Quality & Quantity (2024) 58:5683–5713
https://doi.org/10.1007/s11135-024-01909-7

Examining the environmental Phillips curve hypothesis in G7 nations: critical insights from wavelet coherence and wavelet causality analysis

Mohammad Naim Azimi[1] · **Mohammad Mafizur Rahman**[1]

Accepted: 17 May 2024 / Published online: 6 June 2024

Abstract

This study aims to examine the emerging Environmental Phillips-Curve (EPC) hypothesis across G7 nations from 1990 to 2022, employing the cross-sectionally augmented autoregressive distributed lags (CS-ARDL), wavelet coherence, and wavelet causality techniques. CS-ARDL analysis reveals negative impacts of the unemployment rate on CO_2e, with economic growth exerting positive effects on CO_2e over short- and long-term periods. Additionally, renewable energy and technological innovations demonstrate mitigating effects on CO_2e, while population is identified as a contributor to CO_2e in the long-term. Concurrently, economic policy uncertainty emerges as a significant driver of heightened CO_2e over the short- and long-term. The inverse relationship between CO_2e and unemployment rate corroborates the validity of the EPC hypothesis within G7 nations. Furthermore, country-specific wavelet coherence and causality analyses unveil varying degrees of co-movement and causal links among variables across diverse frequencies and time intervals. Key findings indicate an out-of-phase nexus between the unemployment rate and CO_2e, thus cross-validating the EPC hypothesis. These results underscore the necessity for creative solutions to address the trade-off between CO_2e reduction and potential employment impacts. Policymakers must promote green-tech adoption and sustainable practices to mitigate environmental harm while fostering green employment growth. Addressing economic policy uncertainty is imperative to ensure environmental sustainability. G7 nations should enact policies that incentivize green investments through higher capital gains, tax-free investments, and subsidies for environmental technologies to catalyze long-term green employment and growth.

Keywords EPC · Unemployment rate · Renewable energy · Technological innovations · Wavelet analysis

✉ Mohammad Naim Azimi
naeem.azimi@gmail.com

[1] School of Business, University of Southern Queensland, Toowoomba, QLD 4350, Australia

1 Introduction

In recent decades, there has been a notable rise in the degradation of global environmental quality, particularly evident from the 1990s to the present era. A prime example of this alarming trend is the escalating impact of global warming on our environment, stemming from unsustainable industrial practices and individual behavior that neglect environmental protection. The excessive combustion of fossil fuels in industries leads to an overproduction of greenhouse gases (GHGs), particularly CO_2e, resulting in a concurrent rise in global temperatures and unpredictable climate changes worldwide (Quéré et al. 2020; Voumik et al. 2023). The depletion of ozone layers, a critical concern, is primarily caused by fluorinated substances, promising dire environmental consequences that profoundly affect eco-systems, disrupt contemporary environmental conditions, and challenge global energy regulations (Patel et al. 2021; Ukaogo et al. 2020). Consequently, a vast body of literature has delved into the multitude of factors driving environmental degradation, emphasizing the significance of CO_2e as a potent GHGs (Erickson 2017; Raihan and Tuspekova 2022; Maji et al. 2022; Amin et al. 2022). However, the formulation of effective energy and environmentally conducive policies remains limited, particularly in redirecting the future policy trajectories of influential global entities such as the G7 nations.

Considering these pressing concerns, this study delves into a pivotal policy discussion focused on examining the emerging hypothesis regarding the inverse relationship between the unemployment rate and CO_2e, known as the Environmental Phillips Curve (EPC), within the G7 nations. The outcome of this investigation holds critical implications for the formulation of environmental and economic policies across these nations. Presently, the G7 nations hold considerable economic influence, with the United States boasting the highest per capita GDP at $62,866, and Italy ranking the lowest at $32,902 (refer to Fig. 1). These nations are recognized as high-income and highly industrialized economies (World Bank 2023). However, their intricate economic landscapes, rapid industrialization, and technological advancement have led to significant challenges in addressing carbon emissions and energy contaminants. As illustrated in Fig. 2, despite their strong commitment to sustainable environmental practices and a collective target of net zero emissions by 2050, the level of CO_2e remains dangerously high, posing severe threats to living organisms.

Source: Authors' depiction.

Source: Authors' depiction.

Existing literature has extensively explored the myriad determinants influencing CO_2e, including various factors such as economic growth (Marques et al. 2018; Karedla et al. 2021), financial market behavior (Habiba and Xinbang 2022; Petrović and Lobanov 2022), trade openness (Chen et al. 2021; Dou et al. 2021), population growth (Lawal 2019; Shaari et al. 2021), energy consumption (Akbar et al. 2018; Al-mulali and Binti Che Sab, 2012), renewable energy (Grodzicki and Jankiewicz 2022; Li et al. 2020), industrialization and urbanization (Lin et al. 2015; Liu and Bae 2018), and globalization (Jahanger 2022; Koengkan et al. 2020). Despite this comprehensive exploration, scant attention has been directed towards investigating the intricate nexus between CO_2e and the unemployment rate. Employment stands as a pivotal macroeconomics strand, directly linked to both economic growth and living standards (Ioan 2014). A higher employment rate typically stimulates increased consumption, evident through both firms and households' disposable income expenditures, thereby fostering business growth and enhancing economic stability. Despite the observed

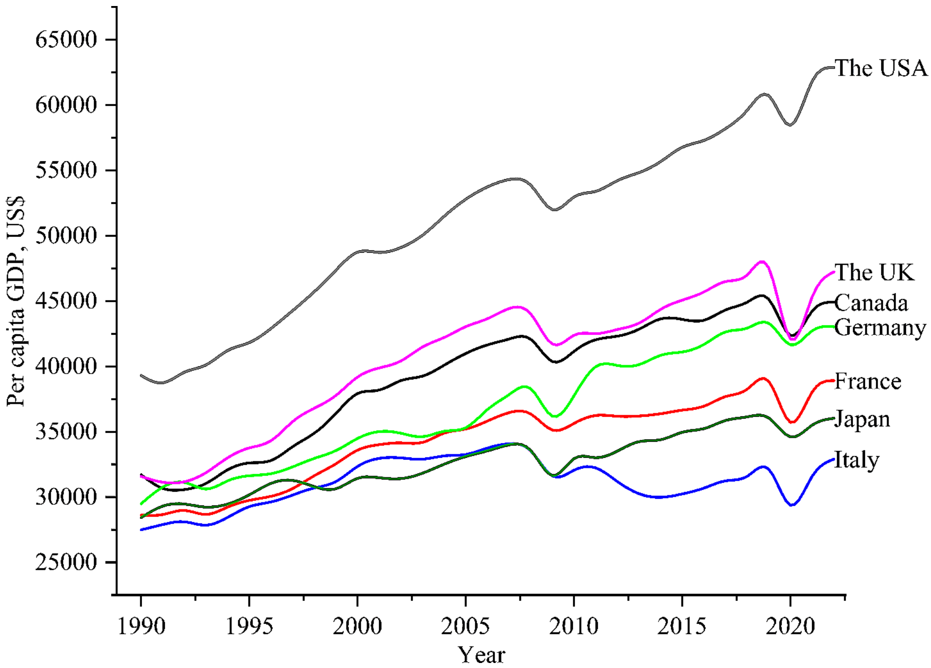

Fig. 1 Per capita GDP in G7 nations

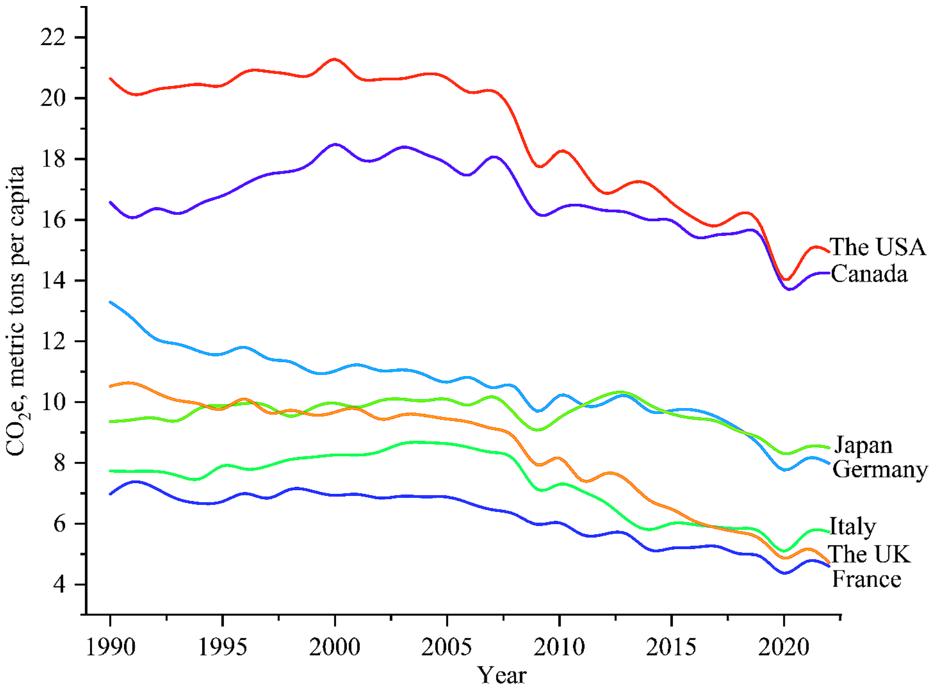

Fig. 2 CO_2e in metric tons per capita in G7 nations

volatility in unemployment rates across G7 nations (refer to Fig. 3), a notable upward shift was apparent during the global outbreak in 2020. The industrial revolution, beginning in the 18th century, significantly accelerated human interactions, particularly within the G7 countries, leading to heightened carbon emissions resulting from increased combustion of fossil fuels, gas, and oil. Consequently, environmental vulnerability reached unprecedent levels (Pata and Aydin 2023). However, recent studies, such as Xin et al. (2023), Cui et al. (2022), and Wang and Li (2021) have observed a positive relationship between the unemployment rate and CO_2e. These outcomes suggest that they tend to move together in a positively linear direction, highlighting the complexities of the relationship between employment dynamics and environmental impacts.

Source: Authors' depiction.

A recent study by Kashem and Rahman (2020) proposed a significant insight into the dynamics between the unemployment rate and CO_2e within the Organization for Economic Cooperation and Development (OECD) and Asian NICs. This study suggests an intriguing inverse relationship, indicating that higher unemployment rates correspond to lower CO_2e within an economy, introducing the Environmental Phillips Curve (EPC) hypothesis. This empirical proposition, albeit recent in the literature, carries critical implications for policymakers aiming to devise strategies that address both economic and environmental concerns simultaneously. However, it is crucial to subject the EPC hypothesis to rigorous examination across diverse contexts, considering potential additional influencing predictors such as renewable energy, technological innovation, economic policy uncertainty, and population dynamics. This is essential as it implies a trade-off, wherein improvements in environmental

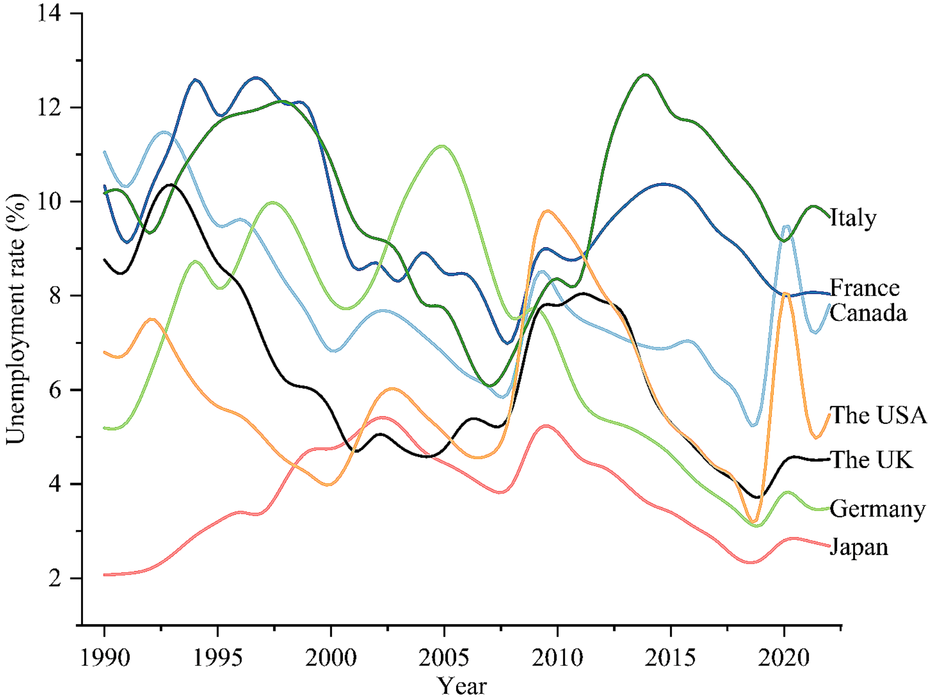

Fig. 3 Unemployment rate in G7 nations

quality come at the expense of other socioeconomic values. While existing studies, regardless of the methodological approaches employed, have explored the EPC hypothesis across a very limited number of nations (see Sect. 2.1), there remains a notable gap regarding its rigorous examination within the G7 nations. Thus, this study primarily seeks to bridge this gap by adopting a novel perspective, devising its primary objectives, and leading the discussion through the following three contemporary research questions: Firstly, does the EPC truly manifest in the context of G7 nations? Secondly, how do variables such as renewable energy, technological innovations, economic policy uncertainty, population dynamics, and economic growth define the relationship between the unemployment rate and CO_2e in various levels of responses? Thirdly, is there a discernible causal link between the unemployment rate and CO_2e? Addressing these critical questions not only scrutinizes the validity of the EPC hypothesis but also evaluates its sensitivity in the presence of major environmental efficiency instruments and observable macroeconomic volatilities.

The present piece of inquiry, however, is not exhaustive in the sense of the evolving EPC hypothesis but is an imperative empirical investigation of the nexus between the unemployment rate and CO_2e that enhances the contemporary body of knowledge and contributes to the emerging literature from several perspectives: Firstly, unlike recent studies, this article examines the validity of the EPC and underlines its sensitivity using novel wavelet coherence and wavelet causality techniques to scrutinize the precise link between the unemployment rate and CO_2e at diverse frequencies, time, and magnitude. This methods, in contrast to common econometric analysis used by Kashem and Rahman (2020), Bhowmik et al. (2022), and Anser et al. (2021), help us to explore both the short- and long-run co-movements between the unemployment rate and CO_2e, considering the heterogenous features of each nation. Recent conclusions on the short-run effects of the unemployment rate on the subject have overruled the initial assumption of the Phillips Curve (1958).

Secondly, we employ an analytical context (the G7), which is, perhaps highly influential on global environmental policies. Major policy decisions made at the G7 level impact environmental policies in a global context. To the best of our knowledge, this is the first piece of inquiry examining the EPC hypothesis in the G7 countries. Thirdly, diverging form prior studies, our research delves into the intricate interplay between the unemployment rate and CO_2e, considering the multifaceted impacts of renewable energy, technological innovations, economic policy uncertainty, economic growth, and population dynamics. This nuanced understanding of the relationships among these predictors and CO_2e yields specific policy implications crucial for policymakers grappling with contemporary challenges in G7 nations. Crucially, the presence of EPC hypothesis underscores a critical dilemma between reducing unemployment rate and curbing emissions. Deliberately increasing unemployment rate through economic cycle suppression to mitigate emissions is deemed impractical solution. The insights gleaned from this study can help policymakers in G7 nations in devising strategies to simultaneously lower emissions and the unemployment rate. For instance, the mitigating effect of technological innovation underlines the importance of boosting investments in eco-friendly technologies, offering dual benefits by reducing emissions through low-carbon-generating technologies while creating job opportunities. Similarly, prioritizing renewable energy sources not only mitigates emissions but also fosters green growth, albeit requiring shifts in investment patterns. The negative association of population dynamics with CO_2e pinpoints the importance of promoting sustainable population practices, coupled with knowledge dissemination, to effectively reduce emissions. Additionally, addressing economic policy uncertainties can stimulate higher investments in eco-friendly technologies, thereby improving employment prospects and contributing to emission reduction efforts.

The rest of this article has been structured as follows: Section two reviews relevant empirical literature. Section three presents the data and describes the variables used in the study. Section four explains the econometric methods employed to analyze the data. Section five presents the results and offers a brief discussion of the findings. Section six concludes the paper.

2 Literature review

2.1 The EPC hypothesis

A significant portion of the existing body of literature within environmental economics has been framed around the Environmental Kuznets Curve (EKC) hypothesis, originating from the seminal work of Kuznets (1995). The literature presents a diverse array of findings regarding the validity of the EKC hypothesis, showcasing varying shapes and magnitudes across different studies (see, for instance, Bernaciak 2013; Esmaeili, Balsalobre Lorente, et al., 2023; Tao 2021; Tsuzuki 2009; Khan et al. 2021b). Recently, Kashem and Rahman (2020) drew inspiration from a prominent macroeconomic proposition—the Phillips Curve (1958) (PC)—which originally postulated an inverse relationship between unemployment and inflation rates within an economy. Phillip's proposition was rooted in the notion that inflation, derived from economic growth, contributes to reducing unemployment in a stable economy (Riddell 1979; Rudd 2022).

Upon this background, Kashem and Rahman (2020) presumably hypothesized the existence of an inverse correlation between environmental degradation, CO_2e in particular, and the unemployment rate, akin to the pattern that observed in the PC. This hypothesis finds its initial support from the well-documented relationship between environmental degradation and per capita real income, as evidenced across a plethora of studies (*inter alia*, Abdouli and Omri 2021; Atay and Ergun 2018; Ganda 2022; Hao 2022; Pao and Tsai 2010; Rafindadi 2016; Saboori and Sulaiman 2013; Shaari et al. 2020; Zhu 2022). Elevated production levels invariably translate into heightened pollution outputs within the economy, as each incremental unit of output tends to introduce additional pollutant particles. Conversely, the nexus between production, unemployment, and income is equally intricate. As income and pollution surge, the unemployment rate typically declines. This phenomenon is rooted in the dynamic nature of economic activity, wherein increased production fosters greater employment opportunities, thereby driving down the unemployment rate (Kashem and Rahman 2020). Drawing on this notion, Kashem and Rahman (2020) introduced the Environmental Phillips Curve (EPC) hypothesis, which postulates that certain forms of environmental degradation decline as unemployment increases, particularly in stable and industrialized economies. While they did not explicitly specify the nature of CO_2e escalation within an economy in their seminal work, they drew parallel to the foundational theory of the PC. They suggested that, among other factors, unemployment stemming from the industrial sector could potentially lead to a reduction in CO_2e over the long-term, thereby potentially validating the existence of the EPC. This notion finds further support in the findings presented by studies conducted by Xin et al. (2023), Liu and Feng (2022), Cetin and Bakirtas (2020), Chen and Semmler (2018), Meyer (2016), and numerous others.

2.2 Empirical review

Since the emergence of the EPC hypothesis in environmental analysis literature by Kashem and Rahman (2020), the scholarly exploration of this hypothesis has remained relatively scarce, with only a handful of studies—barely reaching the count of 16—venturing into this area. These studies have often taken either a country-specific approach or utilized panel data methodologies to unravel the intricate dynamics of the EPC hypothesis at play. Yet, despite the limited presence of empirical studies within the literature, particularly concerning the G7 nations, we embark on the bold journey to develop deep into the existing repository.

Ng et al. (2023) examined the Environmental Kuznets Curve (EKC) hypothesis and the EPC assumption in a set of panel containing 36 member countries of the OECD over the period from 1995 to 2015. The authors employed the common correlated effect (CCE) model with augmented mean group estimators to test their competing hypotheses. They found that while the EKC hypothesis does not exist, the EPC is valid in the context of their recipient panel. Hacıimamoğlu (2023) aimed to examine the validity of the EPC hypothesis in a panel of Next-11 economies over the period from 1991 to 2018. The authors employed the dynamic common correlated effects (DCCE) and augmented mean group (AMG) approaches for panel data analysis. The author observed a negative association between the unemployment rate and ecological footprint; as a result, the EPC hypothesis was found to be valid in the Next-11 countries.

Çakmak et al. (2023) examined the challenging EPC hypothesis in a set of panel data categorized under high-, upper-middle-, and lower-middle-income economies over the period from 1990 to 2020. For analysis, the authors employed the autoregressive distributed lags model. They found that although the EPC assumption does not exist in the panel of high-income countries, it is found to be valid in the upper-middle-income countries and neutral in the panel of lower-middle-income countries. The authors also found that energy consumption and economic growth worsen environmental quality, whereas renewable energy consumption improves it. Yavus and Kilic (2023) employed the augmented autoregressive distributed lags (AARDL) model with a set of time series data over the period from 1982 to 2022 to test the competing EPC hypothesis in the context of Turkey. The authors found that the unemployment rate has an effective role in improving environmental quality, and thus their results support the EPC hypothesis that exists in Turkey. Moreover, the authors noticed that GDP, energy consumption, and natural resource rents have negative impacts on environmental quality.

Djedaiet (2023) examined the validity of the EPC in African OPEC nations from 1990 to 2019. In addition to the unemployment rate, the author has also tested the effects of the inflation rate on CO_2e. Using the non-linear autoregressive distributed lags model, the author found statistical validation of the EPC, implying that the unemployment and inflation rates have negative impacts on CO_2e. However, the results of this study deviate from theoretical expectations and empirical evidence; the author observed that a higher inflation rate reduces CO_2e. Malik and Shaikh (2023) aimed to examine the validity of the EPC hypothesis and delved into the impact of the unemployment rate, oil rent, and renewable energy on greenhouse gas emissions (GHGs) in the G20 economies over the period from 1991 to 2020. The authors used the dynamic common correlated effects (DCCE) model and found that the EPC exists in the G20 countries. They also observed that renewable energy consumption has a negative impact on GHGs while positively affecting oil rent in their recipient panel.

Dogan et al. (2022) evaluated the effects of the unemployment rate, real output, non-renewable, and renewable energy on the ecological footprint in South Asian countries over the period from 1990 to 2017 using fully modified ordinary least squares (FMOLS) and dynamic ordinary least squares (DOLS) models. However, there is a strong empirical criticism of using FMOLS and DOLS in the presence of cross-sectional dependence among units; the authors observed an adverse impact of renewable energy and the unemployment rate on the ecological footprint. Their overall results support the existence of the EPC hypothesis in South Asia. Shang and Xu (2022) attempted to test the dynamic behavior of the EPC assumption and the EKC hypothesis in a panel of provincial data relevant to China over the period from 2005 to 2019. The authors employed the generalized method of moment (GMM) model to test their competing hypotheses. They noticed that there exists an inverted U-shaped curve between CO_2e and employment rate in China; however, the magnitude of the effects varies across the provinces in China. The authors argued that the EKC hypothesis suits China's environmental context better in shape and magnitude than the EPC assumption.

Tanveer et al. (2022) employed three proxies for environmental degradation including, CO_2e, CH_4, and ecological footprint, to test their association with the unemployment rate while controlling for the effects of economic growth, FDI, energy consumption, and globalization in Pakistan over the period from 1975 to 2014. The authors employed the asymmetric autoregressive distributed lags model and found that there is a negative nexus between unemployment rate and CO_2e, ecological footprint, and CH_4 in the long run in Pakistan. While their results validated the EPC hypothesis, they noticed a positive effect of energy consumption on CO_2e, ecological footprint, and CH_4. Finally, Anser et al. (2021) used a panel of data for Brazil, Russia, India, China, South Africa, and Turkey (BRICST) from 1992 to 2016 to test the validity of the EPC employing the autoregressive distributed lags model with pooled mean group estimators. The authors found that a trade-off between environmental degradation and the unemployment rate, concluding the existence of EPC in their recipient panel.

2.3 Empirical gaps

The EPC hypothesis, despite its emergence, remains underexplored in the literature, representing several empirical gaps that need addressing as the EPC discourse evolves in the literature. These gaps have driven our piece of research, aiming to both supplement the existing body of the EPC literature and pave the way for further empirical discussions on the subject. Specifically, we observed the following gaps: Firstly, we observed that the existing number of studies about the EPC is not exhaustive enough to provide robust support for contemporary and challenging global environmental policies. The existing studies fall short in fully delineating the EPC hypothesis and capturing all facets of its empirical pattern. Second, as the literature evolves, new environmental and unemployment drivers need to be tested within the EPC framework. We fill part of this gap by testing the sensitivity of the EPC in the presence of technological innovation, renewable energy, and economic policy uncertainties. Third, methodological sophistication may enhance the pattern of the

EPC hypothesis. Although recent studies have used both dynamic and static models, we add to these sophistications by employing both common dynamics and novel wavelet analysis, particularly wavelet coherence and wavelet causality techniques to precisely highlight the co-movement between the unemployment rate and CO_2e across various frequencies and time horizons. Fourth, among all, the literature reports that Malik and Shaikh (2023) have delved into the subject in the G20 countries; other studies, however, are valuable in enhancing the existing knowledge about the EPC hypothesis; they are not sufficiently supportive of policy formulations. To address this important gap, this article explores the EPC hypothesis in the context of G7 nations, which is imperative and influential on concurrent global environmental policies.

3 Data and variables

3.1 Data

The study uses a set of panel data spanning from 1990 to 2022 for G7 nations. These include Canada, France, Germany, Italy, Japan, the United Kingdom, and the United States of America. To ensure data consistency, the period of study begins from 1990 for certain variables, focusing particularly on achieving a balanced panel for unemployment rate. Additionally, the choice of G7 countries is twofold: Firstly, as a coalition of advanced economies, the G7 nations hold significant sway in addressing emergent global environmental issues and shaping international trends (Qin et al. 2021). Secondly, amidst the urgent need to combat climate change and transition to sustainable energy sources, the G7 serves as a crucial context for environmental sustainability research. Addressing emergent environmental policy concerns within the G7 framework can catalyze broader global actions, setting important precedents for nations worldwide to follow suit.

3.2 Variables

3.2.1 Dependent variable

The study selects and employs variables that align with prior literature and the conceptual framework of the EPC. The dependent variable chosen for analysis is carbon dioxide emissions (CO_2e), measured in metric tons per capita. CO_2e encompasses emissions originating from fossil fuels and industrial activities, containing carbon dioxide generated in the process of consuming liquid, solid, and gas flaring (World Bank 2023). Previous studies by Mehmood and Tariq (2020), Shoaib et al. (2020), Szetela et al. (2022), and many others have used CO_2e as a proxy for environmental degradation. Recognized as a critical indicator of environmental degradation, CO_2e reflects the impact of human activities on the environment and is central to understanding and addressing climate change issues.

3.2.2 Explanatory variables

Our analysis incorporates several explanatory variables, namely, the unemployment rate (UR), renewable energy (RE), economic policy uncertainty index (EPU), and technological innovations (TI). Of particular interest is UR, which plays a critical role in assessment of the EPC hypothesis (Shastri et al. 2023; Wang and Li 2021). It is measured as the percentage of the total labor force actively seeking and available for employment. Additionally, RE, expressed as a percentage of final energy consumption, holds significant importance in affecting the validation of the EPC hypothesis. RE serves to diminish environmental burdens caused by non-renewable sources and thus reduce CO_2e (Dong et al. 2020; Khezri et al. 2022; Kwakwa 2023; Bhuiyan et al. 2023). EPU has been employed to assess recent fluctuating economic policies on the EPC trajectory. It is measured in numbers. A higher EPU value indicates elevated levels of uncertainties surrounding economic policies and vice versa. Constructed by Baker et al. (2016), EPU aggregates the value-added average of three uncertainty components: newspaper-based uncertainty, disagreements on government expenditures and consumer price index, and tax-based uncertainty. Prior studies by Esmaeili et al. 2023b); Tee et al. (2023); Su et al. (2022) have also examined the ramifications of EPU, revealing a positive association between EPU and environmental degradation. Furthermore, TI, measured as the number of patent-residents, stands as a crucial indicator that could influence contemporary levels of CO_2e. A greater number of TIs signifies increased collective efforts towards innovating low-carbon-generating technologies and solutions within an economy. Nonetheless, prior literature has shown mixed results on the effects of TI on CO_2e. Achieving net zero emissions and fostering production of clean energy necessitate substantial engagement with technological innovations (Raghutla and Chittedi 2023).

3.2.3 Control variables

It is well-established that CO_2e is influenced by a multitude of factors; however, to avoid overspecification issues, the study incorporates several control variables. Per capita GDP (GDP), expressed in constant 2015 US$, represents the economic variations of a country passing through various development stages, contributes to environmental pressures. Numerous studies, including those by Sirag et al. (2018), Koc and Bulus (2020), Awan and Azam (2022), and Pata and Kartal (2023) have also a similar proxy for economic growth. Certainly, population serves as a critical control variable alongside GDP. While GDP represents the economic performance of a country, POP reflects the size of the market within which these economic activities transpire. Therefore, incorporating POP as a control variable is essential for a comprehensive analysis. POP is measured by millions of people. Likewise, prior studies by Dietz and Rosa (1997), Chaurasia (2020), Namahoro et al. (2021), and Mehmood et al. (2021), have also used POP to measure its effects on the subject.

3.3 Data compilation, transformation, and description

Datasets for CO_2e, UR, GDP, RE, TI, and POP were sourced from the World Development Indicators (WDI). The data for EPU relevant to Canada, France, Germany, Italy, the UK, and the USA was collected from the Economic Policy Uncertainty site (https://www.policyuncertainty.com/) developed by Baker et al. (2016). The dataset for EPU relevant to Japan was compiled from the similar source developed by Arbatli et al. (2019). To ensure consistency and capture any potential heteroskedasticity, the variables are transformed into their natural logarithmic forms. Consequently, lnC, lnU, lnR, lnT, lnE, lnY, and lnP represent the natural logarithms of CO_2e, UR, RE, TI, EPU, GDP, and POP, respectively.

4 Methods

4.1 Baseline model

To examine the impacts of the unemployment rate, renewable energy, technological innovations, economic policy uncertainty, economic growth, and population on CO_2e, we specify the following long-run panel dynamic linear model:

$$\begin{aligned} \ln C_{it} = \theta_i + \vartheta_1 \ln U_{it} + \vartheta_2 \ln R_{it} + \vartheta_3 \ln T_{it} \\ + \vartheta_4 \ln E_{it} + \vartheta_5 \ln Y_{it} + \vartheta_6 \ln P_{it} + e_{it} \end{aligned} \tag{1}$$

where ln denotes the natural logarithms of the variables, θ represents the intercept, ϑ_1 to ϑ_6 indicate the long-run coefficients of the explanatory variables, e_{it} represents the error term, and all variables are as defined earlier. The estimation of Eq. (1) necessitates a series of economic methods to avoid misspecifications. Panel data techniques are advantageous for empirical research but have several limitations, including cross-sectional dependence (CD) and slope heterogeneity (SH). These challenges stem from shared consumption patterns and rapid globalization (Azimi et al. 2023). The study addresses CD using Pesaran's (2004) proposed model and assesses potential SH employing Pesaran and Yamagata's (2008) approach.

For the rejected null hypotheses of no CD and SH, standard panel unit root tests may not adequately capture the true stationarity of the variables. In response, the study turns to the augmented cross-sectional IPS (CIPS) test, as proposed by Pesaran (2007). This method, based on the cross-sectional augmented Dickey and Fuller (CADF) regression, offers superior accuracy in capturing the stationarity of the variables in the presence of CD and SH compared to conventional approaches. Additionally, it is crucial to assess the long-run equilibrium among the variables. Given the rejection of the null hypothesis of no CD and violated SH, common panel cointegration models including Pedroni's (1999) and Kao's (1999) techniques fall short of estimating the long-run relationship between the variables. To address this, the study employs the proposed cointegration model by Westerlund (2007). This method examines the null hypothesis of no cointegration in the presence of CD and SH, while addressing any regime shift and structural breaks in data.

Whether cointegrated or not, in the presence of CD and violated SH assumption, common panel data models would be inconsistent. For example, for the rejected null of data normality and no CD, pooled ordinary least squares (OLS), fixed effects (FE), and random effects (RE) models would produce inconsistent results (Barili et al. 2018). However, the FE model augmented with Driscoll and Kraay's (1998) standard error (FE-DK) approach accounts for CD and residuals' autocorrelations with the explanatory variables (Knight 2014; Hoechle 2007), it is more appropriate for microeconomic analysis. Additionally, the ARDL model of Pesaran et al. (2001) is an empirical competitor to address SH; however, it fails to capture CD in panel data. To address these issues, the study employs the CS-ARDL model proposed by Chudik and Pesaran (2015), which is capable of estimating consistent short- and long-run coefficients in the presence of CD and SH. The compact form of the CS-ARDL model takes the following form:

$$\Delta y_{it} = \alpha_i + \delta_i \left(y_{it-1} - \phi'_i x_{it-1} + \eta_i^{-1} \bar{y}_t + \eta_i^{-1} \varphi' \bar{x}_t \right) + \sum\nolimits_{j=1}^{p} \vartheta_{ij} \Delta y_{it-j} + \sum\nolimits_{j=0}^{q} \lambda_{ij} \Delta x_{it-j} + + \sum\nolimits_{j=0}^{q} \gamma_{ik} \Delta \bar{y}_{t-j} + \sum\nolimits_{j=0}^{q} \theta_{ij} \Delta \bar{x}_{t-j} + \varepsilon_{it} \tag{2}$$

where α_i represents the intercept, δ_i is the coefficient of error-correction, φ_i and η_i are the long-run coefficients, $\bar{y}$ and $\bar{x}$ represent the cross-sectional mean values of the dependent and independent variables, respectively, λ_{ij}, γ_{ij}, and θ_{ij} are the short-run coefficients, and ϵ_{it} represents the error term. The robustness of the results obtained from the CS-ARDL model involves the estimation of the cross-sectional dynamic least squares (CS-DL) model proposed by Chudik et al. (2016), whereas for further verification of the results' validity, we employ the common correlated effects mean group (CCEMG) of Pesaran (2006) and the augmented mean group (AMG) model of Eberhardt and Bond (2009). These tests are valid in the presence of CD, SH, and endogeneity issues.

In addition to rigorously examining the short- and long-term effects of the variables using established techniques in prior literature, this study uses two innovative and robust methods: wavelet coherence and wavelet causality. These advanced techniques offer a nuanced verification of the relationship between CO_2e and the unemployment rate, capturing their co-movements across time and frequency (Liu et al. 2023). The wavelet analysis we employ offers a highly explained depiction of the intricate nexus between CO_2e and the unemployment rate (the EPC), revealing accurate insights for reorientation of the existing policies. To initiate, we first specify a discrete wavelet transformation on the converted data of annual observations into quarterly series for each country as in Mishra et al. (2020), Pata and Aydin (2023), and Adebayo (2020). Subsequently, we utilize the following two key transformative functions:

$$\int \xi(T)\, DT = 0 \qquad \int \xi(T)\, DT = 1 \tag{3}$$

Here, the wavelet including higher (lower) frequency trends is shown by 1 (0) (Torrence and Compo 1998). To depict the wavelet, we use Eqs. (4) and (5):

$$\xi_{jK}(T) = 2^{j \div 2} \xi \left(2^j T - K \right) \tag{4}$$

$$\xi_{jK}(T) = 2^{j \div 2} \Upsilon \left(2^j T - K \right) \tag{5}$$

Building on this foundation, we proceed to specify the wavelet coherence analysis (hereof, WCA), between lnC (natural log of CO_2e) and lnU (natural log of the employment rate) to explore the co-movement suggested by the EPC hypothesis across both temporal and frequency dimensions. The WCA uses the following equation to depict the co-movement between these variables:

$$\Xi_{\mathrm{lnClnU}}(\gamma, \eta) = \Xi_{\mathrm{lnU}}(\gamma, \eta) \Xi^{*}_{\mathrm{lnC}}(\gamma, \eta) \tag{6}$$

where Ξ_{lnUlnC} represents the transformed cross-wavelet for lnC, Ξ_{lnC} represents the transformed cross-wavelet for lnU, and (*) denotes the complex conjugate (Mishra et al. 2020). To test the null of co-movement, we employ the following wavelet coherence equation:

$$\psi_n^2(s) = \frac{\left|N(N^{-1}\Xi_{\mathrm{lnClnU}}(\gamma, \eta)\right|^2}{N\left(N^{-1}|= \Xi_{\mathrm{lnU}}(\gamma, \eta)|^2\right) N\left(N^{-1}|= \Xi_{\mathrm{lnC}}(\gamma, \eta)|^2\right)} \tag{7}$$

Here, the cross-wavelet power spectra are utilized to segment the intervals, underlining the sensitive power across the time, encompassing all frequency and temporal domains (Papadamou et al. 2021). The WCA possesses unique properties that allow it to characterize a large range of intervals and domains when variables co-move across time. The null of no co-movement is rejected when ψ_n^2 approaches to value of 0, and conversely, when ψ_n^2 nears the value of 1. Additionally, to delve into the directional relationships between our focal variables, namely, lnC and lnU, we leverage wavelet causality introduced by Rua (2013) as follows:

$$\begin{aligned} GC_{\mathrm{lnU}\to\mathrm{lnC}}(\upsilon, s) &= \frac{\lambda\left\{s^{-1}\left|\wp\left(\Xi^{\gamma}_{\mathrm{lnUlnC}}(\upsilon, s)\right)\Theta_{\mathrm{lnU}\to\mathrm{lnC}}(\upsilon, s)\right|\right\}}{\lambda\left\{s^{-1}\sqrt{|\Xi^{\gamma}_{\mathrm{lnU}}(\upsilon, s)|^2}\right\}\lambda\left\{s^{-1}\sqrt{|\Xi^{\gamma}_{\mathrm{lnC}}(\upsilon, s)|^2}\right\}} \\ \Theta_{\mathrm{lnU}\to\mathrm{lnC}}(\upsilon, s) &= \begin{cases} 1, \text{ if } \Xi_{\mathrm{lnUlnC}}(\upsilon, s) \in \left(0, \frac{\tau}{2}\right) \cup \left(-\tau, \frac{\tau}{2}\right), \ \Xi_{\mathrm{lnUlnC}}(\upsilon, s) = \tan^{-1}\left(\frac{\Psi_{\mathrm{lnUlnC}}}{\Xi_{\mathrm{lnUlnC}}}\right) \\ 0, \text{ otherwise} \end{cases} \end{aligned} \tag{8}$$

where *GC* denotes the wavelet Granger-causality, $\Xi_{lnUlnC}(\upsilon, s)$, $\Xi_{lnU}(\upsilon, s)$, and $\Xi_{lnC}(\upsilon, s)$ represents transformed wavelet, $\Theta_{lnU\to lnC}$ represents the function of the predictors. Equations (7) and (8) provide a comprehensive analysis of the relationship between lnC and lnU, a pivotal step in validating the emerging hypothesis, EPC. The outcomes of these equations are visually depicted for greater clarity.

5 Results

5.1 Preliminary statistics

The analysis begins by presenting some important summary statistics in Table 1 (logarithmic forms are applied) to exhibit the overall trends in the augmented variables. The mean values indicate lnC at 2.316 metric tons per capita, lnU at 1.895%, lnY at 10.525 US$ per capita, lnR at 1.985 kilowatt-hour per capita, lnE at 4.818, and lnP at 18.209 million people. Notably, the correlation matrix reveals moderate correlations only between lnU and lnT, with no significant correlations among other variables. These findings lend support to the absence of multicollinearity concern, thereby underscoring the rationale for proceeding with further analysis.

Table 1 Results of preliminary tests

	lnC	lnU	lnY	lnR	lnT	lnE	lnP
Summary statistics							
Mean	2.316	1.895	10.525	1.985	10.29	4.818	18.209
Minimum	1.474	0.728	10.222	-0.494	7.688	3.627	17.137
Maximum	3.058	2.540	11.049	3.173	12.867	6.14	19.625
Correlation matrix	lnC	lnU	lnY	lnR	lnT	lnE	lnP
lnC	1						
lnU	-0.164	1					
lnY	0.443	-0.302	1				
lnR	-0.009	0.161	0.169	1			
lnT	-0.223	-0.640	0.244	-0.365	1		
lnE	-0.247	0.365	0.167	0.434	-0.486	1	
lnP	0.309	-0.441	0.458	-0.272	0.883	-0.242	1

Notes: Authors' estimations.

Table 2 CD and SH test results

	CD-test	*p*-value	Corr	Abs(corr)	Result
lnC	21.45***	0.000	0.815	0.815	CD confirmed
lnU	4.18***	0.000	0.164	0.341	CD confirmed
lnY	22.63***	0.000	0.860	0.860	CD confirmed
lnR	18.19***	0.000	0.713	0.714	CD confirmed
lnT	3.52***	0.000	0.137	0.548	CD confirmed
lnE	10.24***	0.000	0.400	0.426	CD confirmed
lnP	18.03***	0.000	0.685	0.685	CD confirmed
Slope heterogeneity test					
$\widehat{\Delta}_{adj}$	11.809***	0.000			SH confirmed
$\widehat{\Delta}$	13.672***	0.000			SH confirmed

Notes: *** rejects the null at 1% significant level. CD: cross-sectional dependence~N (0,1), SH: slope coefficients are heterogeneous. Source: Authors' estimations.

5.2 CD, SH, and panel unit root

Table 2 reveals strong evidence of both CD and SH across all variables. The significance at the 1% level decisively rejects the null hypothesis for both CD and SH. To ensure accurate analysis, we further verify stationarity properties of the variables using the CIPS test of

Table 3 Panel unit root tests results

	CIPS		LLC		IPS		Result
	Level	First-diff.	Level	First-diff.	Level	First-diff.	
lnC	-1.149	-5.526***	3.1519	-6.7937***	4.3958	-8.8699***	I (1)
lnU	-1.945	-3.548***	-2.0002	-5.0105***	0.2016	-5.7314***	I (1)
lnY	-1.391	-4.648***	-1.9376	-8.1734***	-1.1945	-8.7915***	I (1)
lnR	-0.405	-5.081***	-0.0377	-4.0558***	-1.0294	-5.7751***	I (1)
lnT	-1.018	-5.439***	-1.0405	-5.8072***	-0.8748	-5.9325***	I (1)
lnE	-2.745***	-4.741***	-3.9077***	-4.0681***	- 3.3876***	-7.8130***	I (0)
lnP	-0.435	-4.784***	-1.0669	-3.9853***	-0.9352	-4.0509***	I (1)

Notes: *** rejects the null hypothesis of non-stationarity at a 1% significant level. Critical values for CIPS at 1%, 5%, and 10% levels are −2.55, -2.33, and −2.21, respectively.
Source: Authors' estimations.

Table 4 Panel cointegration tests results

	Westerlund		Pedroni		Kao		Result
	Statistics	*p*-value	Statistics	*p*-value	Statistics	*p*-value	
Variance ratio	-6.751***	0.000					Cointegration
Modified Phillips–Perron			-8.411***	0.000			Cointegration
Phillips–Perron			-6.478***	0.000			
Augmented Dickey–Fuller			-6.343***	0.000	-2.027***	0.009	Cointegration
Modified Dickey–Fuller					-3.442***	0.000	
Dickey–Fuller					-3.031***	0.000	

Notes: *** indicates significance at a 1% level.
Source: Authors' estimations.

Pesaran (2007). For cross-validation, the Levin, Lin, and Chu (LLC) (2002) and Im, Pesaran and Shin (IPS) (2003) tests are performed (results in Table 3).

The CIPS, LLC, and IPS tests reveal a mixed order of integration among our variables. While lnE exhibits stationarity at level, all other variables achieve stationarity after first differencing. These findings confirm a mix of I(0) and I(I) processes, strongly supporting the use of long-run cointegration analysis.

5.3 Panel cointegration test

Following the evidence of mixed integrating order of the variables, we investigated cointegration between them, particularly lnC and lnU. Westerlund's (2007) panel cointegration test—robust to CD—confirmed a statistically significant long-run relationship between our variables (Table 4). This suggests that lnU and other explanatory variables have a persistent, non-random impact on lnC in the long-term. To corroborate these findings, Pedroni's (1999) and Kao's (1999) cointegration tests we employed, both supporting the existence of a long-run equilibrium within the augmented variables.

5.4 CS-ARDL estimates

The CS-ARDL model (Table 5), well-suited for our data's characteristics, reveals several crucial insights. The negative impact of lnU (unemployment rate) on lnC (CO_2e), both in the short and long run, confirms the EPC hypothesis for G7 nations. Furthermore, lnY (per capita GDP) positively affects lnC in the short and long run, underscoring the environmental costs of economic growth. lnR (renewable energy) and lnT (technological innovation) lack short-term impact on lnC but have significant, long-term negative effects. Conversely, lnE (economic policy uncertainty) positively drives lnC in both timeframes, while lnP (population) influences lnC upward only in the long run. The negative, significant ECM term indicates a rapid 94.3% annual convergence towards long-run equilibrium, while the insignificant CD-statistic indicates the successful correction of the CD problem.

To ensure robustness, we cross-validated our results using the CS-DL, CCEMG, and AMG estimators (Table 6). These models yielded consistent coefficients with minor variations in magnitude. This outcome strengthens confidence in our findings and suggests the CS-ARDL model offers greater precision in capturing the effects within our dataset.

5.5 Wavelet coherence analysis

Our primary objective was to explore the EPC hypothesis in G7 nations and assess its sensitivity to various scales and frequencies of unemployment rate, employing wavelet coherence analysis. The results displayed in Fig. 4, include the names of all nations examined. In Fig. 4, a value of 1, indicating perfect co-movement, is depicted in red, while the absence of co-movement (0) appears as dark blue. Moderate co-movement is highlighted with a sky-blue color. The results reveal a moderate phase-out co-movement between lnU and lnC across most G7 nations, confirming the EPC hypothesis. For brevity, we present the key results as follows: In Canada, significant moderate co-movement is observed at scales 8 to

Table 5 CS-ARDL results

	Short run effects			Long run effects		
	Coefficient	t-statistics	*p*-value	Coefficient	t-statistics	*p*-value
Lagged lnC	0.811***	5.09	0.000	0.844***	3.87	0.000
lnU	-0.928**	-2.05	0.047	-1.023***	-2.99	0.001
lnY	0.336***	6.10	0.000	0.389***	-4.15	0.000
lnR	-0.109	-0.68	0.345	-0.234***	-3.19	0.000
lnT	-0.0017	-0.84	0.320	-0.019***	-2.83	0.005
lnE	0.015***	2.79	0.006	0.035***	3.11	0.000
lnP	0.148	1.12	0.210	0.510***	5.46	0.000
Constant	-3.027***	-6.15	0.000			
ECM	-0.943***	-4.12	0.000			
Diagnostic checks						
Observations	182					
Group	7					
R-squared	0.43					
CD-statistics	0.99					
F-statistics	5.38***					
Normality	0.87					

Notes: ***, **, and * indicate significance at 1%, 5%, and 10% levels, respectively.

Table 6 Robustness tests' results

	CS-DL			CCEMG			AMG		
	Coefficient	t-statistics	*p*-value	Coefficient	t-statistics	*p*-value	Coefficient	t-statistics	*p*-value
Lagged lnC	0.672***	5.13	0.000	0.815***	6.14	0.000	0.722***	3.88	0.000
lnU	-0.918***	-4.19	0.001	-0.864***	-4.02	0.000	-0.903***	-3.36	0.000
lnY	0.344***	4.37	0.000	0.216***	6.27	0.000	0.305***	3.29	0.000
lnR	-0.286***	-4.28	0.000	-0.245***	-4.19	0.000	-0.339***	-4.01	0.000
lnT	-0.021***	-4.45	0.000	-0.020***	-4.33	0.000	-0.020***	-4.17	0.000
lnE	0.031***	2.99	0.001	0.025***	3.76	0.000	0.041***	3.51	0.000
lnP	0.489***	3.74	0.000	0.377***	3.98	0.000	0.398***	4.12	0.000
Constant	-6.411***	-6.15	0.000	-8.210***	-5.99	0.000	-0.509***	-10.16	0.000

Notes: ***, **, and * indicate significance at 1%, 5%, and 10% levels, respectively.

40, indicating a negative association in the long run. France exhibits stronger co-movement at scales 4 to 16, suggesting a persistent negative co-movement between lnU and lnC. Germany shows a moderate co-movement concentrated at scales 32 and above, implying a phase-out co-movement. Italy demonstrates a negative association, particularly at higher frequencies. Japan and UK display a strong negative nexus, although Japan experiences a period of no co-movement (1990Q4-1995Q1). In the USA, high co-movement across all scales indicates a consistent phase-out relationship between lnU and lnC.

Source: Authors' depiction.

5.6 Wavelet causality

Figure 5 displays the results of wavelet causality analysis, aimed at investigating the causal nexus from lnU to lnU in support of the EPC hypothesis. This innovative method eliminates the need for minimum phase transfer in verifying the causality, considering when, at what scale, and magnitude at which this link is established. The causal link is depicted using a color gradient ranging from the absence of causality (blue) to significant causality (red), using a 5% significance level across 500 bootstrap replications. Additionally, white dashed lines delineate the effectless region (Olayeni 2016; Liu et al. 2023). In Canada, short-term causality from lnU to lnC is observed from 1995Q4 to 2021Q4, while medium-term causality spans from 2000Q1 to 2012Q2. A long-term causal link exists from lnU to lnC from 1993Q3 to 2016Q1. In France, only a medium-term causal link from lnU to lnC is suggested, spanning from 1993Q3 to 2016Q4. For Germany, Italy, and Japan, the study fails to reject the null of time-based causality running from lnU to lnC. Conversely, in the UK, short-term causality from lnU to lnC is observed from 1993Q1 to 2021Q4, with a long-term causal link evident from 1995Q1 to 2012Q1. Finally, in the USA, our results support a short-term causal link from lnU to lnC from 1995Q1 to 2020Q4.

Source: Authors' depiction.

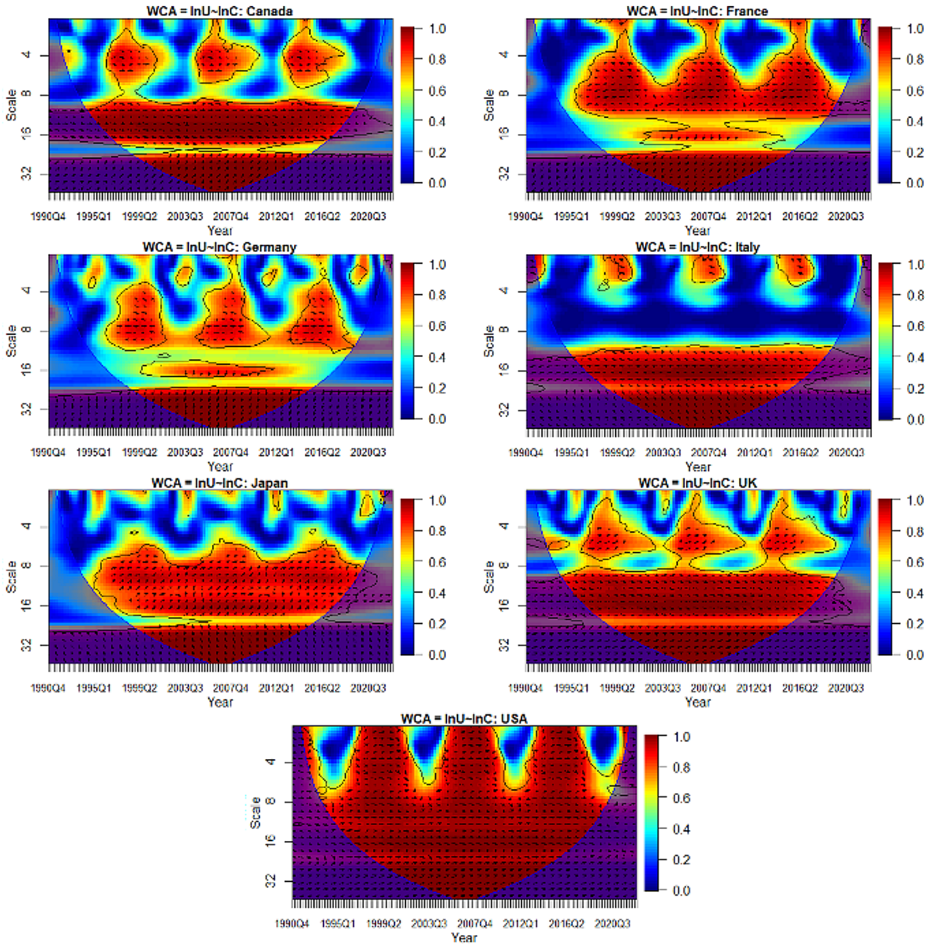

Fig. 4 Cross-country wavelet coherence analysis

6 Discussion

This study advances the exploration of the emerging EPC hypothesis across G7 nations in the presence of key environmental, economic, and demographic predictors. Preliminary analysis underscores significant cross-sectional dependence and slope heterogeneity among the augmented variables (Table 2), while affirming their mixed integrating order of I(0) and I(1) without any higher series (Table 3). Delving deeper, the investigation into CO_2e as the dependent variable reveals a long-run compelling cointegration with renewable energy, technological innovation, economic growth, economic policy uncertainty, and population dynamics (Table 4). These findings suggest a synchronous co-movement among these factors. Building upon these initial empirical insights, the study employs the CS-ARDL model to discern both the short- and long-term effects of the explanatory variables on CO_2e (Table 5). To ensure the robustness of the results obtained from the CS-ARDL model, multiple estimators including CS-DL, CCEMG, and AMG were applied (Table 6). Additionally,

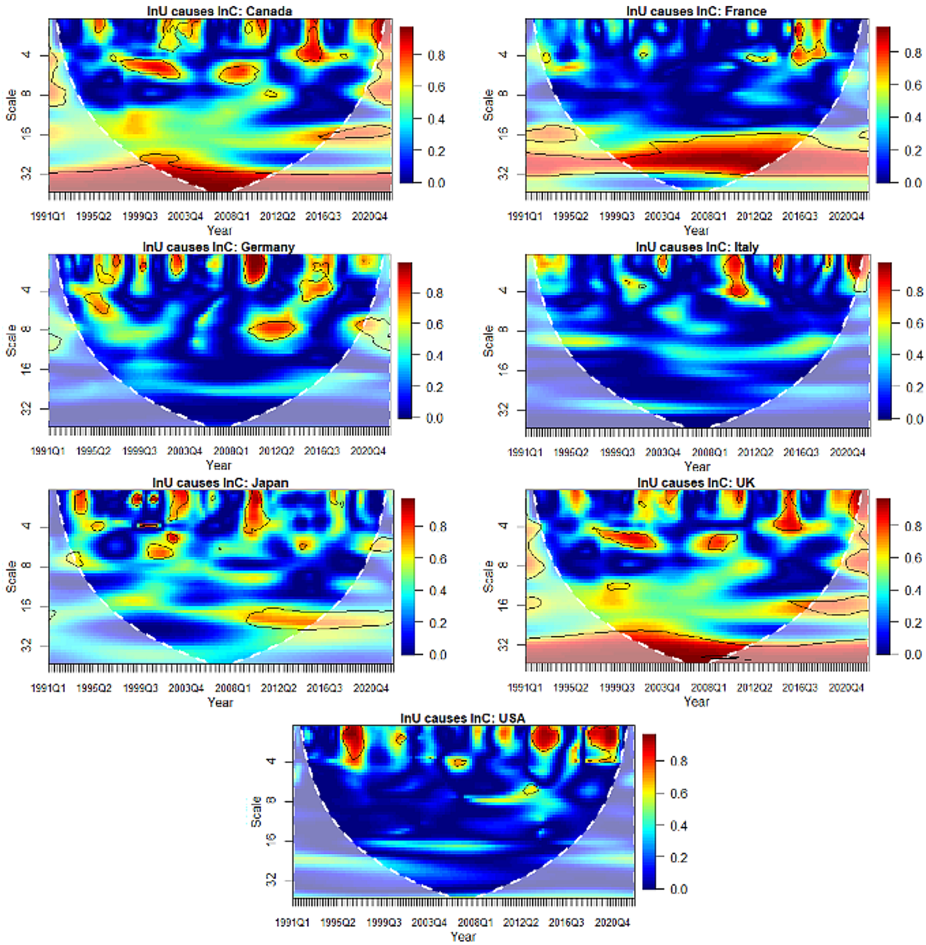

Fig. 5 Wavelet causality results

to discern the time- and frequency-based co-movement of CO_2e and the unemployment rate alongside their temporal dynamics in establishing causal links, the study employs two innovative approaches, namely wavelet coherence and wavelet causality analysis (Figs. 4 and 5).

The analysis reveals a consistent negative association between the unemployment rate and CO_2e, evident across both short- and long-term periods. More precisely, a 1% increase in the unemployment rate corresponds to a 0.928% reduction in CO_2e in the short run, and a slightly higher decrease of 1.023% in the long run. This outcome confirms the validity of the EPC hypothesis within G7 countries, implying that an upsurge in unemployment rate leads to a mitigation of environmental pollution within the examined panel. The results suggest that potential pathways towards sustainable development and growth stewardship necessitate a simultaneous policy consideration of both social impact of the unemployment and environmental quality. Holistic pragmatic approaches, including green employment initiatives could be a promising pathway to mitigate the environmental burdens of pollution-driven employment in the G7 countries. These results are aligned with those conducted by

Kashem and Rahman (2020), Hacıimamoğlu (2023), and Tanveer et al. (2022), who have also validated the EPC hypothesis across diverse nations.

Additionally, the results highlight that economic growth, as represented by per capita GDP, exerts positive effects on CO_2e across both short- and long-term. A 1% increase in economic growth correlates with a 0.336% increase in CO_2e in the short run and a slightly higher increase of 0.389% in the long run. These results underscore the well-established trade-off between industrial-driven economic growth and environmental quality. They emphasize that despite the commitment of G7 nations to achieve the net-zero emissions target by 2050, there are significant policy implications regarding their growth-emissions trajectories. Our results are consistent with prior studies including those conducted by Aydin et al. (2023), Saqib et al. (2022), Pirgaip et al. (2023), and Wang et al. (2024), Banday and Aneja (2019), Jebabli et al. (2023), and Destek et al. (2020).

Regarding renewable energy and technological innovation, the results indicate their absence of short-term effects on CO_2e, yet significant long-term impacts at a 1% level are observed. Specifically, a 1% increase in renewable energy leads to a 0.234% decrease in CO_2e, while a similar increase in technological innovation results in a 0.019% decrease in CO_2e. It is notable that prior literature has acknowledged the intertwined relationship between renewable energy and CO2e, shaping long run dynamics. The lack of short run effects observed may present challenges from a pragmatic standpoint. Both renewable energy and technological innovation are observed as slow-shifting factors impacting emission reduction in the long run. For instance, Wang (2022), Uddin et al. (2023), Shah et al. (2023), and Udeagha and Ngepah (2023) have also observed the long run dynamics of renewable energy and technological innovation influencing environmental degradation. However, studies conducted by Koengkan and Fuinhas (2020), Shaari et al. (2020), Liu (2021), Leitão (2021), Turedi and Turedi (2021), Sahoo and Sahoo (2022), Nguyen and Le (2022), and Massagony and Budiono (2023), observed both short- and long-run negative effects of the renewable energy and on CO_2e.

Conversely, our results reveal that economic policy uncertainty has a positive impact on CO_2e in the short- and long-run, with increases of 0.015% and 0.035% in CO_2e, respectively. The uncertainties in economic policies, stemming from initiatives promoting cost-cutting campaigns and disagreements on national environmental expenditures, contribute to a negative impact on contemporary economic activities. This, in turn, leads to a reduction in short- and long-term investments and an increase in monetary overhang across the nation (Gulen and Ion 2016; Jumah et al. 2023). Such trends are further reinforced by evident environmental consequences. Additionally, recent political tensions between nations have caused higher economic volatility and policy uncertainty (Azimi and Rahman, 2023), due to which national expenditures on innovative projects plunged and, as a result, CO_2e escalated in G7 countries. Prior studies, specifically those conducted by Sadiq et al. (2023), Su et al. (2022), Farooq et al. (2023), Khan et al. (2022), Dogan and Ozturk (2017), Jiang et al. (2019), Wang et al. (2020), and Pirgaip and Dinçergök (2020), noticed similar impacts of lnE on environmental degradation across diverse nations.

Likewise, the results reveal that population has a positive effect on CO_2e in the long run only. A 1% increase in population leads to a 0.510% increase in CO_2e, suggesting the long run negative environmental consequences of overpopulation. In practice, it is difficult to strike a balance between environmental sustainability and population, but policymakers must ensure they implement effective population control measures and promote environmentally friendly practices to lessen the negative effects of population on environmental quality. However, prior studies have presented mixed results on the impact of population on the subject; two strands are clear in the literature. First, low-, lower-middle-, and middle-income economies experience a positive association between population growth and pollutant predictors. It is due to low personal disposable and governments economic capacities to adopt consuming environmentally friendly materials, either at household or production levels (Ahmed et al. 2023; Duan et al. 2022; I. Khan et al. 2021b; Kharitonova et al. 2021; Raupach et al. 2007; Sun et al. 2023; Thio et al. 2022). Second, as stated by Dietz and Rosa (1997), high-income economies still suffer from rapid urbanization due to economic and employment shifts, and as a result, growth in population and population massification in urban areas plunge environmental quality. Our findings align with those of Wang et al. (2015), Rahman et al. (2024Khan et al. 2021b); Rahman (2017); Rahman and Vu (2021); Begum et al. (2015); Dong et al. (2018).

Furthermore, employing two innovative methodologies, say wavelet coherence and wavelet causality analysis (Figs. 4 and 5), this study discerns the sensitivity of the co-movement between CO_2e and the unemployment rate, that is, the confirmed EPC hypothesis across G7 nations. The comprehensive results of wavelet coherence analysis strongly affirm the presence of the EPC hypothesis within these nations, indicating an out-of-phase nexus between CO_2e and unemployment rate. However, intriguing variations in the sensitivity of CO_2e to fluctuations in the unemployment rate are observed. While nations like USA demonstrate a highly out-of-phase co-movement between CO_2e and unemployment rate, others such as Canada, France, UK, Japan, Italy, and Germany exhibit varying degrees of sensitivity in their CO_2e response, spanning from high to moderate scales across the spectrum 4 to 32 scales. These results strongly corroborate the work of Hacıimamoğlu (2023), who validated the EPC within N-11 member countries, Similarly, with Kashem and Rahman (2020), who identified an inverse nexus between CO_2e and unemployment within OECD countries, Shastri et al. (2023) in India, Tariq et al. (2022) in South Asian economies, and Anser et al. (2021) in Brazil, Russia, India, China, South Africa, and Turkey (BRICST) countries from 1992 to 2016. More specifically, our findings align with those of Bhowmik et al. (2022), who observed the EPC in the USA.

Finally, the wavelet causality analysis (Fig. 5) reveals varied temporal dynamics between CO_2e and unemployment rate. In Canada, a multi-dimensional causality pattern emerges, with short-term, medium-term, and long-term causal links observed, highlighting the complexity of their relationship over time. France exhibits a medium-term causal connection, suggesting a more focused impact within a specific timeframe. Conversely, Germany, Italy, and Japan do not exhibit significant time-based causality between CO_2e and unemployment rate, indicating a lack of clear temporal association in these countries. In contrast, the UK displays a short-term causal link alongside a distinct long-term pattern, indicating a nuanced relationship between these variables over different periods. The USA demonstrates a short-term causal link between CO2e and unemployment rate, implying a more immediate impact on emission patterns. While our findings are in line with the conclusions drawn by Çakmak et al. (2023), Shastri et al. (2023), and Meyer (2016), they underscore the diverse temporal dynamics of the causal relationship between CO_2e and unemployment rate across G7 nations, emphasizing the need for nuanced policy responses tailored to specific temporal contexts. Additionally, the EPC should still be approached as a case-based analysis to boost environmental policies at national level. The generalizability of the EPC remains a topic for further exploration in contemporary literature, underscoring the need for comprehensive country-based analysis in this emerging field.

7 Conclusion and policy implications

Addressing the critical issue of environmental degradation requires innovative policy solutions that can effectively balance contemporary environmental quality with socio-economic values. While prior literature has made valuable contributions, there remains a notable scarcity of policy-conducive studies concerning the impact of unemployment rate on CO_2e, a cornerstone of the emerging EPC hypothesis across G7 nations. In this vein, our study aims to examine the EPC hypothesis in the presence of key indicators such as renewable energy, technological innovation, economic growth, and population dynamics within G7 nations from 1990 to 2022. Employing a comprehensive three-step methodology, we use the CS-ARDL model, verified by CS-DL, CCEMG, and AGM techniques, to discern both short- and long-term impacts of the unemployment rate alongside other explanatory variables on CO_2e. Additionally, by leveraging wavelet coherence and wavelet causality techniques, we enhance the precision of the findings on the nuanced relationship between CO_2e, the unemployment rate, and the explanatory variables.

Prominent insights derived from the CS-ARDL model robustly affirm the existence of the EPC hypothesis in G7 nations, delineating both short- and long-term negative effects of the unemployment rate on CO_2e. While the pivotal role of renewable energy and technological innovation in emissions mitigating were underscored, the findings spotlight the detrimental impacts of economic growth, economic policy uncertainty, and population dynamics on CO_2e. Additionally, the outcomes of the wavelet coherence analysis strongly endorse the presence of the EPC hypothesis, unveiling intricate temporal dynamics in the out-of-phase co-movement between CO_2e and the unemployment rate across G7 nations. Conversely, the results of wavelet causality analysis underscore unidirectional causality emanating from unemployment rate to CO_2e, revealing multi-dimensional causality patterns across short-, medium-, and long-term periods within the examined countries. Our findings thus delineate specific areas of policy implications, as outlined below:

7.1 Policy implications

The existence of the EPC hypothesis underscores the critical need for a holistic strategy ensuring enduring success. The findings pinpoint complex policy implications, devoid of singular solution, as delineated below:

- **Technological innovation externalities**: Balancing the reduction of CO_2e and potential rise in unemployment presents a formidable concern, demanding targeted policy interventions that address both objectives concurrently. Policymakers must navigate this dilemma adeptly, devising innovative strategies to mitigate emissions while bolstering employability. A promising avenue lies in macroeconomic policies geared towards bolstering investments in technological innovations. By fostering production and exchange of low-carbon-generating technologies, G7 nations can achieve dual benefits of emissions reduction and job creation. However, realizing these initiatives requires significant reallocation of financial resources.

- **Renewable energy sources**: Addressing emissions reduction and unemployment necessitates transition from conventional energy to cleaner alternatives. This shift entails substantial investments in solar, wind, geothermal, and hydropower technologies, catalyzing job creation across various sectors including manufacturing, installation, and maintenance, while reducing the reliance on fossil fuels. Additionally, the development of smart power grids capable of optimizing energy distribution, promoting efficiency, and incorporating renewable sources, demands a skilled workforce proficient in technical and semi-technical domains, thereby amplifying employment prospects. However, the realization of this shift hinges on the alignment of market dynamics with the transition agenda. Therefore, policymakers within G7 nations must prioritize market incentive mechanisms such as higher capital gains, tax-free investments, and subsidies targeting environmental technologies to surmount this challenge.
- **Economic policy uncertainty**: The results suggest that heightened economic policy uncertainty compounds environmental degradation by dissuading investments in sustainable technologies. It is linked to reluctance among market participants to allocate resources towards innovative technologies aimed at preserving environmental integrity. Elevated levels of economic uncertainty engender monetary overhangs both at institutional and individual levels, thereby impeding investment and consumption patterns. To mitigate the adverse effects of economic policy uncertainty, policymakers in G7 must prioritize enhancing institutional quality through intergovernmental and international cooperations, thereby mitigating the externalities associated with such uncertainties.
- **Population dynamics**: The inverse association between population dynamics and CO_2e pinpoints the significance of promoting sustainable population practices, alongside comprehensive knowledge dissemination efforts, to effectively reduce emissions. Policymakers are urged to prioritize initiatives at augmenting environmental literacy through extensive social campaigns, while concurrently ensuring that informed urbanization strategies are implemented.
- **Economic growth patterns**: Our results indicate a direct relationship between economic growth and CO2e, requiring a fundamental reevaluation of production and consumption paradigms. Policymakers in G7 nations should focus on decoupling economic growth from emissions by implementing large-scale mechanisms focused on improving efficiency across diverse sectors such as industries, transportation, and buildings. This entails a concerted effort to achieve greater economic output with reduced energy input, thereby reducing the demand for energy-intensive growth. Additionally, the implementation of carbon pricing and market mechanisms can be imperative in this context. This includes the imposition of carbon taxes on fossil fuels or activities generating greenhouse gas emissions, rendering pollution costlier and incentivizing businesses and individuals to adopt environmentally friendly practices. Additionally, the establishment of an overall limit on emissions alongside the issuance of tradable permits to polluters creates a market wherein cleaner industries can profit by selling unused permits, encouraging innovation.

7.2 Limitations

To examine the validity of the EPC in G7 countries, our analysis confronted one major limitation: The unavailability of time-consecutive data for research and development (R&D) expenditures forced us to exclude it from our analysis. Monetary-evaluated data for R&D, could have given more precise results of the effects of technological innovation in the concept of the EPC. Upon the availability of the required data, future studies may overcome this empirical limitation while following a similar methodology that has been used in the present article.

Acknowledgements Not applicable.

Authors' contributions Mohammad Naim Azimi: Conception and design of the study, data curation, material preparation, and data analysis. Major-writing. Mohammad Mafizur Rahman: Conception, edited, and supervised the manuscript. Both authors read and approved the final manuscript.

Funding The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.
Open Access funding enabled and organized by CAUL and its Member Institutions

Declarations

Competing Interests The authors have no relevant financial or non-financial interests to disclose.

AI generative works The authors declare that they have used AI (ChatGPT) only for language editing and grammar correction purposes. AI has not been used for content generation. However, the authors take full responsibility of the contents reflected in the manuscript.

References

Abdouli, M., Omri, A.: Exploring the Nexus among inflows, F.D.I., Quality, E., Human Capital, and Economic Growth in the Mediterranean Region. J. Knowl. Econ. **12**(2), 788–810 (2021). https://doi.org/10.1007/s13132-020-00641-5

Adebayo, T.S.: Revisiting the EKC hypothesis in an emerging market: An application of ARDL-based bounds and wavelet coherence approaches. SN Appl. Sci. **2**(12) (2020). https://doi.org/10.1007/s42452-020-03705-y

Ahmed, M., Shuai, C., Ahmed, M.: Analysis of energy consumption and greenhouse gas emissions trend in China, India, the USA, and Russia. Int. J. Environ. Sci. Technol. **20**(3), 2683–2698 (2023). https://doi.org/10.1007/s13762-022-04159-y

Akbar, M., Noor, F., Ahmad, I., Sattar, A.: Impact of energy consumption and CO2 emissions on food production in Pakistan: An econometric analysis. Pakistan J. Agricultural Sci. **55**(2), 455–461 (2018). https://doi.org/10.21162/PAKJAS/18.6703

Amin, A., Ameer, W., Yousaf, H., Akbar, M.: Financial Development, Institutional Quality, and the influence of various environmental factors on Carbon Dioxide emissions: Exploring the Nexus in China. Front. Environ. Sci. **9** (2022). https://doi.org/10.3389/fenvs.2021.838714

Anser, M.K., Apergis, N., Syed, Q.R., Alola, A.A.: Exploring a new perspective of sustainable development drive through environmental Phillips curve in the case of the BRICST countries. Environ. Sci. Pollut. Res. **28**(35), 48112–48122 (2021). https://doi.org/10.1007/s11356-021-14056-5

Atay, P.M., Ergun, S.: The relationship between economic growth, CO2 emissions and health expenditures in Turkey under structural breaks. Bus. Econ. Res. J. **9**(3), 481–497 (2018)

Awan, A.M., Azam, M.: Evaluating the impact of GDP per capita on environmental degradation for G-20 economies: Does N-shaped environmental Kuznets curve exist? Environ. Dev. Sustain. **24**(9), 11103–11126 (2022). https://doi.org/10.1007/s10668-021-01899-8

Aydin, M., Koc, P., Sahpaz, K.I.: Investigating the EKC hypothesis with nanotechnology, renewable energy consumption, economic growth and ecological footprint in G7 countries: Panel data analyses with structural breaks. Energy Sources Part. B: Econ. Plann. Policy. **18**(1) (2023). https://doi.org/10.1080/15567249.2022.2163724

Azimi, M., Naim, Rahman, M., Mafizur, Nghiem, S.: Linking governance with environmental quality: A global perspective. Sci. Rep. **13**(15086) (2023). https://doi.org/10.1038/s41598-023-42221-y

Baker, S.R., Bloom, N., Davis, S.J.: Measuring economic policy uncertainty. Quart. J. Econ. **131**(4), 1593–1636 (2016). https://doi.org/10.1093/qje/qjw024

Banday, U.J., Aneja, R.: Energy consumption, economic growth and CO2 emissions: Evidence from G7 countries. World J. Sci. Technol. Sustainable Dev. **16**(1), 22–39 (2019). https://doi.org/10.1108/WJSTSD-01-2018-0007

Barili, F., Parolari, A., Kappetein, P.A., Freemantle, N.: Statistical primer: Heterogeneity, random- or fixed-effects model analyses? Interact. Cardiovasc. Thorac. Surg. **27**(3), 317–321 (2018). https://doi.org/10.1093/icvts/ivy163

Begum, R.A., Sohag, K., Abdullah, S.M.S., Jaafar, M.: CO2 emissions, energy consumption, economic and population growth in Malaysia. Renew. Sustain. Energy Rev. **41**, 594–601 (2015). https://doi.org/10.1016/j.rser.2014.07.205

Bernaciak, A.: The environmental Kuznetz curve in transition countries on the example of Poland. Economic Environ. Stud. **13**(3), 279–293 (2013). http://hdl.handle.net/10419/93197

Bhowmik, R., Syed, Q.R., Apergis, N., Alola, A.A., Gai, Z.: Applying a dynamic ARDL approach to the Environmental Phillips Curve (EPC) hypothesis amid monetary, fiscal, and trade policy uncertainty in the USA. Environ. Sci. Pollut. Res. **29**(10), 14914–14928 (2022). https://doi.org/10.1007/s11356-021-16716-y

Bhuiyan, M.A., Kahouli, B., Hamaguchi, Y., Zhang, Q.: The role of green energy deployment and economic growth in carbon dioxide emissions: Evidence from the Chinese economy. Environ. Sci. Pollut. Res. **30**(5), 13162–13173 (2023). https://doi.org/10.1007/s11356-022-23026-4

Cetin, M.A., Bakirtas, I.: The long-run environmental impacts of economic growth, financial development, and energy consumption: Evidence from emerging markets. Energy Environ. **31**(4), 634–655 (2020). https://doi.org/10.1177/0958305X19882373

Chaurasia, A.: Population effects of increase in world energy use and CO2 emissions: 1990–2019. J. Popul. Sustain. **5**(1) (2020). https://doi.org/10.3197/jps.2020.5.1.87

Chen, P., Semmler, W.: Short and long effects of Productivity on unemployment. Open. Econ. Rev. **29**(4), 853–878 (2018). https://doi.org/10.1007/s11079-018-9486-z

Chen, F., Jiang, G., Kitila, G.M.: Trade openness and CO2 emissions: The heterogeneous and mediating effects for the belt and road countries. Sustain. (Switzerland). **13**(4), 1–16 (2021). https://doi.org/10.3390/su13041958

Chudik, A., Pesaran, M.H.: Common correlated effects estimation of heterogeneous dynamic panel data models with weakly exogenous regressors. J. Econ. **188**(2), 393–420 (2015). https://doi.org/10.1016/j.jeconom.2015.03.007

Chudik, A., Mohaddes, K., Pesaran, M.H., Raissi, M.: Long-run effects in large heterogeneous panel data models with cross-sectionally correlated errors. Adv. Econometrics. **36**, 85–135 (2016). https://doi.org/10.1108/S0731-905320160000036013

Cui, Y., Wang, G., Irfan, M., Wu, D., Cao, J.: The effect of green finance and unemployment rate on carbon emissions in China. Front. Environ. Sci. **10** (2022). https://doi.org/10.3389/fenvs.2022.887341

Destek, M.A., Shahbaz, M., Okumus, I., Hammoudeh, S., Sinha, A.: The relationship between economic growth and carbon emissions in G-7 countries: Evidence from time-varying parameters with a long history. Environ. Sci. Pollut. Res. **27**(23), 29100–29117 (2020). https://doi.org/10.1007/s11356-020-09189-y

Dietz, T., Rosa, E.A.: Effects of population and affluence on CO2 emissions. Proc. Natl. Acad. Sci. U.S.A. **94**(1), 175–179 (1997). https://doi.org/10.1073/pnas.94.1.175

Djedaiet, A.: Does environmental quality react asymmetrically to unemployment and inflation rates? African OPEC countries' perspective. Environ. Sci. Pollut. Res. **30**(46), 102418–102427 (2023). https://doi.org/10.1007/s11356-023-29621-3

Dogan, E., Ozturk, I.: The influence of renewable and non-renewable energy consumption and real income on CO2 emissions in the USA: Evidence from structural break tests. Environ. Sci. Pollut. Res. **24**(11), 10846–10854 (2017). https://doi.org/10.1007/s11356-017-8786-y

Dogan, E., Majeed, M.T., Luni, T.: Revisiting the nexus of ecological footprint, unemployment, and renewable and non-renewable energy for south Asian economies: Evidence from novel research methods. Renew. Energy. **194**, 1060–1070 (2022). https://doi.org/10.1016/j.renene.2022.05.165

Dong, K., Hochman, G., Zhang, Y., Sun, R., Li, H., Liao, H.: CO2 emissions, economic and population growth, and renewable energy: Empirical evidence across regions. Energy Econ. **75**, 180–192 (2018). https://doi.org/10.1016/j.eneco.2018.08.017

Dong, K., Dong, X., Jiang, Q.: How renewable energy consumption lower global CO2 emissions? Evidence from countries with different income levels. World Econ. **43**(6), 1665–1698 (2020). https://doi.org/10.1111/twec.12898

Dou, Y., Zhao, J., Malik, M.N., Dong, K.: Assessing the impact of trade openness on CO2 emissions: Evidence from China-Japan-ROK FTA countries. J. Environ. Manage. **296**, 113241 (2021). https://doi.org/10.1016/j.jenvman.2021.113241

Driscoll, J.C., Kraay, A.C.: Consistent covariance matrix estimation with spatially dependent panel data. Rev. Econ. Stat. **80**(4), 549–559 (1998). https://doi.org/10.1162/003465398557825

Duan, C., Zhu, W., Wang, S., Chen, B.: Drivers of global carbon emissions 1990–2014. J. Clean. Prod. **371** (2022). https://doi.org/10.1016/j.jclepro.2022.133371

Eberhardt, M., Bond, S.: Cross-section dependence in nonstationary panel models: a novel estimator. *Social Research*, *17870*. (2009). http://mpra.ub.uni-muenchen.de/17870/2/2009-10-06_MC_simulations_paper_b.pdf

Erickson, L.E.: Reducing greenhouse gas emissions and improving air quality: Two global challenges. In *Environmental Progress and Sustainable Energy* (Vol. 36, Issue 4, pp. 982–988). (2017). https://doi.org/10.1002/ep.12665

Esmaeili, P., Rafei, M., Balsalobre-Lorente, D., Adedoyin, F.F.: The role of economic policy uncertainty and social welfare in the view of ecological footprint: Evidence from the traditional and novel platform in panel ARDL approaches. Environ. Sci. Pollut. Res. **30**(5), 13048–13066 (2023b). https://doi.org/10.1007/s11356-022-23044-2

Farooq, U., Gillani, S., Subhani, B.H., Shafiq, M.N.: Economic policy uncertainty and environmental degradation: The moderating role of political stability. Environ. Sci. Pollut. Res. **30**(7), 18785–18797 (2023). https://doi.org/10.1007/s11356-022-23479-7

Ganda, F.: The Environmental Impacts of Human Capital in the BRICS economies. J. Knowl. Econ. **13**(1), 611–634 (2022). https://doi.org/10.1007/s13132-021-00737-6

Grodzicki, T., Jankiewicz, M.: The impact of renewable energy and urbanization on CO2 emissions in Europe – Spatio-temporal approach. Environ. Dev. **44** (2022). https://doi.org/10.1016/j.envdev.2022.100755

Gulen, H., Ion, M.: Policy uncertainty and corporate investment. Rev. Financial Stud. **29**(3), 523–564 (2016). https://doi.org/10.1093/rfs/hhv050

Habiba, U., Xinbang, C.: The impact of financial development on CO2 emissions: New evidence from developed and emerging countries. Environ. Sci. Pollut. Res. **29**(21), 31453–31466 (2022). https://doi.org/10.1007/s11356-022-18533-3

Hacıimamoğlu, T.: A New Approach to Sustainable Development: Analysis of the Environmental Phillips Curve Hypothesis. Sosyoekonomi. **31**(56), 11–25 (2023). https://doi.org/10.17233/sosyoekonomi.2023.02.01

Hao, Y.: Effect of economic indicators, renewable energy consumption and Human Development on Climate Change: An empirical analysis based on Panel Data of selected countries. Front. Energy Res. **10** (2022). https://doi.org/10.3389/fenrg.2022.841497

Hoechle, D.: Robust standard errors for panel regressions with cross-sectional dependence. Stata J. **7**(3), 281–312 (2007). https://doi.org/10.1177/1536867x0700700301

Ioan, D.: Employment – cause and Effect of the Economic Growth. Procedia Econ. Finance. **8**, 268–274 (2014). https://doi.org/10.1016/s2212-5671(14)00090-2

Jahanger, A.: Impact of globalization on CO2 emissions based on EKC hypothesis in developing world: The moderating role of human capital. Environ. Sci. Pollut. Res. **29**(14), 20731–20751 (2022). https://doi.org/10.1007/s11356-021-17062-9

Jebabli, I., Lahiani, A., Mefteh-Wali, S.: Quantile connectedness between CO2 emissions and economic growth in G7 countries. Resour. Policy. **81** (2023). https://doi.org/10.1016/j.resourpol.2023.103348

Jiang, Y., Zhou, Z., Liu, C.: Does economic policy uncertainty matter for carbon emission? Evidence from US sector level data. Environ. Sci. Pollut. Res. **26**(24), 24380–24394 (2019). https://doi.org/10.1007/s11356-019-05627-8

Jumah, Z., Younas, Z.I., Al-Faryan, M.A.S.: Economic policy uncertainty, corporate diversification, and corporate investment. Appl. Econ. Lett. **30**(19), 2732–2742 (2023). https://doi.org/10.1080/13504851.2022.2106028

Kao, C.: Spurious regression and residual-based tests for cointegration in panel data. J. Econ. **90**(1), 1–44 (1999). https://doi.org/10.1016/S0304-4076(98)00023-2

Karedla, Y., Mishra, R., Patel, N.: The impact of economic growth, trade openness and manufacturing on CO2 emissions in India: An autoregressive distributive lag (ARDL) bounds test approach. J. Econ. Finance Administrative Sci. **26**(52), 376–389 (2021). https://doi.org/10.1108/JEFAS-05-2021-0057

Kashem, M.A., Rahman, M.M.: Environmental Phillips curve: OECD and Asian NICs perspective. Environ. Sci. Pollut. Res. **27**(25), 31153–31170 (2020). https://doi.org/10.1007/s11356-020-08620-8

Khan, M.I., Kamran Khan, M., Dagar, V., Oryani, B., Akbar, S.S., Salem, S., Dildar, S.M.: Testing Environmental Kuznets Curve in the USA: What Role Institutional Quality, Globalization, Energy Consumption, Financial Development, and Remittances can Play? New Evidence From Dynamic ARDL Simulations Approach. *Frontiers in Environmental Science*, *9*. (2021b). https://doi.org/10.3389/fenvs.2021.789715

Khan, Y., Hassan, T., Kirikkaleli, D., Xiuqin, Z., Shukai, C.: The impact of economic policy uncertainty on carbon emissions: Evaluating the role of foreign capital investment and renewable energy in east Asian economies. Environ. Sci. Pollut. Res. **29**(13), 18527–18545 (2022). https://doi.org/10.1007/s11356-021-17000-9

Kharitonova, N.A., Kharitonova, E.N., Pulyaeva, V.N.: Carbon footprint of Russia: Realities and prospects of economic development. Russian J. Industrial Econ. **14**(1), 50–62 (2021). https://doi.org/10.17073/2072-1633-2021-1-50-62

Khezri, M., Heshmati, A., Khodaei, M.: Environmental implications of economic complexity and its role in determining how renewable energies affect CO2 emissions. Appl. Energy. **306** (2022). https://doi.org/10.1016/j.apenergy.2021.117948

Knight, K.W.: Temporal variation in the relationship between environmental demands and well-being: A panel analysis of developed and less-developed countries. Popul. Environ. **36**(1), 32–47 (2014). https://doi.org/10.1007/s11111-013-0200-1

Koc, S., Bulus, G.C.: Testing validity of the EKC hypothesis in South Korea: Role of renewable energy and trade openness. Environ. Sci. Pollut. Res. **27**(23), 29043–29054 (2020). https://doi.org/10.1007/s11356-020-09172-7

Koengkan, M., Fuinhas, J.A.: Exploring the effect of the renewable energy transition on CO2 emissions of Latin American & Caribbean countries. Int. J. Sustain. Energ. **39**(6), 515–538 (2020). https://doi.org/10.1080/14786451.2020.1731511

Koengkan, M., Fuinhas, J.A., Santiago, R.: Asymmetric impacts of globalisation on CO2 emissions of countries in Latin America and the Caribbean. Environ. Syst. Decisions. **40**(1), 135–147 (2020). https://doi.org/10.1007/s10669-019-09752-0

Kwakwa, P.A.: Climate change mitigation role of renewable energy consumption: Does institutional quality matter in the case of reducing Africa's carbon dioxide emissions? J. Environ. Manage. **342** (2023). https://doi.org/10.1016/j.jenvman.2023.118234

Lawal, I.M.: Impact of population growth on Carbon Dioxide (CO2) emission: Empirical evidence from Nigeria. Jurnal Perspektif Pembiayaan Dan. Pembangunan Daerah. **6**(6), 701–708 (2019). https://doi.org/10.22437/ppd.v6i6.6730

Le Quéré, C., Jackson, R.B., Jones, M.W., Smith, A.J.P., Abernethy, S., Andrew, R.M., De-Gol, A.J., Willis, D.R., Shan, Y., Canadell, J.G., Friedlingstein, P., Creutzig, F., Peters, G.P.: Temporary reduction in daily global CO2 emissions during the COVID-19 forced confinement. Nat. Clim. Change. **10**(7), 647–653 (2020). https://doi.org/10.1038/s41558-020-0797-x

Leitão, N.C.: The effects of corruption, renewable energy, trade and CO2 emissions. Economies. **9**(2) (2021). https://doi.org/10.3390/economies9020062

Li, P., Ouyang, Y., Zhang, L.: The nonlinear impact of renewable energy on CO2 emissions: Empirical evidence across regions in China. Appl. Econ. Lett. **27**(14), 1150–1155 (2020). https://doi.org/10.1080/13504851.2019.1673878

Lin, B., Omoju, O.E., Okonkwo, J.U.: Impact of industrialisation on CO2 emissions in Nigeria. In *Renewable and Sustainable Energy Reviews*. (2015). https://doi.org/10.1016/j.rser.2015.07.164

Liu, X.: The impact of renewable energy, trade, economic growth on CO2 emissions in China. Int. J. Environ. Stud. **78**(4), 588–607 (2021). https://doi.org/10.1080/00207233.2020.1834686

Liu, X., Bae, J.: Urbanization and industrialization impact of CO2 emissions in China. J. Clean. Prod. (2018). https://doi.org/10.1016/j.jclepro.2017.10.156

Liu, Y.Q., Feng, C.: The effects of nurturing pressure and unemployment on carbon emissions: Cross-country evidence. Environ. Sci. Pollut. Res. **29**(34), 52013–52032 (2022). https://doi.org/10.1007/s11356-022-19515-1

Liu, X., Adebayo, T.S., Ramzan, M., Ullah, S., Abbas, S., Olanrewaju, V.O.: Do coal efficiency, climate policy uncertainty and green energy consumption promote environmental sustainability in the United States? An application of novel wavelet tools. J. Clean. Prod. **417** (2023). https://doi.org/10.1016/j.jclepro.2023.137851

Maji, I.K., Saari, M.Y., Habibullah, M.S., Mohd Saudi, N.S.: Clean energy, institutional quality and environmental sustainability in sub-saharan Africa. Clean. Mater. **6** (2022). https://doi.org/10.1016/j.clema.2022.100135

Marques, A.C., Fuinhas, J.A., Leal, P.A.: The impact of economic growth on CO2 emissions in Australia: The environmental Kuznets curve and the decoupling index. Environ. Sci. Pollut. Res. **25**, 27283–27296 (2018). https://doi.org/10.1007/s11356-018-2768-6

Massagony, A., Budiono: Is the environmental Kuznets curve (EKC) hypothesis valid on CO2 emissions in Indonesia? Int. J. Environ. Stud. **80**(1), 20–31 (2023). https://doi.org/10.1080/00207233.2022.2029097

Mehmood, U., Tariq, S.: Globalization and CO2 emissions nexus: Evidence from the EKC hypothesis in south Asian countries. Environ. Sci. Pollut. Res. **27**, 37044–37056 (2020). https://doi.org/10.1007/s11356-020-09774-1

Mehmood, U., Tariq, S., Haq, Z.: Effects of population structure on CO2 emissions in south Asian countries: Evidence from panel estimation. Environ. Sci. Pollut. Res. **28**(47), 66858–66863 (2021). https://doi.org/10.1007/s11356-021-14976-2

Meyer, A.: Is unemployment good for the environment? Resour. Energy Econ. **45**, 18–30 (2016). https://doi.org/10.1016/j.reseneeco.2016.04.001

Mishra, S., Sinha, A., Sharif, A., Suki, N.M.: Dynamic linkages between tourism, transportation, growth and carbon emission in the USA: Evidence from partial and multiple wavelet coherence. Curr. Issues Tourism. **23**(21), 2733–2755 (2020). https://doi.org/10.1080/13683500.2019.1667965

Mohammad Mafizur Rahman, Muhammad Iftikhar ul Husnain, M. N. A: An environmental perspective of energy consumption, overpopulation, and human capital barriers in South Asia. *Scientific Reports*, *14*(1), 4420. (2024)

Namahoro, J.P., Wu, Q., Xiao, H., Zhou, N.: The impact of renewable energy, economic and population growth on co2 emissions in the east African region: Evidence from common correlated effect means group and asymmetric analysis. Energies. **14**(2) (2021). https://doi.org/10.3390/en14020312

Ng, C.F., Yii, K.J., Lau, L.S., Go, Y.H.: Unemployment rate, clean energy, and ecological footprint in OECD countries. Environ. Sci. Pollut. Res. **30**(15), 42863–42872 (2023). https://doi.org/10.1007/s11356-021-17966-6

Nguyen, V.C.T., Le, H.Q.: Renewable energy consumption, nonrenewable energy consumption, CO2 emissions and economic growth in Vietnam. Manage. Environ. Quality: Int. J. **33**(2), 419–434 (2022). https://doi.org/10.1108/MEQ-08-2021-0199

Olayeni, O.R.: Causality in continuous Wavelet Transform without Spectral Matrix Factorization: Theory and application. Comput. Econ. (2016). https://doi.org/10.1007/s10614-015-9489-4

Pao, H.T., Tsai, C.M.: CO2 emissions, energy consumption and economic growth in BRIC countries. Energy Policy. **38**(12), 7850–7860 (2010). https://doi.org/10.1016/j.enpol.2010.08.045

Papadamou, S., Fassas, A., Kenourgios, D., Dimitriou, D.: Flight-to-quality between global stock and bond markets in the COVID era. Finance Res. Lett. **38** (2021). https://doi.org/10.1016/j.frl.2020.101852

Pata, U.K., Aydin, M.: Persistence of CO2 emissions in G7 countries: A different outlook from wavelet-based linear and nonlinear unit root tests. Environ. Sci. Pollut. Res. **30**(6), 15267–15281 (2023). https://doi.org/10.1007/s11356-022-23284-2

Pata, U.K., Kartal, M.T.: Impact of nuclear and renewable energy sources on environment quality: Testing the EKC and LCC hypotheses for South Korea. Nuclear Eng. Technol. **55**(2), 587–594 (2023). https://doi.org/10.1016/j.net.2022.10.027

Patel, H., Shakhreliya, S., Maurya, R., Pandey, V.C., Gohil, N., Bhattacharjee, G., Alzahrani, K.J., Singh, V.: CRISPR-assisted strategies for futuristic phytoremediation. In *Assisted Phytoremediation* (pp. 203–220). (2021). https://doi.org/10.1016/B978-0-12-822893-7.00006-9

Pedroni, P.: Critical values for cointegration tests in heterogeneous panels with multiple regressors. Oxf. Bull. Econ. Stat. **61**(SUPPL), 653–670 (1999). https://doi.org/10.1111/1468-0084.61.s1.14

Pesaran, M.H.: General diagnostic tests for cross section dependence in panels. *University of Cambridge, Faculty of Economics, Cambridge Working Papers in Economics No. 0435*, 1–37. (2004)

Pesaran, M.H.: Estimation and inference in large heterogeneous panels with a multifactor error structure. Econometrica. **74**(4), 967–1012 (2006). https://doi.org/10.1111/j.1468-0262.2006.00692.x

Pesaran, M.H.: A simple panel unit root test in the presence of cross-section dependence. J. Appl. Econom. **22**(2), 265–312 (2007). https://doi.org/10.1002/jae.951

Pesaran, M.H., Shin, Y., Smith, R.J.: Bounds testing approaches to the analysis of level relationships. J. Appl. Econom. **16**, 289–326 (2001). https://doi.org/10.1002/jae.616

Petrović, P., Lobanov, M.M.: Impact of financial development on CO2 emissions: Improved empirical results. Environ. Dev. Sustain. **24**(5), 6655–6675 (2022). https://doi.org/10.1007/s10668-021-01721-5
Pirgaip, B., Dinçergök, B.: Economic policy uncertainty, energy consumption and carbon emissions in G7 countries: Evidence from a panel Granger causality analysis. Environ. Sci. Pollut. Res. **27**(24), 30050–30066 (2020). https://doi.org/10.1007/s11356-020-08642-2
Pirgaip, B., Bayrakdar, S., Kaya, M.V.: The role of government spending within the environmental Kuznets curve framework: Evidence from G7 countries. Environ. Sci. Pollut. Res. **30**(34), 81513–81530 (2023). https://doi.org/10.1007/s11356-023-25180-9
Qin, L., Kirikkaleli, D., Hou, Y., Miao, X., Tufail, M.: Carbon neutrality target for G7 economies: Examining the role of environmental policy, green innovation and composite risk index. J. Environ. Manage. **295**, 113119 (2021). https://doi.org/10.1016/j.jenvman.2021.113119
Rafindadi, A.A.: Revisiting the concept of environmental Kuznets curve in period of energy disaster and deteriorating income: Empirical evidence from Japan. Energy Policy. **94**, 274–284 (2016). https://doi.org/10.1016/j.enpol.2016.03.040
Raghutla, C., Chittedi, K.R.: The effect of technological innovation and clean energy consumption on carbon neutrality in top clean energy-consuming countries: A panel estimation. Energy Strategy Reviews. **47** (2023). https://doi.org/10.1016/j.esr.2023.101091
Rahman, M.M.: Do population density, economic growth, energy use and exports adversely affect environmental quality in Asian populous countries? Renew. Sustain. Energy Rev. **77**, 506–514 (2017). https://doi.org/10.1016/j.rser.2017.04.041
Rahman, M.M., Vu, X.B.: Are energy consumption, population density and exports causing environmental damage in China? Autoregressive distributed lag and vector error correction model approaches. Sustain. (Switzerland). **13**(7) (2021). https://doi.org/10.3390/su13073749
Raihan, A., Tuspekova, A.: The nexus between economic growth, renewable energy use, agricultural land expansion, and carbon emissions: New insights from Peru. Energy Nexus. **6** (2022). https://doi.org/10.1016/j.nexus.2022.100067
Raupach, M.R., Marland, G., Ciais, P., Le Quéré, C., Canadell, J.G., Klepper, G., Field, C.B.: Global and regional drivers of accelerating CO2 emissions. Proc. Natl. Acad. Sci. U.S.A. **104**(24), 10288–10293 (2007). https://doi.org/10.1073/pnas.0700609104
Riddell, W.C.: The empirical foundations of the Phillips curve: Evidence from Canadian wage Contract Data. Econometrica. **47**(1), 1 (1979). https://doi.org/10.2307/1912343
Rua, A.: Worldwide synchronization since the nineteenth century: A wavelet-based view. Appl. Econ. Lett. **20**(8), 773–776 (2013). https://doi.org/10.1080/13504851.2012.744129
Rudd, J.B.: Why do we think that inflation expectations matter for inflation? (and should we?). Revista De Economia Institucional. **24**(47), 213–243 (2022). https://doi.org/10.18601/01245996.v24n47.10
Saboori, B., Sulaiman, J.: CO2 emissions, energy consumption and economic growth in association of south-east Asian nations (ASEAN) countries: Acointegration approach. Energy. **55**, 813–822 (2013). https://doi.org/10.1016/j.energy.2013.04.038
Sadiq, M., Hassan, S.T., Khan, I., Rahman, M.M.: Policy uncertainty, renewable energy, corruption and CO2 emissions nexus in BRICS-1 countries: A panel CS-ARDL approach. Environ. Dev. Sustain. (2023). https://doi.org/10.1007/s10668-023-03546-w
Sahoo, M., Sahoo, J.: Effects of renewable and non-renewable energy consumption on CO2 emissions in India: Empirical evidence from disaggregated data analysis. J. Public. Affairs. **22**(1) (2022). https://doi.org/10.1002/pa.2307
Saqib, N., Usman, M., Radulescu, M., Sinisi, C.I., Secara, C.G., Tolea, C.: Revisiting EKC hypothesis in context of renewable energy, human development and moderating role of technological innovations in E-7 countries? Front. Environ. Sci. **10** (2022). https://doi.org/10.3389/fenvs.2022.1077658
Shaari, M.S., Abidin, N.Z., Karim, Z.A.: The impact of renewable energy consumption and economic growth on CO2 emissions: New evidence using panel ardl study of selected countries. Int. J. Energy Econ. Policy. **10**(6), 617–623 (2020). https://doi.org/10.32479/ijeep.9878
Shaari, M.S., Abidin, N.Z., Ridzuan, A.R., Meo, M.S.: The impacts of rural population growth, energy use and economic growth on co2 emissions. Int. J. Energy Econ. Policy. **11**(5), 553–561 (2021). https://doi.org/10.32479/ijeep.11566
Shah, W.U.H., Hao, G., Yan, H., Zhu, N., Yasmeen, R., Dincă, G.: Role of renewable, non-renewable energy consumption and carbon emission in energy efficiency and productivity change: Evidence from G20 economies. Geosci. Front. (2023). https://doi.org/10.1016/j.gsf.2023.101631
Shang, L., Xu, P.: Can Carbon Emission Regulation achieve a dual target of low Carbon and Employment? An empirical analysis based on China's Provincial Panel Data. Front. Energy Res. **10** (2022). https://doi.org/10.3389/fenrg.2022.926443

Shastri, S., Mohapatra, G., Giri, A.K.: The Environmental Philips curve from a gender perspective: Empirical evidence from India. Environ. Sci. Pollut. Res. **30**(7), 17487–17496 (2023). https://doi.org/10.1007/s11356-022-23336-7

Shoaib, H.M., Rafique, M.Z., Nadeem, A.M., Huang, S.: Impact of financial development on CO2 emissions: A comparative analysis of developing countries (D8) and developed countries (G8). Environ. Sci. Pollut. Res. **27**, 12461–12475 (2020). https://doi.org/10.1007/s11356-019-06680-z

Sirag, A., Matemilola, B.T., Law, S.H., Bany-Ariffin, A.N.: Does environmental Kuznets curve hypothesis exist? Evidence from dynamic panel threshold. J. Environ. Econ. Policy. **7**(2), 145–165 (2018). https://doi.org/10.1080/21606544.2017.1382395

Su, H., Geng, Y., Xia, X.Q., Wang, Q.J.: Economic policy uncertainty, Social Development, Political regimes and Environmental Quality. Int. J. Environ. Res. Public Health. **19**(4) (2022). https://doi.org/10.3390/ijerph19042450

Sun, D., Kyere, F., Sampene, A.K., Asante, D., Kumah, N.Y.G.: An investigation on the role of electric vehicles in alleviating environmental pollution: Evidence from five leading economies. Environ. Sci. Pollut. Res. **30**(7), 18244–18259 (2023). https://doi.org/10.1007/s11356-022-23386-x

Szetela, B., Majewska, A., Jamroz, P., Djalilov, B., Salahodjaev, R.: Renewable Energy and CO2 emissions in top natural resource rents depending countries: The role of Governance. Front. Energy Res. **10** (2022). https://doi.org/10.3389/fenrg.2022.872941

Tanveer, A., Song, H., Faheem, M., Chaudhry, I.S.: Validation of environmental Philips curve in Pakistan: A fresh insight through ARDL technique. Environ. Sci. Pollut. Res. **29**(17), 25060–25077 (2022). https://doi.org/10.1007/s11356-021-17099-w

Tao, J.: Modeling and analysis of the hindrance of environmental pollution to the development of circular economy in underdeveloped areas. Fresenius Environ. Bull. **30**(6), 5855–5861 (2021)

Tariq, S., Mehmood, U., Haq, Z., Mariam, A.: Exploring the existence of environmental Phillips curve in south Asian countries. Environ. Sci. Pollut. Res. **29**(23), 35396–35407 (2022). https://doi.org/10.1007/s11356-021-18099-6

Tee, C.M., Wong, W.Y., Hooy, C.W.: Economic policy uncertainty and carbon footprint: International evidence. J. Multinatl. Financial Manag. **67** (2023). https://doi.org/10.1016/j.mulfin.2023.100785

Thio, E., Tan, M.X., Li, L., Salman, M., Long, X., Sun, H., Zhu, B.: The estimation of influencing factors for carbon emissions based on EKC hypothesis and STIRPAT model: Evidence from top 10 countries. Environ. Dev. Sustain. **24**(9), 11226–11259 (2022). https://doi.org/10.1007/s10668-021-01905-z

Torrence, C., Compo, G.P.: A practical guide to Wavelet Analysis. Bull. Am. Meteorol. Soc. **79**(1), 61–78 (1998). https://doi.org/10.1175/1520-0477(1998)079<0061:APGTWA>2.0.CO;2

Tsuzuki, Y.: Environmental kuznets curve (ekc) relationships between pollutant discharge per capita (pdc) of domestic wastewater and income indicators. J. Global Environ. Eng. **14**, 37–46 (2009)

Turedi, N., Turedi, S.: The effects of renewable and non-renewable energy consumption and economic growth on CO2 emissions: Empirical evidence from developing countries. Bus. Econ. Res. J. **12**(4), 751–765 (2021). https://doi.org/10.20409/berj.2021.350

Uddin, I., Usman, M., Saqib, N., Makhdum, M.S.A.: The impact of geopolitical risk, governance, technological innovations, energy use, and foreign direct investment on CO<inf>2 emissions in the BRICS region. Environ. Sci. Pollut. Res. **30**(29), 73714–73729 (2023). https://doi.org/10.1007/s11356-023-27466-4

Udeagha, M.C., Ngepah, N.: Achieving decarbonization goals in BRICS economies: Revisiting the joint role of composite risk index, green innovation, and environmental policy stringency. Cogent Social Sci. **9**(1) (2023). https://doi.org/10.1080/23311886.2023.2234230

Ukaogo, P.O., Ewuzie, U., Onwuka, C.V.: Environmental pollution: Causes, effects, and the remedies. Microorganisms Sustainable Environ. Health. 419–429 (2020). https://doi.org/10.1016/B978-0-12-819001-2.00021-8

Voumik, L.C., Islam, M.A., Ray, S., Mohamed Yusop, N.Y., Ridzuan, A.R.: CO2 emissions from renewable and non-renewable electricity generation sources in the G7 countries: Static and Dynamic Panel Assessment. Energies. **16**(3) (2023). https://doi.org/10.3390/en16031044

Wang, L.: Research on the dynamic relationship between China's renewable energy consumption and carbon emissions based on ARDL model. *Resources Policy*, *77*. (2022). https://doi.org/10.1016/j.resourpol.2022.102764

Wang, Q., Li, L.: The effects of population aging, life expectancy, unemployment rate, population density, per capita GDP, urbanization on per capita carbon emissions. Sustainable Prod. Consum. **28**, 760–774 (2021). https://doi.org/10.1016/j.spc.2021.06.029

Wang, S.X., Fu, Y.B., Zhang, Z.G.: Population growth and the environmental Kuznets curve. China Econ. Rev. **36**, 146–165 (2015). https://doi.org/10.1016/j.chieco.2015.08.012

Wang, Q., Xiao, K., Lu, Z.: Does economic policy uncertainty affect CO2 emissions? Empirical evidence from the United States. Sustain. (Switzerland). **12**(21), 1–11 (2020). https://doi.org/10.3390/su12219108

Wang, Q., Wang, X., Li, R., et al.: Reinvestigating the environmental Kuznets curve (EKC) of carbon emissions and ecological footprint in 147 countries: A matter of trade protectionism. Humanit. Social Sci. Commun. **11**(160) (2024). https://doi.org/10.1057/s41599-024-02639-9

Westerlund, J.: Testing for error correction in panel data. Oxf. Bull. Econ. Stat. **69**, 0305–9049 (2007). https://doi.org/10.1111/j.1468-0084.2007.00477.x

World Bank: World Development Indicators | data. World Development Indicators (2023). https://databank.worldbank.org/source/world-development-indicators

Xin, Y., Yang, S., Rasheed, M.F.: Exploring the impacts of education and unemployment on CO2 emissions. Economic Research-Ekonomska Istrazivanja. **36**(1), 3542–3554 (2023). https://doi.org/10.1080/1331677X.2022.2110139

Zhu, M.: The role of human capital and environmental protection on the sustainable development goals: New evidences from Chinese economy. Economic Research-Ekonomska Istrazivanja. **36**(1), 1–18 (2022). https://doi.org/10.1080/1331677X.2022.2113334