystem, social development, and human health and life. The IPCC report emphasizes that climate change and global warming will lead to frequent extreme weather events, food crises, floods, drought, and, counterintuitively, heat waves. Today, scientists agree that the massive and rapidly increasing carbon dioxide emission caused by human activities is the primary driver of climate warming. Human activities will increase the level of greenhouse gases in the atmosphere, leading to global surface temperature rise, exacerbated by the greenhouse effect, and causing still more global warming (Mossler et al., 2017).

The increasing threats of global warming have led to a surge in innovations aimed at energy efficiency and sustainable practices. As CO_2 levels rise, there is an observed positive response in climate-change-related innovations, especially in the energy sector (Su and Moaniba, 2017). Innovations in technology and practices can, if not eliminate, certainly ameliorate the impact of climate change by reducing the amount of CO_2 that human activity puts into the atmosphere.

Many studies have identified factors that affect CO_2 emissions. They include: economic growth; foreign direct investment; renewable energy consumption; real effective exchange and, international trade. However,

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tourism may also have some impact on CO_2 emissions. Although tourism is low energy consumption, low pollution industry, and a "smokeless industry," tourism still has many carbon emissions, mainly from tourism activities and industrial links that consume more energy such as transportation, especially air flight, accommodation, theme park entertainment, and skiing. According to the latest research by the World Tourism Organization, global carbon emissions from tourism transportation are expected to increase from 1.697 billion tons in 2016 to 1.998 billion tons by 2030, accounting for 5.3 % of the total anthropogenic CO_2 emissions. The current research results regarding the relationship between tourism and carbon dioxide emissions are mixed. Some studies found that the number of tourists increased by 1 %, and the carbon dioxide emissions increased by 0.98 % (Rabindra et al., 2019). However, some studies have reached the opposite conclusion. Those researchers found that due to the development of sustainable tourism, tourism is conducive to reducing CO_2 emissions (Wan and Tantatape, 2013).

In addition, the geopolitical risk (hereafter cited as "GPR") index is usually ignored when the analysis of climate change is undertaken. Nevertheless, the GPR directly reflects the impact of international tensions, terrorism, and other malignant events. Since the beginning of the new century, with the accelerated evolution of the world's unprecedented changes, notably the ongoing so-called "global war on terror," geopolitical risks have become increasingly significant. As geopolitical tensions impact a country or region's economy, they will, inevitably, affect the uncertainty of the real economy, financial markets, and future policies. Since 1961, history has shown that years with an increase in GPR often correspond to adverse shocks such as a significant decrease in the global Gross Domestic Product (hereafter cited as "GDP") growth rate. As a member of the G7 countries, since 1985 in the United States, with the increase of GPR, financial market volatility has increased, stocks, international oil prices, and other indicators have shown a downward trend, and the labor market has continued to deteriorate.

The growing digital economy introduces new geopolitical risks, including, for example, cyber warfare, data privacy concerns, and digital trade barriers. The shift to a digital economy can lead to a decrease in traditional industrial energy consumption. However, the energy demands of data centers, digital infrastructures, and electronic devices are on the rise. As a significant component of the digital economy, although e-commerce can reduce the need for physical store visits, the increase in delivery vehicles can offset these benefits, influencing carbon emissions through logistics and transportation. These can influence international relations and, indirectly, energy markets. As a net energy importer, the UK, one of the G7 countries, was severely affected by the energy supply crisis caused by the Russia-Ukraine War and experienced severe inflation. In July 2022, the UK's consumer price inflation rate jumped to 10.1 %, the highest since February 1982.

Researchers have studied the uncertain impact of the GPR index on the macro effects of the global oil market (Gu et al., 2021). Subsequently, the QARDL method was used to study the asymmetric impact of geopolitical risks on China's crude oil prices. Ren et al. (2023) found that geopolitical risk factors can trigger an increase in energy prices in the short term. As the GPR index continues to increase, the oil market's volatility shows price increases in the vast array of products dependent on oil. Conflicts or geopolitical shocks between countries can lead to a short-term increase in the GPR index, resulting in significant fluctuations in energy prices. As an example of how these factors interrelate, consider the case of the ongoing Russia-Ukraine war. Russia is a major net exporter of oil. However, due to the outbreak of the Russia-Ukraine War on February 24, 2022, geopolitical instability caused huge losses to the economy, politics, and people's livelihoods of each country, but also led to a surge in oil and gas prices, tense international energy supply and demand relations, and to some extent, had an impact on the international energy market, all of which suggests decision makers should pay more attention to the importance of GPR.

To understand the factors influencing climate change, this study addresses the following questions: (1) Does geopolitical risk in the digital age affect CO_2 emissions? If so, what is the impact path and direction? (2) Is the EKC framework incorporating geopolitical risk factors influential in G7 countries? It has been noted that tourism often affects fossil fuel use and land degradation, thereby increasing CO_2 emissions (Gössling, 2002). However, the existing literature rarely quantifies these impacts.

In contrast, qualitative research on the ecological effects of tourism is more common (Cadarso et al., 2015). By way of example, a research study of the relationship between tourism and carbon dioxide emissions in Türkiye involved controlling GDP and energy consumption during 1960–2014 and found that higher energy consumption in the tourism sector and the establishment of new tourism facilities will promote carbon dioxide emissions, soil structure deterioration, and pollution (Eyuboglu and Uzar, 2020). Other research has also shown the relationship between geopolitical risk and carbon emissions. China's data were used to confirm that the upper quantiles of factors such as geopolitical risk show a positive and significant correlation with CO_2 emissions (Du and Wang, 2023). To understand the impact of energy, exports, tourism development, and geopolitical risks on carbon dioxide emissions, this study conducted an empirical analysis based on the annual data provided by the World Bank and examined the factors affecting the carbon dioxide emissions of G7 countries from 1990 to 2021.

The present study is designed to make necessary recommendations for future actions to reduce carbon emissions, reduce the impact of geopolitical risk factors on carbon dioxide emissions, and help the government formulate corresponding policies and strategies to achieve sustainable environmental development. It makes several contributions to the existing knowledge of the causes and effects of climate change. Previous studies have addressed the relationship between energy, import and export trade, tourism or, tourism growth, and energy growth consumption. This research project is the first to incorporate energy, exports, tourism, and geopolitical risks into a diverse framework, analyzing the relationship between energy and the environment and the EKC hypothesis.

In addition, this study focuses on the G7 country group because the total GDP of the G7 accounts for about 45 % of the world's GDP. Since the G7 is such a large component of the world's economy, it plays a vital role in the energy, trade, and tourism sectors. Anything that affects the group responsible for such a significant part of the world's economy and, therefore, generating such a large component of greenhouse gas emissions, needs such in-depth study. As a methodological contribution, this study uses unit root tests (HT, Breitung, and CIPS panel unit root tests) and kao cointegration since the refusal to acknowledge cross-sectional correlation problems can lead to unreliable results. This approach addresses the problem of cross-sectional correlation since Pesaran's CD test (Pesaran, 2021), shows that perturbations in each panel time-series data are cross-sectionally correlated. In addition, the long-run coefficients are estimated using a dynamic ordinary least squares model. Furthermore, unlike the standard causality test approach, which assumes that all coefficients vary across the cross-section, the Dumitrescu-Hurl causality test works well enough for cross-sectional dependence.

The remainder of the paper is organized as follows: Section 2 summarizes essential literature on the impact of the tourism sector, GDP, energy consumption, export, and GPR on CO_2 emissions; Section 3 presents the econometric methodology and data; Section 4 presents the empirical results and discusses the economic significance of the findings; and, Section 5 is the conclusion.

2. Literature review

The existing research results hold two opposite views on the impact of tourism on carbon emissions. The energy-economy structure is complex and must be considered when projecting the consequences of climate warming for energy, economics, and carbon emissions (Hadley et al., 2006; Pata et al., 2024). Among the two viewpoints, the primary one is based on the environmental Kuznets curve model. The Kuznets curve was first proposed by Simon Kuznets, a renowned American economist and Nobel laureate in economics, in a speech at the American Economic Association in 1955, to describe the relationship between economic growth and income inequality. In 1991, American economists Grossman and Krueger conducted empirical research on the relationship between environmental quality and per capita income in response to concerns about the deterioration of Mexico's environment and its impact on the domestic environment during the North American Free Trade Area negotiations (Grossman and Krueger, 1995). They pointed out that the relationship between pollution and per capita income was that "pollution increases with per capita GDP at low-income levels and decreases with GDP growth at high-income levels." In 1993, Panayotou borrowed the inverted U-shaped curve between per capita income and income inequality defined by Kuznets in 1955, and for the first time referred to this relationship between environmental quality and per capita income as the Environmental Kuznets Curve (EKC) (Panayotou., 1993). The EKC reveals that the growth of a country's GDP can damage the environment; When the economic level reaches a certain level, the ecological environment no longer deteriorates and then continues to recover with the development of the national economy, that is, GDP and the ecological environment show an inverted U-shaped relationship. In many ways, this relationship supports the adage that "only prosperous societies clean up their messes (Yang, 2021)." Several studies have applied the EKC model to the impact of tourism on GDP, real GDP squared, trade openness, and energy consumption of CO_2 emissions in some OECD countries (Dogan, 2015; Elheddad et al., 2021). Using dynamic ordinary least squares (hereafter cited as "DOLS") estimation techniques, it has been confirmed that the development of the tourism industry will result in increased carbon dioxide emissions and reduce environmental quality through numerous transportation channels, construction of tourism facilities, and local and government services (Škare and Porada-Rochoń, 2023).

Eyuboglu and Uzar (2020) used three cointegration tests to analyze the relationship between carbon dioxide emissions, tourists, energy consumption, and economic growth in Türkiye from 1960 to 2014. The study found that tourism, economic development, and energy consumption result in increased carbon dioxide emissions in both the long and short term. Yet other studies demonstrate that the impact of tourism on carbon dioxide emissions depends on the indicators used to represent it (Erdoğan et al., 2022; Koçak et al., 2020). In the context of the most visited countries in the world, the author uses the continuously updated Full Modified (CUP-FM) and constantly updated Bias Corrected (CUPBC) estimators to find that the more international tourists arrive, the greater the carbon dioxide emissions, while the higher the tourist income, the lower the carbon dioxide emissions.

On the other hand, tourism can promote the reduction of carbon emissions through energy and technology. The impact of investment in EU countries on tourism development and CO_2 emissions from 1990 to 2013 was estimated in two separate studies (Acheampong et al., 2022; Paramati et al., 2018). The research results show that tourism investment has a significant positive correlation with tourism development and has significantly contributed to reducing carbon dioxide emissions. In addition, well-managed tourism can help protect the environment by promoting environmentally sound technologies and transportation. More lanes, higher quality, safer roads, and rail transport can reduce carbon dioxide emissions by reducing fuel consumption on a per-passenger-mile basis. Some studies took Singapore as the research subject to empirically examine the relationship between CO_2 emissions, GDP, energy consumption, and tourist numbers using the DOLS method under the premise of the EKC hypothesis (Katircioğlu, 2014). The results showed a long-term relationship between tourism and CO_2 and confirmed the EKC hypothesis in both the short and long term. At the same time, the results also indicate that the impact coefficient of tourism on carbon dioxide emissions is statistically significantly negative, indicating that the impact of tourism on carbon dioxide emissions is gradually decreasing.

Other studies find the above examples, both positive and negative findings are incorrect. Based on the theory of complex adaptive systems, multiple spatial econometric models are used to test the relationship among the tripartite roles of tourism agglomeration, household income, and direct carbon dioxide emissions of urban residents. One study found that tourism agglomeration has a dual impact on direct carbon dioxide emissions of urban residents and an inverted U-shaped effect on household income (Zhou et al., 2023).

On this basis, some studies have confirmed the relationship between green finance, technological innovation, and sustainable development. For example, in terms of green finance, some studies have shown that the transition to green and renewable energy is crucial for sustainable economic growth. Countries investing in green innovation have shown a reduction in CO_2 emissions, indicating a shift towards a more sustainable energy consumption pattern would be desirable (Guo et al., 2021). There are also studies suggesting that green finance policies can help reduce carbon emissions and mitigate climate impacts. However, they might also fuel credit booms and increase public debt, indicating the need for a balanced approach (Lamperti et al., 2021). In addition, financial development and technological innovation can significantly stabilize green growth, emphasizing the role of finance in sustainable development (Cao et al., 2021). Technological advancements have a direct impact on CO_2 emissions. Countries that invest more in innovation tend to have reduced carbon emissions, suggesting that innovation plays a pivotal role in combating climate change (Atsu and Adams, 2021a, 2021b; Zhao et al., 2021). Overall, the interaction between financial development and technological innovation can significantly influence the volatility of green growth, highlighting the intertwined relationship between finance, technology, and sustainable development (Cao et al., 2021; Lasisi et al., 2022).

GDP measures the total value of the final products and services produced and provided by a country or region over a certain period. With the continuous growth of GDP, the demand for resources has also increased, bringing continuous pressure to the environment. In one study, based on the environmental Kuznets curve assumption, using time series data and cointegration analysis, the relationship between Tunisian economic growth (GDP) and pollutant (CO_2 and SO_2) emissions from 1961 to 2004 was analyzed (Fodha and Zaghdoud, 2010). The results show a stable and unique long-term linear relationship between per capita GDP and pollutant emissions. The study also found that as the per capita GDP grew, the environment was gradually degraded. In addition, using the panel data of eight Asia-Pacific countries from 1971 to 2005, one study found a long-term equilibrium relationship between GDP growth, energy consumption, and carbon emissions. In the long run, there is a robust causal relationship between GDP and CO_2 emissions in developed countries. Still, it is not established in developing countries (Niu et al., 2011). Some studies have also introduced technological innovation into the EKC framework, reflecting the reality that technological innovation is crucial for achieving long-term economic growth. While technological innovation will increase energy consumption, thereby increasing carbon emissions, such innovation is not an important determinant of EU carbon dioxide emissions (Acheampong et al., 2022; Sakariyahu et al., 2023).

Linear and nonlinear ARDL models explored the impact of Türkiye's foreign trade and foreign direct investment (hereafter cited as "FDI") on CO_2 (Haug and Ucal, 2019). That study found that FDI has a significant asymmetric impact on CO_2 emissions per capita. Still, this factor had no statistically significant long-term impact (Sbia et al., 2014). The empirical results show cointegration between these variables in the long run. At the same time, foreign direct investment and trade liberalization help to reduce greenhouse gas emissions to a certain extent,

A group of studies that focused on the existence of the EKC hypothesis in the early days also studied trade from the perspective of trade increasing energy consumption. (Suri and Chapman, 1998). To quantify the impact of the actual flow of goods between countries, researchers pooled data sets from 33 countries from 1971 to 1990 or 1991 depending on the data available for the country being studied. The research results showed that with the continuous increase in trade volume, the inflection point of the EKC curve continued to move to the right, indicating that international trade hurts environmental levels at least in the early stages of modernization. At the same time, research has found that exporting manufactured goods from industrialized countries can lead to an upward inclination of EKC.

In contrast, imports from industrialized countries can lead to a downward inclination of EKC. However, some studies explored the impact of financial development, economic growth, coal consumption, and trade openness on environmental performance based on the time series data of South Africa from 1965 to 2008 (Shahbaz et al., 2013). The study found that trade liberalization can reduce the growth of energy pollutants and thus have a positive effect on environmental quality. In the Turkish economy, the validity of the EKC hypothesis was also confirmed (Ozturk and Acaravci, 2013).

In recent years, some literature constructed a dynamic spatial econometric model based on 30-year panel data based on EKC assumptions. This model innovatively tested the mechanism by which FDI affects carbon emissions through energy intensity and the moderating role of the emissions trading system in the above process. It demonstrated that FDI is forcing China's current carbon emissions. One of the reasons for the increase in emissions is that there is an "inverted U"-shaped nonlinear relationship between FDI and carbon emissions. In this analysis, as the proportion of FDI in GDP increases, the role of FDI in promoting emissions first increases and then decreases as energy usage, a reasonable proxy for measuring prosperity, increases and then levels out (Pang et al., 2022; Wang et al., 2021). Some studies have empirically verified the environmental Kuznets curve between energy, poverty alleviation, and carbon emissions at the rural level through fixed-effect models and found that there is an inverted U-shaped effect (Li et al., 2023). Some studies have also proposed a Stochastic Environmental Kuznets Frontier to benchmark each country differently around the turning point, thus indicating how a country's economy can grow or improve to reduce its carbon dioxide emissions (Badunenko et al., 2023). The EKC hypothesis has also been proven to effectively describe conditions in EU countries and human capital has been shown to contribute to carbon reduction. In Germany, the implementation of new environmental patents helps reduce carbon dioxide emissions (Pata et al., 2024).

Cointegration and error correction models can incorporate import and export trade into the analysis framework and use this to examine the role of trade in carbon dioxide emissions at two levels based on consumption and territory. The results show that exports and imports have statistically significant effects of opposite signs on consumption-based CO_2 emissions in the long and short run. Moreover, the impact of changes in the relationship between trade and CO_2 emissions is fully absorbed in about three years (Hasanov et al., 2018). Later, some studies also found that an open trade policy can reduce the emission intensity of exports by promoting the selection of products with higher added value but lower emission intensity. Due to carbon leakage, economies with stricter environmental policies have lower export emission intensity but higher import emission intensity (Zhong et al., 2022).

On the relationship between geopolitical risk and carbon emissions, in a highly uncertain economic environment, weak public and financial sector policies will reduce consumer spending, thereby reducing CO_2 emissions (Aastveit et al., 2017). Taking the United States as the research background, ARDL, FMOLS, and DOLS techniques can also be used to examine the impact of militarization on CO_2 emissions, and the higher the degree of militarization, the more significant the increase in CO_2 emissions (Bildirici, 2017). Another study used the panel ARDL model to study the relationship between the uncertainty of economic policies and geopolitical risks of resource-rich countries and carbon dioxide emissions from 1996 to 2017 (Adams et al., 2020). That research concluded that economic policy uncertainty will promote carbon dioxide emissions, and geopolitical risks will aggravate environmental degradation in the short term. However, from the analysis of long-term results, the conclusion is contrary, and geopolitical risks will reduce carbon dioxide emissions to a certain extent. Recently, some studies have verified that geopolitical risks retard energy transition and the realization of sustainable development goals (Chishti et al., 2023). Chen et al. (2023) investigates how geopolitical risk and resource rents affect CO_2 emissions, and they find evidence that Geopolitical risk, natural resource rents, and per capita income increase CO_2 emissions.

Throughout current research, the influencing factors of carbon dioxide emissions are demonstrated to be multi-level. The significant dependency structure between the business cycle and carbon dioxide emissions has been confirmed (Gozgor et al., 2019). The positive impact of the Green Quality Index (GQI) on reducing carbon dioxide emissions in energy consumption in the United States has also been validated (Lau et al., 2023). Some studies have also verified the negative and significant impact of green technology innovation and renewable energy consumption on carbon dioxide emissions from an African perspective (Obobisa et al., 2022). In small open economies such as Nordic countries, domestically developed environmental technologies and technology spillovers from foreign economies have also been proven to reduce carbon emissions from their energy and industrial sectors (Alola and Rahko, 2024). Chen et al. (2024) examines the interdependence among geopolitical risk, capital-labour ratio, and income increase CO_2 emissions inequality, they find long-run relationship among Geopolitical risk, capital-labour ratio, income, and CO_2 emissions inequality.

2.1. Literature review summary

The influence paths of different factors and the influence direction of the same elements are entirely different in the results of various studies. Different sample selection intervals can lead to different results. Most significantly, previous studies have lacked focus on the relationship between anthropogenic risk and CO_2 emissions. Therefore, this paper introduces the risk caused by GPR as a control variable, conducts empirical analysis, and observes its impact on carbon dioxide emissions to formulate sustainable tourism policies and maintain an eco-friendly environment.

This study is expected to contribute to relevant literature in two ways:

First, most research on the influencing factors of carbon dioxide emissions has focused on natural risks such as natural disasters and accidents. The research on environmental impacts caused by economic activities is minimal. Any factor that leads to uncertainty may impact economic activities and the environment. For countries prone to terrorism-related threats and wars, consideration of GPR is essential to develop projections of environmental impacts.

Second, current research work on GPR's relationship to CO_2 emissions is minimal. Moreover, current research does not take into account cross-sectional dependencies across countries. This will lead to misleading results on ranking the relationship between tourism development and carbon dioxide emissions and may even make wrong policy recommendations. Based on the existing relevant studies, GPR will affect carbon dioxide emissions. After introducing GPR into the EKC framework for empirical research, we found that GPR has long promoted carbon dioxide emissions, confirming and enriching previous research results.

3. Model and data

3.1. Model specification

Some studies have shown the relationship between environment-output-energy under the EKC framework (Ang, 2007; Chandran and Tang, 2013; Omri, 2013; Wang et al., 2011). According to the most basic

EKC hypothesis, energy consumption is a key determinant of carbon dioxide emissions, and there is an inverted U-shaped relationship between per capita real GDP and per capita carbon dioxide emissions. Hence, the use of a quadratic specification is necessary to capture the long-run relationship of these variables. In this framework, polluting gas emissions decrease with GDP growth, the square of GDP, and energy consumption. The long-term steady-state relationship between carbon dioxide emissions, energy use, and output can be written as:

$$(CO_2)_{it} = \beta_0 + \beta_1 GDP_{it} + \beta_2 GDP_{it}^2 + \beta_3 EG_{it} + e_{it} \quad (1)$$

As research found that tourism has a significant statistical impact on the environment (Katircioğlu, 2014; Lee and Brahmasrene, 2013), the model needed revision. Therefore, to study the real impact of economic development on the environment, tourism needs to be added to the EKC model as a separate factor, as shown in Eq. (2):

$$(CO_2)_{it} = \beta_0 + \beta_1 GDP_{it} + \beta_2 GDP_{it}^2 + \beta_3 EG_{it} + \beta_4 TR_{it} + e_{it} \quad (2)$$

Yet another modification to the model was required when the negative impact of exports on consumption-based carbon emissions was confirmed by long-run and short-run empirical evidence (Khan et al., 2020). Therefore, the variable of export is introduced into the EKC model to make the influencing factors of carbon emissions in the model more complete, as shown in Eq. (3):

$$(CO_2)_{it} = \beta_0 + \beta_1 GDP_{it} + \beta_2 GDP_{it}^2 + \beta_3 EG_{it} + \beta_4 EXP_{it} + e_{it} \quad (3)$$

Recently, under the theoretical framework of the EKC theory, other factors, such as geopolitical risk, are positively correlated with CO_2 emissions, and the upper quantile is highly significant (Du and Wang, 2023; Li, 2023). Therefore, geopolitical risk factors can be introduced into the EKC framework, as shown in Eq. (4):

$$(CO_2)_{it} = \beta_0 + \beta_1 GDP_{it} + \beta_2 GDP_{it}^2 + \beta_3 EG_{it} + \beta_4 GPR_{it} + e_{it} \quad (4)$$

As our marginal contribution to the existing literature, we combine Eqs. (2), (3), and (4) to estimate how the CO_2 emissions will change with the changes in tourism, exports, and geopolitical risks under the revised EKC framework. Our new model takes the form of Eq. (5):

$$(CO_2)_{it} = \beta_0 + \beta_1 GDP_{it} + \beta_2 GDP_{it}^2 + \beta_3 EG_{it} + \beta_4 EXP_{it} + \beta_5 TR_{it} + \beta_6 GPR_{it} + e_{it} \quad (5)$$

where i and t stand for cross sections and the time; e denotes normally distributed error term; and β1, β2, β3, β4, β5, and β6 are the coefficient estimates of the relevant variables. This study helps to understand whether tourism and geopolitical factors are essential in the EKC model and the importance of cross-sectoral dependence.

3.2. Data

Our empirical analysis is based on data from the G7 countries (Canada, Germany, the U.S., France, Italy, Japan and the United Kingdom). The annual panel time-series data for the G7 countries were collected over the period 1990 to 2021 for the following variables: the per capita carbon dioxide emissions in metric tons (CO_2); international tourism revenue as a percentage of total exports (TR); per capita oil equivalent of energy use in metric kg (EG); exports of goods and services as a percentage of GDP (EXP); per capita GDP in current US dollars (GDP); square of GDP (GDP2); and, geopolitical risk index (GPR). CO_2 emissions, tourism revenue, energy use, exports of goods and services, and GDP were obtained from the World Bank (http://data.worldbank.org). GDP2 is calculated by taking the square of the logarithm of GDP, while the geopolitical risk index was obtained from the Economic Policy Uncertainty. Lowercase letters represent these variables, using the analysis's natural logarithms of CO_2 emissions, GDP, and economic policy uncertainty index. The longer time horizon was selected to make the results more accurate and persuasive. The tourism data provided was not available before 1995. To obtain the balanced panel data, we used the filling method to make the data complete. The meaning of each variable is shown in Table 1.

Table 2 and Figs. 1–6 provide summary statistical data for each country regarding the variables considered in this study. It can be seen that G7 countries have shown different levels of tourism, energy consumption, exports, GDP, geopolitical risks, and carbon dioxide emissions. Overall, the carbon dioxide emissions and energy consumption of each country have shown a downward trend during the sample period. The GDP of the United States has achieved a steady upward trend, while Japan's GDP has not shown a significant increase over the past 30 years, while the GDP of the other five countries has been fluctuating upwards. Since the beginning of the new century, geopolitical risks have doubled, with the attacks of September 11, 2001, and the subsequent so-called Global War on Terror increasing the geopolitical risks in the United States. The COVID-19 pandemic in 2020 severely damaged the tourism industry in the United States, France, Italy and Japan. The United States has the highest average carbon dioxide emissions, the highest percentage of tourism revenue to exports, and the highest level of geopolitical risk, indicating that the tourism industry and geopolitical risk factors may harm the environment during this period, which can damage the environment. Canada has the highest average energy consumption and ranks second in carbon dioxide emissions, indicating that energy consumption seriously pollutes the environment. At the same time, Germany's exports have the highest proportion of GDP. The difference in gross domestic product levels among these countries is not significant.

4. Empirical results and discussions

There are two key research findings of the article. First, energy consumption and geopolitical risks have a negative impact on environmental quality. Second, the increase in export levels and the development of the tourism industry are conducive to reducing carbon dioxide emissions. The conclusions drawn have given us a deeper understanding of the relationship between the economy, energy, and environmental protection.

This study first examines the comprehensive characteristics of CO_2, GDP (GDP2), energy consumption, exports, tourism, and geopolitical risks through the pre-application of the Pesaran CD test (Pesaran, 2021) to study whether there is a cross-section independence in the panel time series data. The CD test results of each variable are reported in Table 3. We have strong evidence to reject the null hypothesis of the cross-sectional independence of all of the analyzed variables. In other words, CO_2, GDP (GDP2), energy consumption, exports, tourism, and geopolitical risks have cross-sectoral dependencies.

We continue our analysis with testing for unit roots on CO_2 emissions and related variables, using the HT test (Harris and Tzavalis, 1999) and the Breitung test (Breitung, 2000). We also use the IPS test (Im et al., 2003) unit root test, which overcomes the shortcomings of the common root hypothesis. Because the first generation unit root test is no longer valid when the variables have cross-section correlation, the second generation unit root test must be calculated.

The results reported in Table 4 show that all of these unit root tests reject the null hypothesis of a unit root for the variables in first differences, thus sanctioning the stationary property of these variables. Consequently, modeling the first differences.

Further, we conducted a panel cointegration test to examine whether a long-term balanced cointegration relationship exists between variables. The traditional processing method for the variable with a unit root is to carry out the first-order difference to obtain the stationary sequence. However, the economic meaning of the variables after the first-order difference is different from the original series, and we use the original sequence for regression. After passing the unit root test, we conducted a panel cointegration test to verify whether there is a "long-term equilibrium relationship" between multiple unit root variables due to specific economic forces, proving the stationarity of their equation

Table 1
List of variables.

Variable	Definition	Notation	Data type	Source	ID (World Bank)
Dependent variable					
CO_2	CO_2 emissions (metric tons per capita)	co2	Natural logarithm	Climate Watch. 2020. GHG Emissions. Washington, DC: World Resources Institute.	EN.ATM. CO2E.PC
Independent variables					
TR	International tourism, receipts (% of total exports)	tr	Percentage	World Tourism Organization, Yearbook of Tourism Statistics, Compendium of Tourism Statistics and data files, and IMF and World Bank export estimates.	ST.INT. RCPT.XP.ZS
EG	Energy use (kg of oil equivalent per capita)	eg	Natural logarithm	Energy use refers to primary energy before transformation to other end-use fuels, equal to indigenous production plus imports and stock changes minus exports and fuels supplied to ships and aircraft engaged in international transport.	EG.USE. PCAP.KG.OE
EXP	Exports of goods and services (% of GDP)	exp	Percentage	World Bank national accounts data, and OECD National Accounts data files.	NE.EXP. GNFS.ZS
GDP	GDP per capita (current US$)	GDP	Natural logarithm	World Bank national accounts data, and OECD National Accounts data files.	NY.GDP. PCAP.CD
GDP2	Square of GDP	gdp2	Natural logarithm	Obtained by taking the square of the logarithmic GDP.	–
GPR	Geopolitical risk index	GPR	Index	Economic Policy Uncertainty.	–

Table 2
Summary of basic statistics.

		Canada	France	Germany	Italy	Japan	UK	US
CO_2	Mean	2.77	1.72	2.29	2.06	2.23	2.08	2.89
	Standard deviation	0.04	0.11	0.09	0.33	0.04	0.19	0.11
TR	Mean	3.95	8.54	3.63	8.63	2.20	8.26	9.49
	Standard deviation	0.29	1.16	0.43	1.59	1.23	0.25	1.62
EG	Mean	8.98	8.30	8.31	7.95	8.25	8.16	8.93
	Standard deviation	0.03	0.05	0.04	0.08	0.06	0.10	0.05
EXP	Mean	33.52	26.80	35.98	25.57	13.33	26.79	11.05
	Standard deviation	4.97	3.24	9.88	4.00	3.36	2.57	1.41
GDP (GDP2)	Mean	10.40	10.38	10.46	10.24	10.54	10.43	10.64
	Standard deviation	0.37	0.27	0.27	0.25	0.14	0.32	0.32
GPR	Mean	0.21	0.53	0.37	0.14	0.23	0.99	2.27
	Standard deviation	0.09	0.17	0.13	0.05	0.10	0.37	0.81

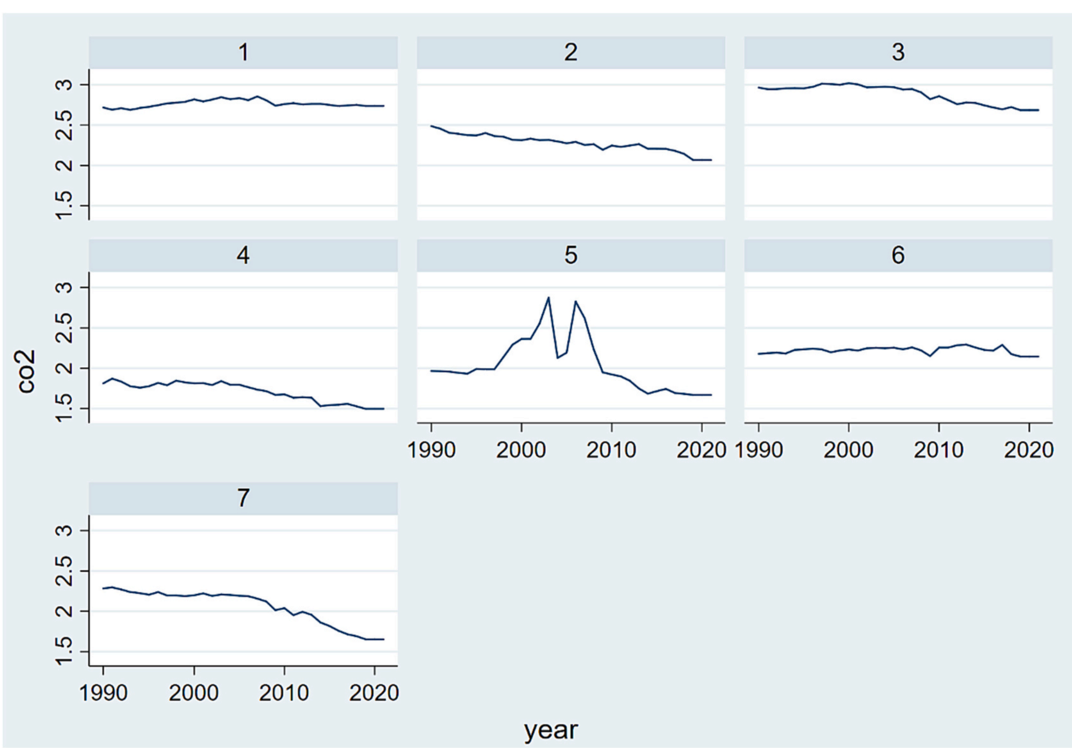

Fig. 1. Trend of CO_2.
Note: Id1-7 represents Canada, Germany, United States, France, Italy, Japan and United Kingdom in G7 countries, respectively.

Fig. 2. Trend of tr.
Note: Id1-7 represents Canada, Germany, United States, France, Italy, Japan and United Kingdom in G7 countries, respectively.

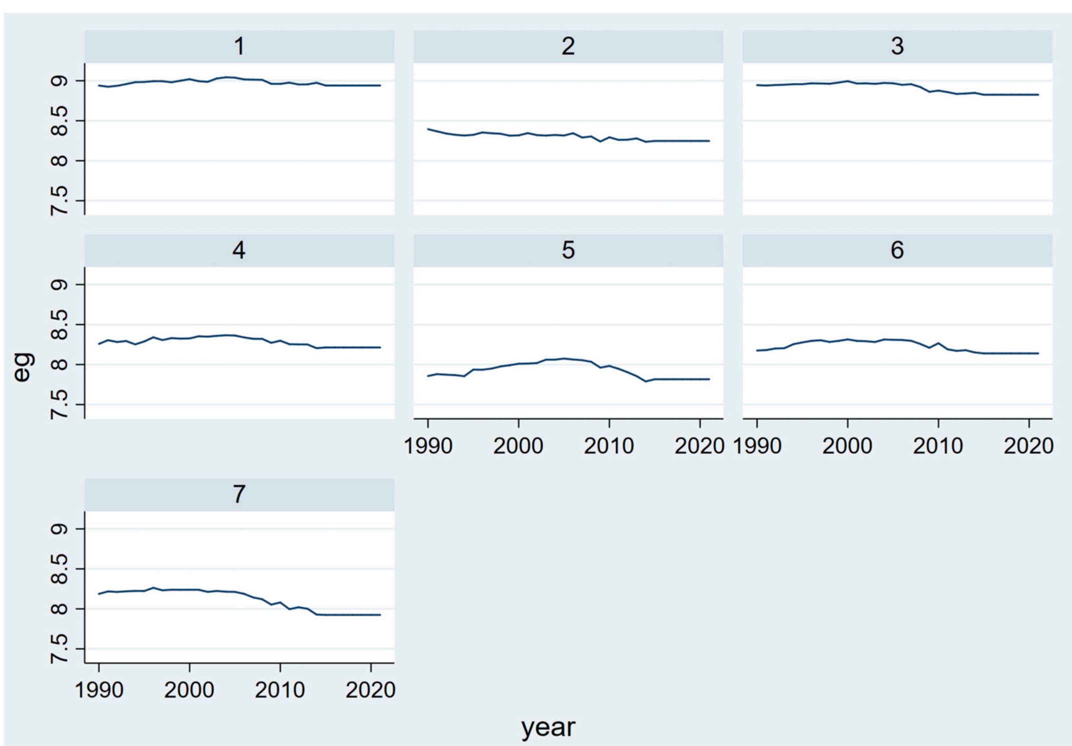

Fig. 3. Trend of eg.
Note: Id1-7 represents Canada, Germany, United States, France, Italy, Japan and United Kingdom in G7 countries, respectively.

regression residuals, to obtain more accurate results in the subsequent regression. We perform the Kao tests (Kao, 1999) of cointegration on a panel dataset. The cointegrating regression model may include panel-specific means (fixed effects) and panel-specific time trends. The null hypothesis of the Kao test is that there is no cointegration between panels. The alternative hypothesis is that the variables are cointegrated. The test results are shown in Table 5, indicating a cointegration relationship between CO_2, GDP (GDP2), energy consumption, exports,

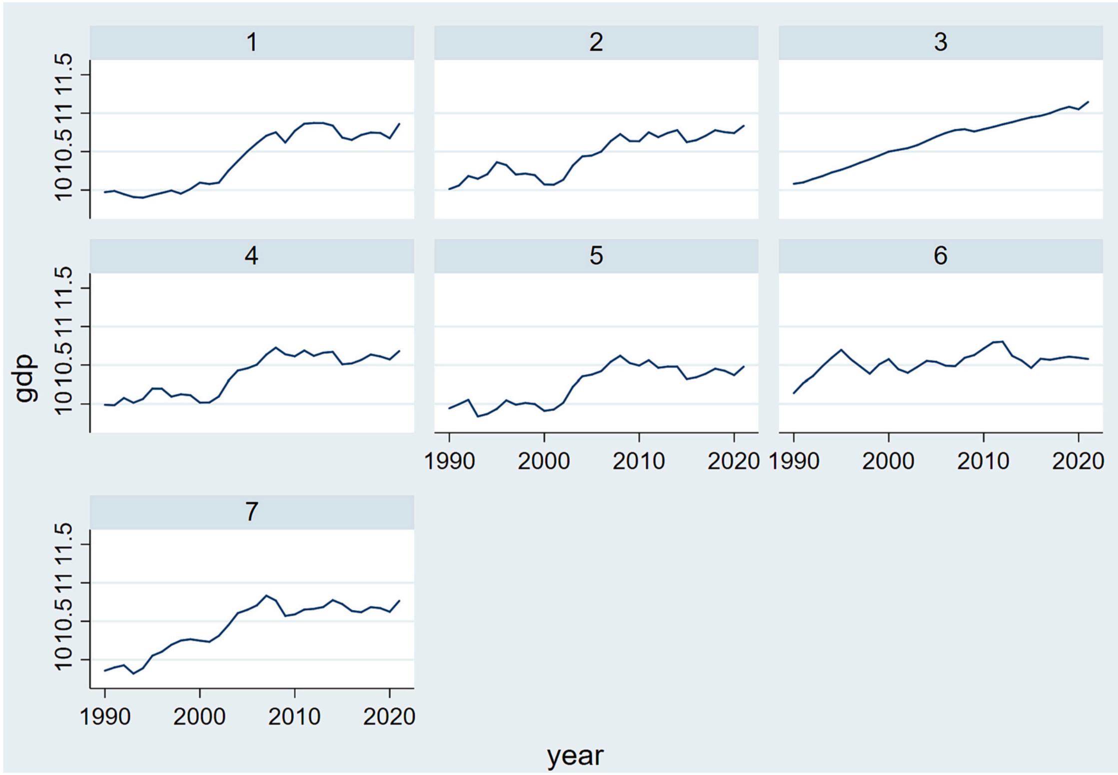

Fig. 4. Trend of gdp.
Note: Id1-7 represents Canada, Germany, United States, France, Italy, Japan and United Kingdom in G7 countries, respectively.

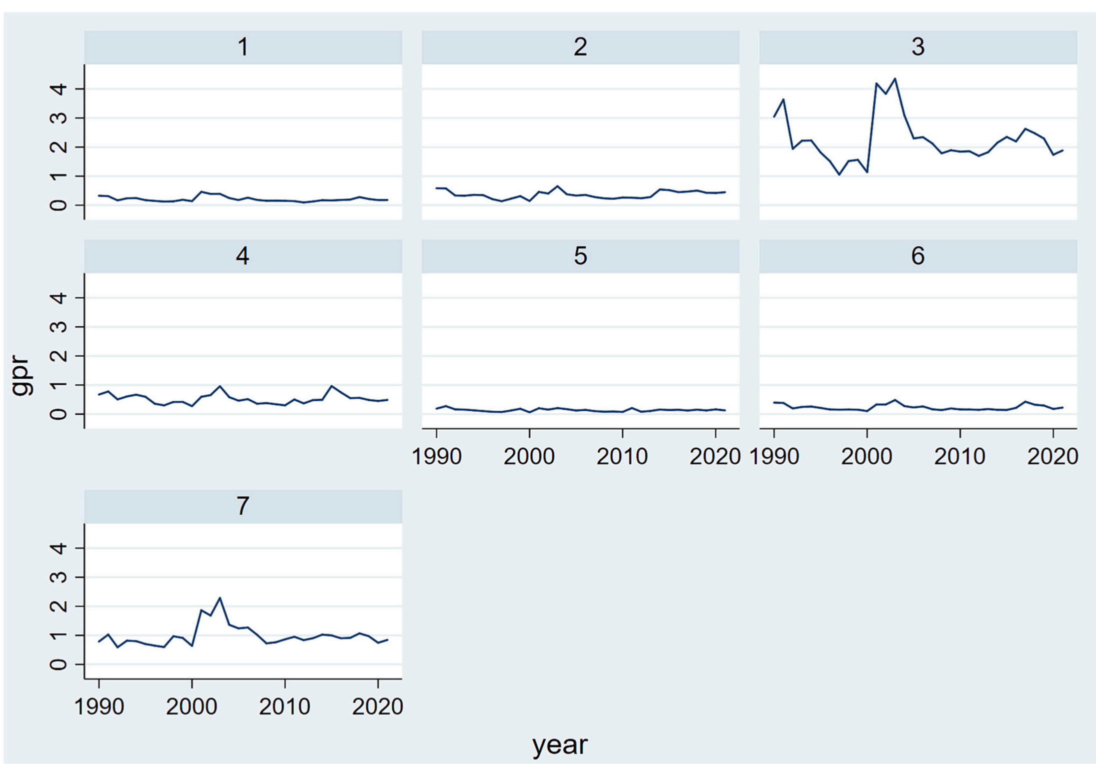

Fig. 5. Trend of gpr.
Note: Id1-7 represents Canada, Germany, United States, France, Italy, Japan and United Kingdom in G7 countries, respectively.

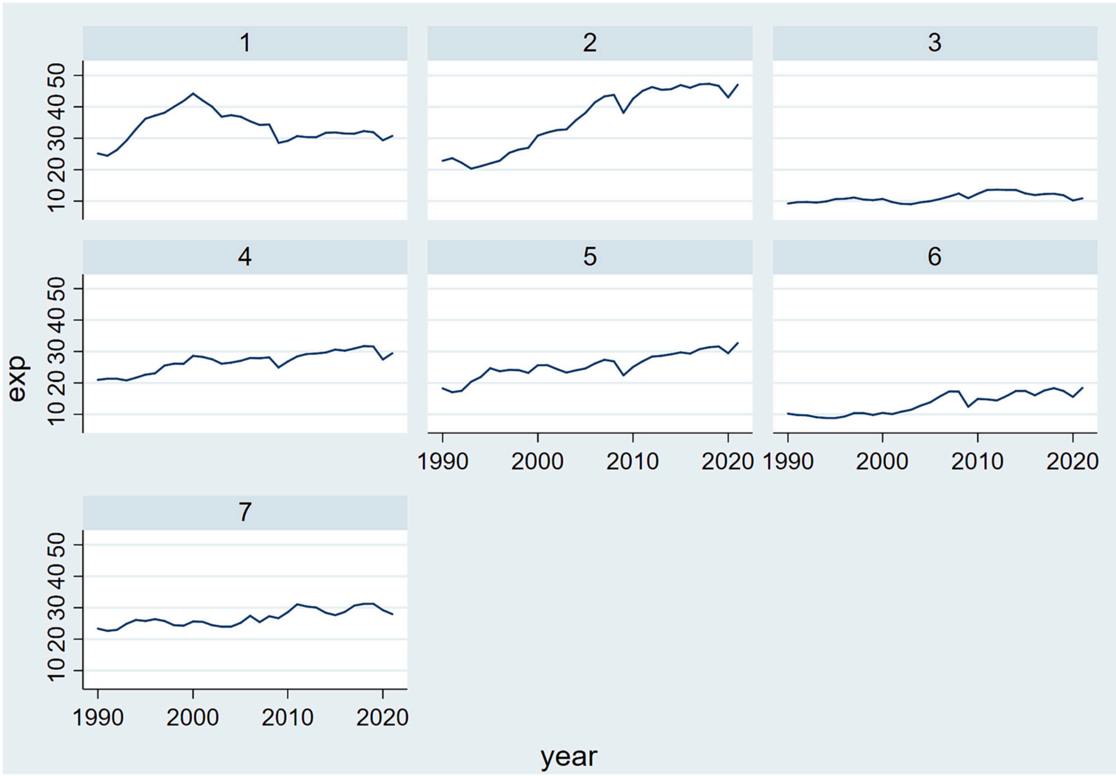

Fig. 6. Trend of exp.
Note: Id1-7 represents Canada, Germany, United States, France, Italy, Japan and United Kingdom in G7 countries, respectively.

Table 3
Results from cross-sectional dependence test for panel data.

	CO_2	GDP(GDP2)	EG	EXP	TR	GPR
CD test	13.43***	21.29***	20.03***	13.90***	8.28***	17.73***
p-Value	0.00	0.00	0.00	0.00	0.00	0.00

Notes: The LM test performs the null hypothesis of cross-sectional independence. The asterisks *, **, and *** indicate significance at the 10 %, 5 %, and 1 % levels, respectively.

Table 4
Panel unit root tests.

Variables	Harris-Tzavalis	Breitung	IPS
co2	0.69*	−0.30	1.82
Δco2	−0.07***	−5.68***	−5.30***
tr	0.73	3.32	−0.14
Δtr	−0.04***	3.45	1.55
eg	0.75	−0.33	−0.77
Δeg	−0.22***	−4.21***	−4.25***
exp	0.85	−0.77	−0.56
Δexp	0.33***	−1.01	−1.84*
gdp(gdp2)	0.76	−1.90**	−0.69
Δgdp(gdp2)	0.21***	−3.11***	−3.84***
gpr	0.57***	−2.84***	−1.25
Δgpr	−0.22***	−5.22***	−3.76***

Notes: HT, Breitung, and IPS are the empirical statistics of the Harris and Tzavalis (1999), Breitung (2001), and the Im et al. (2003) unit root tests. The asterisks *, **, and *** indicate significance at the 10 %, 5 %, and 1 % levels, respectively.

tourism, and geopolitical risks. It can be seen that there is a long-term equilibrium relationship between these variables in G7 countries from 1990 to 2021. That is, there is a long-term consistency.

We estimate the impact of these variables on carbon dioxide. The estimated results are shown in Table 6. We found that tourism, energy consumption, exports, and geopolitical risks have a highly significant impact on carbon dioxide at the 95 % significance level. Energy consumption and geopolitical risks can promote carbon emissions. In contrast, tourism and exports will reduce carbon emissions.

Table 5
Panel cointegration test.

	Statistic	p-Value
Modified Dickey-Fuller t	−2.29**	0.01
Dickey-Fuller t	−2.63***	0.00
Augmented Dickey-Fuller t	−2.93***	0.00
Unadjusted modified Dickey-Fuller t	−7.97***	0.00
Unadjusted Dickey-Fuller t	−4.72***	0.00

Note: The asterisks *, **, and *** indicate significance at the 10 %, 5 %, and 1 % levels, respectively.

Panel Fully Modified Ordinary Least Squares (FMOLS) and panel dynamic ordinary least squares (DOLS) are implemented as alternative measures to Ordinary Least Squares in the case of invalid standard errors due to second-order asymptotic bias. The DOLS model can estimate the long-run equilibrium, and the correction for possible simultaneity bias among the regressors was first proposed by Stock and Watson (1993). The DOLS model designed by Stock and Watson is robust and practical (Rumi and M.M., 1996). They provide evidence based on Monte Carlo simulations to prove that the estimator is superior not only to adapt to

Table 6
Regression results.

Dependent variable: co2			
Independent variables	Coeff.	Z-Stats	Prob.
tr	−0.02***	−3.30	0.00
gdp	−4.61	−1.32	0.18
gdp2	0.22	1.28	0.20
eg	0.84***	17.30	0.00
exp	−0.01***	−3.11	0.00
gpr	0.07**	2.28	0.02
Constant	20.21	1.11	0.27

Note: The asterisks *, **, and *** indicate significance at the 10 %, 5 %, and 1 % levels, respectively.

higher order integration but also to explain the potential possible simultaneity within a regressor of a demand system. Dynamic least squares models have also been found to outperform FMOLS and OLS for small-sample panel data (Kao and Chiang, 2000).

Furthermore, shrinkage estimation using a dynamic ordinary least squares cointegration estimator can extend the model for the case of multicollinearity among the explanatory variables in the cointegration vector (Månsson et al., 2018). Recently, much literature has used the DOLS model to discuss the influencing factors of CO_2 emissions. Some researchers combine the EKC and DOLS models to explore the relationship between economic growth and environmental degradation (Jiang et al., 2022; Kostakis et al., 2023). We perform DOLS estimation on panel data for G7 countries. There may be endogeneity problems between variables in panel data, such as problems with reverse causality or co-determination. The DOLS model was used to address this issue, and the regression model was corrected for endogeneity by considering unit roots and common trend issues.

The basic theory of the DOLS model is to add the dynamic characteristics of time series based on the OLS model. Unlike the traditional OLS model, the DOLS model takes into account the autocorrelation and heteroscedasticity problems existing in the data, preprocesses the data by introducing the lag variables, first-order difference, and trend items of the time series, and then constructs a model with dynamic characteristics. At the same time, the DOLS model also adopts an adaptive method to determine the order of delay, which can more accurately estimate the parameters in the model. Due to the relatively small size of our sample data, this study uses the DOLS model to reveal the long-run coefficient estimates for GDP, GDP2, EG, TR, EXP, and GPR. The regression of the DOLS estimator is given in Eq. (6):

$$Y_{it} = \alpha_i + \beta_i X_{it} + \sum_{i=-p_i}^{p_i} c_{ip} \triangle X_{it-p} + \mu_{it} \tag{6}$$

where Y_{it} is CO2, and X_{it} represents the vector of GDP, GDP2, EG, TR, EXP, and GPR in the present study. In addition, α_i, β_i, $-p_i$, p_i, and μ_{it} represent individual effect, coefficient of slope, lead and lag of difference, and error term, respectively.

Table 7 presents the findings of the DOLS test. The obtained p-value and statistics show that the reported coefficient estimates are statistically significant at the 95 % significance level. From the economic growth perspective, the research results indicate that the coefficients of GDP, both positive and negative, and the square of GDP are respectively negative and positive. This suggests that there exists a U-shaped relationship between income and CO_2 emissions. This study obtains GDP's (partial) marginal effect on CO_2 emissions by β1 + 2 *β2 *GDP (−0.882 + 2 *0.467 *GDP). GDP's (partial) marginal impact is negative for low-income levels. Still, it increases and eventually becomes positive as the G7 members reach higher income levels. This implies no evidence of an inverted U-shaped relationship or evidence of the Environmental Kuznets Curve (EKC) hypothesis for the examined G7 member countries. In other words, the findings suggest that increases in real output cause environmental degradation after surpassing a certain threshold level.

Table 7
Panel DOLS results.

Dependent variable: co2			
Independent variables	Coeff.	Z-Stats	Prob.
tr	−0.03***	−3.81	0.00
gdp	−0.88***	−3.65	0.00
gdp2	0.47***	3.58	0.00
eg	0.79***	4.36	0.00
exp	−0.01**	−2.09	0.04
gpr	0.09***	4.46	0.00

Note: The asterisks *, **, and *** indicate significance at the 10 %, 5 %, and 1 % levels, respectively.

Considering the impact of energy consumption on pollution, the increase in energy consumption significantly affects CO_2 emission levels. When energy consumption increases by 1 %, carbon dioxide emissions increase by 0.79 %. As expected, the use of energy has exacerbated the deterioration of the environment. This result is consistent with the results of almost all studies in the literature. Considering the impact of exports on CO_2 emissions, when exports increase by 1 %, CO_2 emissions will decrease by 0.006 %. Although it is statistically significant, the economic impact of exports on carbon emissions is almost negligible. Geopolitical risk is the last variable to be explained in this study. Table 7 shows that the elasticity of gas emissions to geopolitical risks is 0.09. In other words, geopolitical risks increased by 1 % in the long run, and carbon dioxide emissions increased by 0.09 %. This correlation reflects the complexity and nonlinear relationship of market behavior. From the technology perspective, the growth of geopolitical risks may affect the energy production and transformation of G7 countries, reduce the speed and efficiency of energy transformation, and increase carbon emissions. From a policy perspective, growing geopolitical risks may affect the government's energy and environmental protection policies. To deal with this problem, we need to strengthen international cooperation and coordination.

Tourism has a negative and significant impact on CO_2 emissions. The research shows that if the percentage of tourism revenue in exports increases by 1 %, gas emissions will decrease by 0.03 %. For G7 countries, which play an essential role in the global economy and trade, the relationship between their economic development and environmental protection is closer. Specifically, the tourism industry in G7 countries has a low demand for fossil energy in terms of transportation and accommodation. It pays more attention to environmental protection and sustainable development. Tourism development can promote the growth of the local economy and employment opportunities, thus reducing the poverty and backwardness of people and further improving society's quality of life. At the same time, G7 countries also pay more attention to environmental awareness and action, promote the concept of ecological tourism, and advocate environmental protection policies to guide tourists to pay more attention to and protect the local environment, reduce the damage and pollution to the environment, and thus reduce the emission of CO_2.

Once a long-term relationship is established between variables and long-term estimates are reported, the researchers were interested in using Granger causality tests to reveal causal relationships between carbon emissions and economic growth, energy consumption, exports, and tourism. Understanding the direction of causality helps to further understand the relationship between these variables and carbon emissions, thus aiding decision-makers in achieving sustainable economic growth. We utilize the Dumitrescu and Hurlin Granger non-causal test (hereafter cited as "DH") (Dumitrescu and Hurlin, 2012).

Unlike the standard Granger causality method, this statistical test tests the causal relationship between time series, which is especially suitable for panel data analysis. It allows for coefficients to vary across cross-sections. This method is based on the classic Granger causality test. In traditional Granger causality tests, we assume that the past values of one time series can provide additional information about the future importance of another time series to determine whether there is a causal relationship between the two-time series. However, in the case of panel data analysis, if we only use the information from a single time series to determine causality, we may ignore the cross-sectional correlation. Therefore, DH proposes a panel Granger causality test method that considers inter-individual and inter-temporal correlation. The DH panel Granger causality test first calculates the mean of the panel data. It constructs a "pooled" time series based on the mean. Then, the traditional Granger causality test is applied using this "pooled" time series. Finally, the presence of causality in the panel data is determined by comparing the Granger causality test results of the panel data and the "pooled" data. The theoretical basis of this method is built on the Generalized Method of Moments (GMM) framework. It uses a set of appropriate instrumental variables to address potential endogeneity issues, and relevant test statistics to test the causality in panel data.

Specifically, the null hypothesis supports the absence of homogeneous Granger causality across all cross-sectional units. In contrast, the alternative theory assumes at least one causal relationship exists in the panel data. The causal relationship tests for the present study are presented in Table 8. We have strong evidence supporting bidirectional causality between energy consumption and gas emissions, tourism and CO_2 emissions, GDP and tourism, and tourism and exports. Additionally, we found unidirectional causality between economic growth and environmental pollution, exports and CO_2 emissions, GDP and energy consumption, tourism and energy consumption, exports and energy consumption, geopolitical risk, and tourism. As shown in Table 8, all survey results are statistically significant.

Table 8
Results from Granger non-causality tests.

Hypothesis	W-statistic	Prob.	Result	Conclusion
gdp(gdp2) → co2	3.41***	0.00	Yes	gdp does Granger-cause co2
co2 → gdp (gdp2)	1.49	0.49	No	CO2 does not Granger-cause gdp
eg → co2	2.39**	0.03	Yes	eg does Granger-cause co2
co2 → eg	2.49**	0.02	Yes	co2 does Granger-cause eg
tr → co2	2.53**	0.02	Yes	tr does Granger-cause co2
co2 → tr	2.88***	0.00	Yes	co2 does Granger-cause tr
exp → co2	3.34***	0.00	Yes	exp does Granger-cause co2
co2 → exp	2.03	0.12	No	co2 does not Granger-cause exp
gpr → co2	0.69	0.52	No	gpr does not Granger-cause co2
co2 → gpr	0.43	0.29	No	co2 does not Granger-cause gpr
tr → gdp(gdp2)	2.78***	0.00	Yes	tr does Granger-cause gdp
gdp(gdp2) → tr	2.98***	0.00	Yes	gdp does Granger-cause tr
eg → gdp(gdp2)	0.86	0.72	No	eg does not Granger-cause gdp
gdp(gdp2) → eg	7.88***	0.00	Yes	gdp does Granger-cause eg
exp → gdp (gdp2)	1.58	0.41	No	exp does not Granger-cause gdp
gdp(gdp2) → exp	1.92	0.17	No	gdp does not Granger-cause exp
gpr → gdp (gdp2)	1.97	0.14	No	gpr does not Granger-cause gdp
gdp(gdp2) → gpr	0.65	0.49	No	gdp does not Granger-cause gpr
eg → tr	0.98	0.87	No	eg does not Granger-cause tr
tr → eg	5.51***	0.00	Yes	tr does Granger-cause eg
exp → tr	2.40**	0.03	Yes	exp does Granger-cause tr
tr → exp	3.62***	0.00	Yes	tr does Granger-cause exp
gpr → tr	0.05*	0.09	Yes	gpr does Granger-cause tr
tr → gpr	0.46	0.31	No	tr does not Granger-cause gpr
exp → eg	7.70***	0.00	Yes	exp does Granger-cause eg
eg → exp	1.02	0.93	No	eg does not Granger-cause exp
gpr → eg	1.16	0.89	No	gpr does not Granger-cause eg
eg → gpr	0.47	0.32	No	eg does not Granger-cause gpr
exp → gpr	0.92	0.79	No	exp does not Granger-cause gpr
gpr → exp	0.45	0.30	No	gpr does not Granger-cause exp

Notes: This test selects 1 as the lagging order. The asterisks *, **, and *** indicate significance at the 10 %, 5 %, and 1 % levels, respectively.

Continuous economic development has increased GDP. The economic activities of G7 countries require a significant amount of energy, usually derived from burning fossil fuels, which produces a substantial amount of greenhouse gases and other harmful substances. However, these gas emissions also affect energy consumption. For instance, the concentration of carbon dioxide in the atmosphere can influence the reflection and absorption of solar radiation, ultimately impacting energy production and use. In addition to being significant energy consumers, G7 countries are popular tourist destinations that rely heavily on transportation and energy consumption, contributing to a substantial amount of carbon dioxide and other harmful substances. The attractiveness of the tourism industry can be impacted by natural disasters, climate change, and environmental pollution.

Moreover, the development of the tourism industry is intertwined with the GDP. The increase in economic growth and per capita income typically enhances the demand and expenditure level of the tourism industry, thus propelling its development. Furthermore, the development of the tourism industry contributes to GDP growth, increased employment opportunities, and trade income, among other factors. G7 countries are also significant exporters; tourism has significantly contributed to exports. For example, developing the tourism industry can promote export growth, encouraging the export of tourism products and services. Conversely, exports also promote the development of the tourism industry, attracting more foreign tourists.

Overall, the Granger non-causality tests prove that economic growth and trade significantly impact environmental pollution. In contrast, ecological degradation does not significantly affect economic growth or trade. These findings have important policy implications for countries balancing economic growth with ecological sustainability. Policymakers should prioritize adopting sustainable and eco-friendly practices to promote economic growth without compromising environmental quality. Moreover, promoting environmentally sustainable trade policies can reduce the adverse effects of international trade on the environment.

A robustness test was also applied. Due to the possibility of bias in the regression results caused by the selection of core variables, the second largest component gas of carbon emissions, methane, was selected. The explanatory variable CO_2 emissions were replaced with methane (CH4) emissions, which refer to thousands of tons of carbon dioxide equivalent generated by human activities such as agricultural and industrial methane production. A series of regression analyses were conducted again, and the test results of the DOLS model are shown in Table 9. The robustness test results of methane as the dependent variable are almost consistent with expectations. When energy consumption and geopolitical risk increase by 1 %, methane emissions increase by 1.04 % and 5.23 %, respectively. Compared with CO_2, this effect is more significant, and the weak impact of exports is ignored. The reliability of the model and associated conclusions has been confirmed.

Regarding possible endogeneity issues, the results of Table 8 indicate that there may be endogeneity issues caused by mutual causality

Table 9
Robustness test results.

Dependent variable: ch4			
Independent variables	Coeff.	Z-Stats	Prob.
tr	0.08***	7.21	0.00
gdp	−7.47**	−2.15	0.03
gdp2	0.34**	2.14	0.03
eg	1.04***	4.45	0.00
exp	0.00	0.65	0.51
gpr	0.52***	19.91	0.00

Note: The asterisks *, **, and *** indicate significance at the 10 %, 5 %, and 1 % levels, respectively.

Table 10
Endogeneity test results.

Dependent variable: co2			
Independent variables	Coeff.	Z-Stats	Prob.
L.tr	−0.04***	−4.36	0.00
gdp	−14.29***	−5.08	0.00
gdp2	0.68***	5.01	0.00
L.eg	0.74***	4.00	0.00
exp	−0.01**	−2.07	0.04
gpr	0.11***	5.54	0.00

Note: The asterisks *, **, and *** indicate significance at the 10 %, 5 %, and 1 % levels, respectively.

between tourism, energy consumption, and the dependent variable CO_2 in the explanatory variables. Regarding this, a regression analysis was conducted after lagging the variables of tourism and energy consumption for one period, and the results are shown in Table 10. Tourism and energy consumption still have a negative and positive impact on CO_2 emissions at the 1 % level, which is consistent with the original results in both numerical and directional results.

5. Conclusion

This study examines and models the long-term trends of CO_2 emissions, GDP, GDP2, energy consumption, exports, tourism, and geopolitical risks in G7 member countries between 1990 and 2021. We address the potential cross-sectional correlation in the panel time series data and perform panel cointegration tests. Moreover, we compare the results of the DOLS model estimation with those of the panel data linear regression model and Dumitrescu-Hurlin causality test, building upon previous research. Additionally, we redefine the validity range of the EKC hypothesis by incorporating geopolitical risk factors. Then, robustness tests were conducted and endogeneity issues were ruled out, resulting in relatively reliable research results.

The CD test report shows a 99 % significant cross-sectional dependence among CO_2 emissions, GDP, GDP2, energy consumption, exports, tourism, and geopolitical risks. Harris-Tzavalis, Breitung, and IPS panel unit root tests confirm that all analyzed variables are stationary at a 95 % significance level at the first-order difference. The Kao test further shows that the analyzed variables are cointegrated and have a long-term relationship. Thus, the coefficient estimation is both economically reliable and meaningful. Using the DOLS method, this study finds that energy consumption and geopolitical risks lead to environmental deterioration. At the same time, tourism and exports positively affect the environment.

Moreover, due to the negative and positive impact of GDP and GDP2 on CO_2 emissions, the EKC hypothesis is invalid for G7 member countries, indicating a U-shaped relationship. Dumitrescu-Hurlin causality test results demonstrate a two-way causality between energy consumption and gas emissions, tourism and CO_2 emissions, GDP and tourism, and tourism and exports. Additionally, this study reveals a one-way causal relationship from economic growth to CO_2 emissions, from exports to CO_2 emissions, from economic development to energy consumption, from tourism to energy consumption, from exports to energy consumption, and from geopolitical risks to tourism.

From a socio-economic perspective, the development of the tourism industry promotes local economic development and brings more energy consumption. At the same time, energy consumption leads to an increase in greenhouse gas emissions. On the other hand, the development of the tourism industry and the increase in exports mutually promote each other. The income generated by tourism activities provides funds for the protection and optimization of the local ecological environment, Moreover, the technological changes brought about by the economic development driven by tourism and exports may make the country pay more attention to carbon reduction. At the same time, export tax rebate policies can reduce the burden on enterprises, improve the competitiveness of exported goods, and reduce the excessive exploitation and utilization of natural resources, ultimately resulting in a positive impact on the environment through tourism and exports.

Due to geopolitical tensions and conflicts, countries may compete for resources, including energy resources, which may lead to excessive resource development. Geopolitical conflicts may also result in a large number of people being displaced, and the influx of refugees can bring social, economic, and environmental pressure to the receiving country, further exacerbating environmental problems. At the same time, geopolitical risks may hinder the development of tourism and cause technological change to occur later, This leads to a country generating more carbon emissions at a lower level of technology.

To maintain a balance in the carbon cycle, the policy implications of the research results can be considered from the perspectives of tourism and energy consumption. First, the government can encourage the development of low-carbon tourism, such as reducing carbon emissions through the use of public transportation, cycling, walking, and other means. At the same time, restrict or impose tax penalties on high carbon emitting tourism methods; Strengthen environmental education and promotion for tourists through media, schools, communities, and other channels, and enhance their environmental awareness and behavior. Second, the government can promote clean energy, encourage and support research and use of clean energy such as solar, wind, and hydro, and reduce dependence on fossil fuels. By adopting a circular economy model, we aim to minimize resource consumption and waste generation while improving resource utilization efficiency. Governments should establish stricter energy efficiency standards to encourage enterprises and individuals to improve energy utilization efficiency and reduce carbon emissions. At the economic level, the government provides green financial support, loans, and financing support for low-carbon environmental protection projects, and encourages enterprises and individuals to invest in low-carbon industries. Finally, strengthen cooperation with other countries and regions to jointly research and implement policies and measures related to carbon cycling, and jointly address global climate change issues.

Overall, to reduce environmental pollution and promote sustainable economic development in G7 countries, policymakers should take the following measures:

1. Enhance foresight and initiative, improve the ability to predict geopolitical risks, and propose technological solutions to geopolitical risks. Advanced monitoring and predictive analysis can help nations anticipate and mitigate the effects of geopolitical events on energy prices and supplies. At the same time, using decentralized energy solutions, such as microgrids powered by renewable sources, can enhance energy security in times of geopolitical tensions.
2. Strengthen energy transformation and technological innovation, and support research and development in green tech innovations, such as carbon capture and sequestration (CCS) technology. Promoting technological progress in smart grids, IoT devices, and AI-driven energy management systems, as well as innovation in renewable energy technologies, such as improved solar panels and wind turbines, can help G-7 countries transition away from fossil fuels. Technological innovations in energy storage and distribution can reduce a country's dependence on foreign energy sources, mitigating geopolitical risks.
3. Encourage digital transformation, adopt digital technologies to improve energy efficiency and reduce carbon emissions, and utilize the digital economy to develop sustainable tourism. The digital economy can lead to new business models that prioritize sustainability. For instance, the sharing economy (e.g., ride-sharing, co-working spaces) can reduce carbon emissions by maximizing resource utilization. Moreover, The rise of virtual tourism, augmented reality (AR), and virtual reality (VR) experiences can offer alternatives to traditional travel, potentially reducing the

carbon footprint associated with trans-portation, or launching digital platforms and apps to promote sustainable tourism and reduce the negative impact of tourism activities on the environment by providing travelers with eco-friendly options and real-time carbon footprint tracking.

4. Enterprises are encouraged to reduce emissions and innovate by strengthening environmental supervision, implementing laws and regulations to control pollutant emissions, and implementing ecological tax policies.
5. Reduce energy demand by promoting the development of green finance. Finally, strengthen international cooperation and knowledge sharing, jointly address global environmental issues, and achieve sustainable development goals.

CRediT authorship contribution statement

Xiuhua Zhang: Writing – original draft, Supervision, Funding acquisition. **Chi Keung Marco Lau:** Writing – review & editing, Writing – original draft, Methodology, Data curation, Conceptualization. **Ruoyao Li:** Writing – original draft, Formal analysis, Data curation. **Yihan Wang:** Writing – original draft, Methodology, Formal analysis. **Roseline Wanjiru:** Writing – review & editing. **Neelu Seetaram:** Writing – review & editing.

Data availability

Data will be made available on request.

References

Aastveit, K.A., Natvik, G.J., Sola, S., 2017. Economic uncertainty and the influence of monetary policy. J. Int. Money Financ. 76, 50–67.

Acheampong, et al., 2022. Unveiling the effect of transport infrastructure and technological innovation on economic growth, energy consumption and CO_2 emissions. Technol. Forecast. Soc. Chang. 182, 121843.

Adams, S., Adedoyin, F., Olaniran, E., Bekun, F.V., 2020. Energy consumption, economic policy uncertainty and carbon emissions; causality evidence from resource rich economies. Econ. Anal. Policy 68, 179–190.

Alola, Rahko, 2024. The effects of environmental innovations and international technology spillovers on industrial and energy sector emissions – evidence from small open economies. Technol. Forecast. Soc. Chang. 198, 123024.

Ang, J.B., 2007. CO_2 emissions, energy consumption, and output in France. Energy Policy 35 (10), 4772–4778.

Atsu, F., Adams, S., 2021a. Energy consumption, finance, and climate change: does policy uncertainty matter? Econ. Anal. Policy 70, 490–501.

Atsu, Adams, 2021b. Energy consumption, finance, and climate change: does policy uncertainty matter? Econ. Anal. Policy 70, 490–501.

Badunenko, O., Galeotti, M., Hunt, L.C., 2023. Better to grow or better to improve? Measuring environmental efficiency in OECD countries with a stochastic environmental Kuznets frontier (SEKF). Energy Econ. 121, 106644.

Bildirici, M.E., 2017. The effects of militarization on biofuel consumption and CO_2 emission. J. Clean. Prod. 152, 420–428.

Blunden, J., Boyer, T., 2022. State of the climate in 2021. Bull. Am. Meteorol. Soc. 103 (8), S1–S465.

Breitung, J., 2000. The local power of some unit root tests for panel data. In: SFB 373 Discussion Papers, vol. 15(15), pp. 161–177.

Breitung, J., 2001. The local power of some unit root tests for panel data. In: Nonstationary panels, panel cointegration, and dynamic panels. Emerald Group Publishing Limited, pp. 161–177.

Cadarso, M.Á., Gómez, N., López, L.A., Tobarra, M.Á., Zafrilla, J.E., 2015. Quantifying Spanish tourism's carbon footprint: the contributions of residents and visitors: a longitudinal study. J. Sustain. Tour. 23 (6), 922–946.

Cao, J., Law, S.H., Samad, A., Mohamad, W., Wang, J., Yang, X., 2021. Impact of financial development and technological innovation on the volatility of green growth-evidence from China. Environ. Sci. Pollut. Res. Int. 28 (35), 48053–48069.

Chandran, V.G.R., Tang, C.F., 2013. The impacts of transport energy consumption, foreign direct investment and income on CO_2 emissions in ASEAN-5 economies. Renew. Sust. Energ. Rev. 24, 445–453.

Chen, L., Gozgor, G., Mahalik, M.K., Pal, S., Rather, K.N., 2023. How does geopolitical risk affect CO_2 emissions? The role of natural resource rents. Res. Policy 87, 104321.

Chen, L., Gozgor, G., Lau, C.K.M., Mahalik, M.K., Rather, K.N., Soliman, A.M., 2024. The impact of geopolitical risk on CO_2 emissions inequality: evidence from 38 developed and developing economies. J. Environ. Manag. 349, 119345.

Chishti, M.Z., Sinha, A., Zaman, U., Shahzad, U., 2023. Exploring the dynamic connectedness among energy transition and its drivers: understanding the moderating role of global geopolitical risk. Energy Econ. 119, 106570.

Dogan, E., 2015. The relationship between economic growth and electricity consumption from renewable and nonrenewable sources: A study of Turkey. Renew. Sust. Energ. Rev. 52, 534–546.

Du, Y., Wang, W., 2023. The role of green financing, agriculture development, geopolitical risk, and natural resources on environmental pollution in China. Res. Policy 82, 103440.

Dumitrescu, E.I., Hurlin, C., 2012. Testing for Granger non-causality in heterogeneous panels. Econ. Model. 29 (4), 1450–1460.

Elheddad, et al., 2021. The effect of the Fourth Industrial Revolution on the environment: the relationship between electronic finance and pollution in OECD countries. Technol. Forecast. Soc. Chang. 163, 120485.

Erdoğan, et al., 2022. Eco-friendly technologies, international tourism and carbon emissions: evidence from the most visited countries. Technol. Forecast. Soc. Chang. 180, 121705.

Eyuboglu, K., Uzar, U., 2020. The impact of tourism on CO_2 emission in Turkey. Curr. Issue Tour. 23 (13), 1631–1645.

Fodha, M., Zaghdoud, O., 2010. Economic growth and pollutant emissions in Tunisia: an empirical analysis of the environmental Kuznets curve. Energy Policy 38 (2), 1150–1156.

Gössling, S., 2002. Global environmental consequences of tourism. Glob. Environ. Chang. 12 (4), 283–302.

Gozgor, et al., 2019. Dependence structure between business cycles and CO_2 emissions in the U.S.: evidence from the time-varying Markov-Switching Copula models. Energy 188, 115995.

Grossman, Krueger, 1995. Economic growth and the environment. Q. J. Econ. 110 (2), 353–377.

Gu, X., Zhu, Z., Yu, M., 2021. The macro effects of GPR and EPU indexes over the global oil market—are the two types of uncertainty shock alike? Energy Econ. 100, 105394.

Guo, J.J., Zhou, Y., Ali, S., Shahzad, U., Cui, L.B., 2021. Exploring the role of green innovation and investment in energy for environmental quality: an empirical appraisal from provincial data of China. J. Environ. Manag. 292, 112779.

Hadley, S., Erickson, D., Hernandez, J.L., Broniak, C.T., Blasing, T.J., 2006. Responses of energy use to climate change: a climate modeling study. Geophys. Res. Lett. 33.

Harris, R.D., Tzavalis, E., 1999. Inference for unit roots in dynamic panels where the time dimension is fixed. J. Econ. 91 (2), 201–226.

Hasanov, F.J., Liddle, B., Mikayilov, J.I., 2018. The impact of international trade on CO_2 emissions in oil exporting countries: territory vs consumption emissions accounting. Energy Econ. 74, 343–350.

Haug, A.A., Ucal, M., 2019. The role of trade and FDI for CO_2 emissions in Turkey: nonlinear relationships. Energy Econ. 81, 297–307.

Im, K.S., Pesaran, M.H., Shin, Y., 2003. Testing for unit roots in heterogeneous panels. J. Econ. 115 (1), 53–74.

Jiang, Q., Rahman, Z.U., Zhang, X., Guo, Z., Xie, Q., 2022. An assessment of the impact of natural resources, energy, institutional quality, and financial development on CO_2 emissions: evidence from the B&R nations. Res. Policy 76, 102716.

Kao, C., 1999. Spurious regression and residual-based tests for cointegration in panel data. J. Econ. 90 (1), 1–44.

Kao, C., Chiang, M.H., 2000. On the estimation and inference of a cointegrated regression in panel data. In: Nonstationary Panels, Panel Cointegration, and Dynamic Panels, pp. 179–222.

Katircioğlu, S.T., 2014. Testing the tourism-induced EKC hypothesis: the case of Singapore. Econ. Model. 41, 383–391.

Khan, Z., Ali, M., Jinyu, L., Shahbaz, M., Siqun, Y., 2020. Consumption-based carbon emissions and trade nexus: evidence from nine oil exporting countries. Energy Econ. 89, 104806.

Koçak, E., Ulucak, R., Ulucak, Z.Ş., 2020. The impact of tourism developments on CO_2 emissions: an advanced panel data estimation. Tour. Manag. Perspect. 33, 100611.

Kostakis, I., Armaos, S., Abeliotis, K., Theodoropoulou, E., 2023. The investigation of EKC within CO_2 emissions framework: empirical evidence from selected cross-correlated countries. Sustain. Anal. Model. 3, 100015.

Lamperti, F., Bosetti, V., Roventini, A., Tavoni, M., Treibich, T., 2021. Three green financial policies to address climate risks. J. Financ. Stab. 54, 100875.

Lasisi, et al., 2022. The moderating role of environmental-related innovation and technologies in growth-energy utilization nexus in highest-performing eco-innovation economies. Technol. Forecast. Soc. Chang. 183, 121953.

Lau, et al., 2023. The impact of green quality of the energy consumption on carbon emissions in the United States. Econ. Anal. Policy 80, 850–860.

Lee, J.W., Brahmasrene, T., 2013. Investigating the influence of tourism on economic growth and carbon emissions: evidence from panel analysis of the European Union. Tour. Manag. 38, 69–76.

Li, Z., 2023. Do geopolitical risk, green finance, and the rule of law affect the sustainable environment in China? Findings from the BARDL approach. Res. Policy 81, 103403.

Li, J., Gao, M., Luo, E., Wang, J., Zhang, X., 2023. Does rural energy poverty alleviation really reduce agricultural carbon emissions? The case of China. Energy Econ. 119, 106576.

Månsson, K., Kibria, B.G., Shukur, G., Sjölander, P., 2018. On the estimation of the CO_2 emission, economic growth and energy consumption nexus using dynamic OLS in the presence of multicollinearity. Sustainability 10 (5), 1315.

Mossler, M.V., Bostrom, A., Kelly, R.P., Crosman, K.M., Moy, P., 2017. How does framing affect policy support for emissions mitigation? Testing the effects of ocean acidification and other carbon emissions frames. Glob. Environ. Chang. 45, 63–78.

Niu, S., Ding, Y., Niu, Y., Li, Y., Luo, G., 2011. Economic growth, energy conservation and emissions reduction: a comparative analysis based on panel data for 8 Asian-Pacific countries. Energy Policy 39 (4), 2121–2131.

Obobisa, et al., 2022. The impact of green technological innovation and institutional quality on CO_2 emissions in African countries. Technol. Forecast. Soc. Chang. 180, 121670.
Omri, A., 2013. CO_2 emissions, energy consumption and economic growth nexus in MENA countries: evidence from simultaneous equations models. Energy Econ. 40, 657–664.
Ozturk, I., Acaravci, A., 2013. The long-run and causal analysis of energy, growth, openness and financial development on carbon emissions in Turkey. Energy Econ. 36, 262–267.
Panayotou., 1993. Empirical Tests and Policy Analysis of Environmental Degradation at Different Stages of Economic Development, vol. 4.
Pang, et al., 2022. Asymmetric effects of urbanization on shadow economy both in short-run and long-run: new evidence from dynamic panel threshold model. Technol. Forecast. Soc. Chang. 177, 121514.
Paramati, S.R., Alam, M.S., Lau, C.K.M., 2018. The effect of tourism investment on tourism development and CO_2 emissions: empirical evidence from the EU nations. J. Sustain. Tour. 26 (9), 1587–1607.
Pata, et al., 2024. Technological changes and carbon neutrality targets in European countries: a sustainability approach with Fourier approximations. Technol. Forecast. Soc. Chang. 198, 122994.
Pesaran, M.H., 2021. General diagnostic tests for cross-sectional dependence in panels. Empir. Econ. 60 (1), 13–50.
Rabindra, et al., 2019. Tourist arrivals, energy consumption and pollutant emissions in a developing economy: implications for sustainable tourism. Tour. Manag. 72.
Ren, X., An, Y., Jin, C., 2023. The asymmetric effect of geopolitical risk on China's crude oil prices: new evidence from a QARDL approach. Financ. Res. Lett. 53, 103637.
Rumi, M.M., 1996. Stock-Watson dynamic OLS (DOLS) and error-correction modelling approaches to estimating long- and short-run elasticities in a demand function: new evidence and methodological implications from an application to the demand for coal in China's mainland. Energy Econ. 18 (4).
Sakariyahu, et al., 2023. Reflections on COP27: how do technological innovations and economic freedom affect environmental quality in Africa? Technol. Forecast. Soc. Chang. 195, 122782.
Sbia, R., Shahbaz, M., Hamdi, H., 2014. A contribution of foreign direct investment, clean energy, trade openness, carbon emissions and economic growth to energy demand in UAE. Econ. Model. 36, 191–197.
Shahbaz, M., Tiwari, A.K., Nasir, M., 2013. The effects of financial development, economic growth, coal consumption and trade openness on CO_2 emissions in South Africa. Energy Policy 61, 1452–1459.
Škare, Porada-Rochoń, 2023. Are we making progress on decarbonization? A panel heterogeneous study of the long-run relationship in selected economies. Technol. Forecast. Soc. Chang. 188, 122279.
Stock, J.H., Watson, M.W., 1993. A simple estimator of cointegrating vectors in higher order integrated systems. Econometrica 61 (4), 783–820.
Su, H., Moaniba, I.M., 2017. Does innovation respond to climate change? Empirical evidence from patents and greenhouse gas emissions. Technol. Forecast. Soc. Chang. 122, 49–62.
Suri, V., Chapman, D., 1998. Economic growth, trade and energy: implications for the environmental Kuznets curve. Ecol. Econ. 25 (2), 195–208.
Wan, Tantatape, 2013. Investigating the influence of tourism on economic growth and carbon emissions: evidence from panel analysis of the European Union. Tour. Manag. 38.
Wang, S.S., Zhou, D.Q., Zhou, P., Wang, Q.W., 2011. CO_2 emissions, energy consumption and economic growth in China: a panel data analysis. Energy Policy 39 (9), 4870–4875.
Wang, Y., Liao, M., Xu, L., Malik, A., 2021. The impact of foreign direct investment on China's carbon emissions through energy intensity and emissions trading system. Energy Econ. 97, 105212.
Yang, E., 2021. Study finds economic prosperity is associated with a cleaner environment, Human Progress. https://humanprogress.org/study-finds-economic-prosperity-is-associated-with-a-cleaner-environment/ (13 July).
Zhao, et al., 2021. How does financial risk affect global CO_2 emissions? The role of technological innovation. Technol. Forecast. Soc. Chang. 168, 120751.
Zhong, S., Goh, T., Su, B., 2022. Patterns and drivers of embodied carbon intensity in international exports: the role of trade and environmental policies. Energy Econ. 114, 106313.
Zhou, Q., Qu, S., Hou, W., 2023. Do tourism clusters contribute to low-carbon destinations? The spillover effect of tourism agglomerations on urban residential CO_2 emissions. J. Environ. Manag. 330, 117160.

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