Do higher education research and development expenditures affect environmental sustainability? New evidence from Chinese provinces

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Abstract

Even though higher education R&D expenditures (HEEXP) are important determinants of economic growth that facilitate science, technology, new ideas, and innovation, yet its effect on environmental sustainability remains unexplored. This paper examines the nexus between HEEXP and carbon dioxide emissions (CO₂e), followed by control variables such as electricity consumption (EC), foreign direct investment (FDI), gross domestic product (GDP), and total population (TP) for the period 2000Q1–2019Q4. Data were evaluated using different tests, e.g., the cross-sectional dependence test, cross-sectionally augmented Dickey–Fuller unit root test, Westerlund error-correction–based panel cointegration test, mean group, augmented mean group, common correlated effects mean group, and Dumitrescu–Hurlin panel causality test. First, the results validated the cointegration association among HEEXP, EC, FDI, GDP, TP, and CO₂e. Second, the finding showed significant long-term negative nexus between HEEXP and CO₂e. Third, the findings indicated that electricity consumption, foreign direct investment, gross domestic product, and total population are the important factors that intensify the overall situation of CO₂e. Fourth, the results indicated that there exists bidirectional causality between EC and CO₂e; FDI and CO₂e; GDP and CO₂e; POP and CO₂e; and HEEXP and CO₂e. This paper’s findings call for devising policies and strengthening financial support to induce higher education for developing green patents.

Keywords Higher education R&D expenditures · Electricity consumption · FDI · Population · CO₂e

Introduction

Environmental pollution is a major threat to the environment of the world. Rising economic growth and industrialization in emerging economies have fuelled the irresponsible

consumption of fossil fuels. Apart from the speedy depletion of natural resources, this situation has contributed to more waste, residues, and greenhouse gases (GHGs) in the environment. These toxic emissions of various types are considered primary causes of global climate change, rising temperatures, and air pollution. Among them, carbon dioxide is one of the leading pollutants, accounting for about 63% of GHG emissions (Sharif Hossain 2011; Wei 2020). Wei (2020) further reported that the global mean temperature has upsurge by 0.74 centigrade during the last ten decades. Theoretically, the association between gross domestic per capita (GDP) and CO₂e is directly linked to the consumption of different carbon-intensive natural resources, especially fossil fuels. Many scholars have argued that CO₂e, fossil fuel consumption, and economic progress are intimately correlated. Researchers have stated that massive industrialization, resulting from an increase in economic activities, escalates the rate of energy consumption from various nonrenewable sources, thereby causing CO₂e (Rehman et al. 2019).

From the day China adopted the “opening-up policy,” its economy sharply rose from just RMB0.365 trillion (1978) to

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RMB8.272 trillion (2007). With a phenomenal upsurge in the GDP (per capita) growth rate, China has become one of the largest CO₂e emitter in the world (Q. Li et al. 2019). China has mostly relied on nonrenewable energy resources (i.e., coal) to drive its economic growth and industrialization at the cost of high CO₂e, even though it is now cleaning its energy mix (Ahmad and Zhao 2018). Nonetheless, an overdependency on coal has significantly contributed to global warming, climate change, water contamination, soil erosion, and air pollution in China and the world (Ahmad et al. 2018a). With nearly 20% of the global population, China has significantly affected the economic and environmental landscape of the world. Figure 1 presents the historical growth in population, GDP growth, and CO₂e in China.

Besides, previous studies have identified various determinants of CO₂e. These factors include financial development (Ahmad et al. 2018b), technological innovation (Ahmad et al. 2019a), fiscal decentralization (Du and Sun 2021), freight and passenger transportation (Godil et al. 2020), economic growth (Nathaniel et al. 2021d; Solarin et al. 2021), institutional quality (Wawrzyniak and Doryń 2020), urbanization (Ahmad and Zhao 2018; Nathaniel et al. 2021c), exports (Anser et al. 2021), renewable energy consumption (Nathaniel et al. 2021b), corruption (Ren et al. 2021), public-private partnership investment in energy (Raza et al. 2021), aggregate consumption (Ahmad and Khattak 2020), human capital (Asghar et al. 2020), shadow economy (Sohail et al. 2021), higher education (Li et al. 2021), imports (Adewuyi and Awodumi 2020), gross fixed capital formation (Nathaniel and Adeleye 2021), energy demand (Vo and Zaman 2020), foreign direct investment (Rahman et al. 2019b), green technology innovation (Meirun et al. 2021), democratic transition (Mao 2018), inflow of remittances (Ahmad et al. 2019a; Khan et al., 2020), tourism (Aziz et al. 2020), international cooperation (Chen et al. 2020), financial instability (Baloch et al. 2018), fuel tax (Akkaya and Hepsag 2021), income inequality (Guo et al. 2020), premature deindustrialization (Ullah et al. 2020), information and communication technologies (Anser et al. 2021), natural resources rents (Nathaniel 2021; Nathaniel et al. 2021e), military

expenses (Isiksal 2021), globalization (Sharif et al. 2020), real interest rate (Isiksal et al. 2019), trade openness (Iheonu et al. 2021; Nathaniel 2020), commercial policies (Jiang et al. 2021a), globalization (Nathaniel et al. 2021a), and nonrenewable energy (Nathaniel and Iheonu 2019).

This paper focuses on higher education R&D expenditures (HEEXP) as another unexplored determinant of CO₂e for several reasons. First, the HEEXP serves as a core of science, technology, and innovation, which boosts industrialization and economic growth. Thus, this factor could be central to CO₂e mitigation strategies. Second, China recognizes environmental pollution as an urgent threat. It has been extensively funding higher education institutions (HEIs) for education and research projects related to energy, green economy, alternative fuel, and nonrenewables. In response, the HEIs have actively engaged in the education, research, and development activities by developing new ideas, technologies, products, and processes for the benefit of industry, the public, and the environment. Figure 2 depicts the parallel development in the HEEXP and environment-related patents for China for the period 2001–2019, signaling the potential role of HEEXP in eco-related patents. As seen above, a 4% increase in the HEEXP led to a rise in eco-related patents by 21% in 2016. From 2001–2016, an average of 21.18% upsurge in the HEEXP was associated with a parallel increase in eco-related patents by 20.59%, cueing potential implication of the HEEXP on eco-related patent development and environmental pollution in China. Despite that, the existing literature fails to offer any published study that sheds light on how shifts in the HEEXP are shaping environmental pollution dynamics.

The key purpose of this study is to fill this knowledge void by comprehensively analyzing the nexus between HEEXP and CO₂e by using data from thirty-one provinces in China. Some significant contributions of this work are as follows. First, the paper provides an initial insight into the potential nexus between HEEXP and CO₂e, thereby opening a possible research avenue in environmental economics. Second, the article offers the first schematic framework explaining the precise mechanism of how HEEXP affects environmental

Fig. 1 A comparison of CO₂e, population, and GDP growth in China (1981–2019)

Fig. 2 Proportionate changes (%) in HEEXP and eco-related patents

pollution in China. Third, the paper uses second-generation econometric techniques for robust and rigorous analysis. Fourth, through provincial data, the paper presents an in-depth insight into regional and provincial disparities vis-à-vis the HEEXP-CO₂e nexus. Fifth, the article has attempted to integrate two distinct paradigms into a unified framework, i.e., higher education and environmental economics. Most prior studies on CO₂e in the education literature are limited to campus-level surveys. Of the few studies in the economics literature, scholars have used education as a control variable, predominantly using student numbers or percentage of students as proxies. None of the prior studies in both disciplines has linked the HEEXP to CO₂e.

The rest of the paper is categorized as follows. The second section is the “Literature review” section. The third section is the “Conceptual framework, model specification, data, and estimation techniques” section. The “Results and discussions” section focuses on the interpretations of results and discussions, followed by the conclusion, policy recommendations, future directions, and limitations in the “Conclusion and policy implications” section.

Literature review

The relationship between income and CO₂e

The close inverted U-shape association between environmental sustainability and economic progress has gained considerable significance among scholars, especially during the last three decades. Many believe that rapid economic progress and industrialization affect the environment through the

excessive consumption of fossil fuels. Intellectuals have conducted extensive research to find potential determinants of environmental pollution. Past empirical studies have established that dirty and cheap fuel sources (e.g., coal, oil, and natural gas) have been a significant source of increasing global temperature. After the first industrial revolution, entrepreneurs and economies have been striving to control the CO₂e levels to prevent the harmful impact of global warming problems. The environmental Kuznets curve (EKC) hypothesis is probably the most frequently tested framework that explains the link between aggregate income and environmental sustainability (Özcan and Öztürk 2019). Grossman and Krueger (1991) argued that ecological pollution escalates in the initial stage of economic progress due to intense industrial consumption of cheap energy. This situation, however, improves with increased income as more efficient and clean technologies are used in the production process in the latter stages of economic development. This relationship is commonly referred to as the EKC hypothesis. Researchers have validated the EKC hypothesis for different economies, e.g., Iberia (Moutinho et al. 2020); China (Ahmad et al. 2019b; Jiang et al. 2019; Mushtaq et al. 2020; Xiaosan et al. 2021; Zhou et al. 2018); India (Dar and Asif 2017); Pakistan (Ur Rahman et al. 2019); the USA (Alola and Alola 2019); Brazil (Ben Jebli and Ben Youssef 2019); emerging economies (Wawrzyniak and Doryń 2020); NAFTA and BRIC (Khattak et al. 2021; Rahman et al. 2019a); Ukraine (Melnyk et al. 2016); SEE economies (Obradović and Lojanica 2017); developed and developing economies (Anser et al. 2020); and OECD (Ahmad et al. 2019a). Table 1 depicts the summary of the selected studies on the nexus between income and CO₂e.

Table 1 Selected studies on the nexus between income and CO₂e

Authors	Country	Period	Methods	Nexus: income-CO ₂ e
Moutinho et al. (2020)	Iberia	1975–2012	Autoregressive distributed lag	Positive
Mushtaq et al. (2020)	China	1995–2015	Fixed effect	Positive
Zhou et al. (2018)	China	2005–2015	Path analysis method	Positive
Dar and Asif (2017)	India	1971–2013	Autoregressive distributed lag	Positive
Ur Rahman et al. (2019)	Pakistan	1975–2016	Nonlinear autoregressive distributed lag	Positive
Alola and Alola (2019)	USA	1990: Q1–2018: Q2	Autoregressive distributed lag	Positive
Ben Jebli and Ben Youssef (2019)	Brazil	1980–2013	Autoregressive distributed lag	Positive
Wawrzyniak and Doryń (2020)	Emerging economies	1995–2014	Generalized method of moments	Positive
Ahmad et al. (2021a)	China	2004–2017	Augmented mean group	Positive
Rahman et al. (2019a)	NAFTA and BRIC	1992–2016	Panel mean group	Positive
Melnyk et al. (2016)	Ukraine	1999–2010	Linear parametric model	Positive
Obradović and Lojanica (2017)	South Eastern Europe	1980–2010	Vector error-correction model	Positive
Adebayo and Beton Kalmaz (2021)	Egypt	1971–2014	Autoregressive distributed lag	Positive
Mrabet et al. (2017)	Qatar	1980–2011	Autoregressive distributed lag	Not validated
Anser et al. (2020)	Developed and developing economies	1980–2017	Fully modified ordinary least squares	Positive
Uddin (2021)	115 countries	1990–2016	Vector error-correction model	Positive

Relationship between foreign direct investment and CO₂e

The positive link between FDI and CO₂e is known as the pollution haven hypothesis (PHH). This concept explains how sources of pollution transfer between countries and regions due to asymmetries in environmental regulations and industrial locations. Prior evidence indicates that pollution-intensive units, factories, or plants facing stringent regulations and policies in first-world economies moved and sought refuge in developing and third-world economies where laws were either nonexistent or extremely weak. As this trend has continued for a long time, many developing and third-world nations have become pollution havens due to imported pollution-intensive industries from the developed countries. Besides international trade and foreign investments, weak regulations in these economies have also attracted dirty technologies in most emerging economies (Centre et al. 2005). That said, the empirical evidence on the FDI-CO₂e nexus remains controversial. Some proof of the positive relationship between FDI and CO₂e include the newly industrialized economies (Destek and Okumus 2019); Cote d'Ivoire (Assamoi et al. 2020); ASEAN countries (Guzel and Okumus 2020); China (Ahmad et al. 2021c); MINT countries (Balsalobre-Lorente et al. 2019); Turkey (Mert and Caglar 2020); MIKTA economies (Bakirtas and Cetin 2017); Pakistan (Ur Rahman et al. 2019); Asia (Khan and Ozturk 2020); European economies (Mert et al. 2019); BRI region (Khan et al. 2019a); OIC countries (S. Ali et al. 2020); OECD countries (Ahmad et al. 2020); and coastal Mediterranean countries (Nathaniel 2020). Table 2 depicts the summary of the selected studies on the nexus between FDI and CO₂e.

The relationship between population and CO₂e

Globally, the historical shifts in demographics have not only resulted in falling fertility, mortality, and population size, but it is also linked to the developments in composition (age-structural change or population aging), distribution (migration), and density (urbanization). Harper (2013) stated that three sub-factors of the population had played an important role in increasing or decreasing CO₂e. Martínez-zarzoso et al. (2007) believed that although economic activity initiates wealth creation in a society, it damages the environment. The authors further added that the production systems in developed economies had generated massive water, air, and soil pollution, while simultaneously depleting precious global natural resources. The detrimental environmental impact of economic activities on the environment has worsened over the past years due to unparalleled demographic growth. With the global population increasing at an unprecedented rate, the resulting expansion in energy consumption has created higher risks for the environment. Researchers have established a positive link between population and CO₂e for the European countries (Harper 2013; Martínez-zarzoso et al. 2007); developed and developing economies (Dietz and Rosa 1997); selected 93 economies (Shi 2003); Asian economies (Qingquan et al. 2020); China (Khan et al. 2019b; Zhou et al. 2018); MENA economies (Al-mulali et al. 2013); newly industrialized nations (Sharif Hossain 2011); OECD (Liddle 2013); Pakistan (Ullah et al. 2020); OPEC economies (Murshed et al. 2020); and Asian countries (Abbasi et al. 2020). Table 3 depicts the summary of the selected studies on the nexus between population and CO₂e.

Table 2 Selected studies on the nexus between FDI and CO₂e

Authors	Country	Period	Methods	Nexus: FDI-CO ₂ e
Destek and Okumus (2019)	Newly industrialized economies	1982–2013	Common correlated effects estimator	Positive
Assamoi et al. (2020)	Cote d'Ivoire	1980 to 2014	Autoregressive distributed lag	Positive
Guzel and Okumus (2020)	ASEAN countries	1981–2014	Augmented mean group	Positive
Mert and Caglar (2020)	Turkey	1974–2018	Vector error-correction model	Negative
Bakiras and Cetin (2017)	MIKTA economies	1982–2011	Vector error-correction model	Positive
Ur Rahman et al. (2019)	Pakistan	1975–2016	Nonlinear autoregressive distributed lag	Positive
Khan and Ozturk (2020)	Asian states	1980–2014	Fully modified ordinary least squares	Positive
Ahmad et al. (2019a)	Organisation for Economic Co-operation and Development	1990–2014	Fully modified ordinary least squares	Negative
H. Li et al. (2021)	China	2000–2018	Fully modified ordinary least squares	Negative
Manzoor Ahmad et al. (2020)	Organisation for Economic Co-operation and Development	1993–2014	Generalized method of moments	Positive
Ahmad et al. (2021a)	China	1998–2016	Dynamic common correlated effects mean group	Negative
Ahmad et al. (2021b)	China	1999–2017	Aggregation bias tests	Positive
Baek (2016)	ASEAN countries	1981–2010	Pooled mean group	Positive

The relationship between electricity consumption and CO₂e

Electricity is one of the primary sources of energy for all industries. Even though electricity consumption is not directly associated with CO₂e, the vast quantities of nonrenewable fossil fuels used for power generation emit high CO₂e (Zhang 2019). Previously, few academics have examined the relationship between electricity consumption and CO₂e. For example, Zhang (2019) investigated the relationship between electricity consumption and carbon intensity among twenty-seven firms in China using a STIRPAT framework. The results indicated that electricity consumption played a mitigating role in CO₂e. Balsalobre-Lorente et al. (2018) concluded that electricity consumption increased CO₂e in the long run across the European nations. Bélaïd and Youssef (2017) tested the association between energy (renewable and nonrenewable) consumption and CO₂e for Algeria. The ARDL estimates validated the renewable energy consumption-CO₂e led hypothesis. Yorucu and Varoglu (2020) studied the nexus among industrial production, electricity consumption, economic growth, and CO₂e in selected small island states. Based on the FMOLS and DOLS estimations, the authors found that a 1% increase in electricity consumption predicted an upsurge of 0.79% in CO₂e. In the same way, other studies have also reported a positive connection between electricity consumption and CO₂e for China (Akadiri et al. 2020; Munir and Riaz 2020; Ou et al. 2011; Xu et al. 2015; Zhang 2019); Spain (Zarco-Soto et al. 2020); South Asian economies (Munir and Riaz 2019); Bangladesh (Shahbaz et al. 2014); ASEAN countries (Lean and Smyth 2010); Pakistan (Rehman et al. 2019) BRICS (Cowan et al. 2014; Haseeb et al. 2019); and Kuwait (Salahuddin et al. 2018). Table 4 depicts the summary of the selected studies on the nexus between electricity consumption and CO₂e.

Conceptual framework, model specification, data, and estimation techniques

Conceptual framework

Figure 3 illustrates the conceptual framework, depicting the mechanism through which HEEXP may affect CO₂e. The HEIs have contributed to the advancement of knowledge, economy, cultivating students, and conducting research in many fields. Whether it was government intervention or a self-driven agenda, HEIs around the world have undergone enormous transformation and restructuring in areas like organizational practices, research focus, controls, funding structures, and autonomy (Wendt et al. 2015). Governments' funding, therefore, has been crucial for many HEIs to support primary and advanced level research, especially in fields like

Table 3 Selected studies on the nexus between population and CO₂e

Authors	Country	Period	Methods	Nexus: population-CO ₂ e
Abbasi et al. (2020)	8 Asian states	1982–2017	Fully modified ordinary least squares	Positive
Murshed et al. (2020)	OPEC states	1992–2015	spatial econometric models	Positive
Ullah et al. (2020)	Pakistan	1980–2018	Autoregressive distributed lag	Positive
Qingquan et al. (2020)	Asian countries	1990–2014	Panel dynamic least squares	Insignificant
Hussain and Rehman (2021)	Pakistan	1975–2019	Autoregressive distributed lag	Positive
Ahmad and Zhao (2018)	China	2000–2016	Augmented mean group	Positive
Ullah et al. (2020)	Pakistan	1980–2018	Nonlinear autoregressive distributed lag	Positive
Arshad et al. (2020)	South and Southeast Asian states	1990–2014	Pooled mean group	Positive
Raggad (2018)	Saudi Arabia	1971–2014	Autoregressive distributed lag	Negative
Salahuddin et al. (2019)	Sub-Saharan Africa countries	1984–2016	Pooled mean group	Positive
Zhu et al. (2018)	BRICS	1994–2013	Panel quantile regression	Negative
H. S. Ali et al. (2017)	Singapore	1970–2015	Autoregressive distributed lag	Negative

environmental sciences, energy and resources efficiency, sustainability, and other similar areas. Many academic institutions have set up separate departments for energy economics, sustainability, green technology, and eco-innovation while simultaneously initiating programs and activities to achieve green education, green campus, and green economy. With the support of their respective governments, many industries and academic institutions are actively conducting research and developing solutions for sustainable production, responsible consumption, and environmental preservation. These projects reflect two facets: (i) research on green and sustainable technology, methods, processes, and products and (ii) developing and promoting green campuses (GC).

Congruent with the above, academic institutions and governments are equally focused on addressing various crucial issues related to energy consumption and production. A possible explanation resides in the energy resources possessed by a country. If the energy demand exceeds the supply,

governments are left with no choice but to import expensive energy from other countries that undermine their security and environment. With the potential role of renewable and green energy, green technologies, green products, and green services, many governments and institutions have been investing heavily in academic research and development related to eco-innovation, green technologies, and renewable energy solutions. As a result, the number of eco-related patent applications and green research has increased manifolds in the past few decades across developed and developing nations. In terms of environmental benefits, these patents have been used across many industries to solve problems, including energy shortages, fossil fuel dependency, carbon footprint, and low energy efficiency.

Beyond that, academic institutions have been developing and institutionalizing the concept of green campus (GC) and green education. Simply put, GC embodies the development of two critical aspects in an academic institution: (a) energy-

Table 4 Selected studies on the nexus between electricity consumption and CO₂e

Authors	Country	Period	Methods	Nexus: electricity consumption-CO ₂ e
Salahuddin et al. (2018)	Kuwait	1980–2013	Autoregressive distributed lag	Positive
Haseeb et al. (2019)	BRICS	1994–2014	Dynamic seemingly unrelated regression	Positive
Rehman et al. (2019)	Pakistan	1990–2017	Autoregressive distributed lag	Positive
Munir and Riaz (2019)	South Asia	1985–2017	Nonlinear autoregressive distributed lag	Positive
Munir and Riaz (2020)	China	1975–2018	Nonlinear autoregressive distributed lag	Positive
El Menyari (2021)	North Africa	1980–2014	Dynamic seemingly unrelated regression	Positive
Zhang (2019)	China	2007–2016	Fixed effect and random effect	Positive
Akadir et al. (2020)	China	1970–2014	Autoregressive distributed lag	Positive
Etokakpan et al. (2020)	Turkey	1970–2014	Autoregressive distributed lag	Positive
Q. Jiang et al. (2021b)	China	1985–2018	Autoregressive distributed lag	Positive

Fig. 3 The conceptual framework

and resource-efficient campus (ERSC) and (b) campus energy management system (CEMS). The concept of CEMS emphasizes the construction of green education and environment-related technologies for ERSC. The ERSC, however, requires the integration of green ideology into capital operation, infrastructure, logistics, and other departments. The primary purpose of GC is to achieve energy and resources efficiency by saving materials, water, energy, and land; promote the use of green and clean energy sources during official hours; encourage sustainable development in higher education; improve R&D for faculty, staff, students, and society at large; enhance stakeholder engagement on sustainable decision-making; sponsor students and faculty participation in green and sustainability-related activities; and design and implement green curricula. Thus, GC plays a vital role in the implementation of sustainable development goals and green policies. Above all, the exchange and cooperation activities among academic institutions for the advancement of GC ideology offer multiple benefits, in terms of national policy formulation for GC development; attainment of Strategic Development Goals; encouraging collaborative research; enabling the diffusion of carbon- and energy-saving programs, innovation, and carbon-reduction technology in HEIs; initiating training programs for faculty members; and establishing real-time experiment, labs, and demonstration centers for green research,

education, green campus development, and strategy implementation. Through the proper utilization of HEEXP, the GC can find a new way to set the foundations for disseminating the soft power of eco-protection, achieving low-carbon goals, and enabling a smooth transition to a green economy and campus. That said, the development of the GC necessitates the need for educational institutions to focus on the hardware and software of the GC simultaneously. The former pertains to the integration of green aspects in construction, building, infrastructure, and operations. The latter refers to developing and promoting green culture, humanity, green citizenship, and talent for social entrepreneurship. This process, if properly executed, will result in the formation of core green values at all levels (economy, education, society, business), enabling sustainable progress (Tan et al. 2014). In short, it is proposed that the development of GC (through HEEXP) not only helps in mitigating CO₂e but also plays an essential role in promoting sustainable consumption and production across residential and commercial sectors.

Model specification

Below, Eq. (1) represents the dynamic relationship between higher education R&D expenditures (HEEXP), foreign direct investment (FDI), electricity consumption (EC), gross

domestic product (GDP), total population (POP), and CO₂e.

$$CO2e_{it} = \psi_o + \psi_1 HEEXP_{it} + \psi_2 FDI_{it} + \psi_3 EC_{it} + \psi_4 GDP_{it} + \psi_5 POP_{it} + \epsilon_{it} \quad (1)$$

where $CO2e_{it}$ is the carbon dioxide emissions; $HEEXP_{it}$ the higher education R&D expenditures; FDI_{it} the foreign direction investment; EC_{it} the electricity consumption; GDP_{it} the gross domestic product; POP_{it} the total population; ϵ_{it} the error terms; ψ_o the constant; and $\psi_1, \psi_2, \psi_3, \psi_4$, and ψ_5 are the unknown parameters of each variable.

The rationale for using variables, including FDI, EC, GDP, and POP (as control variables), is briefly discussed henceforth. First, China has become one of the most attractive FDI destinations due to low labor costs and weak environmental regulations. Many multinational companies from developed nations have transferred their technologies (FDI), converting China into a pollution haven. Second, China is among the top energy generation countries, where almost 80% of electricity was generated from coal. Third, it is one of the largest economies in the world, vis-a-vis the GDP growth rate. Fourth, China is one of the most populous economies globally, where population growth has contributed to energy consumption among residential and nonresidential consumers, directly and indirectly causing CO₂e.

Data

The data for HEEXP, FDI, EC, GDP, POP, and CO₂e were collected from the National Bureau of Statistics (2019) for 2000–2019. Consistent with the previous studies (cf. Sbiba et al. 2014; Shahbaz et al. 2017), the accuracy and frequency of the data were enhanced through the quadratic match-sum method. All variables were converted into logarithmic forms for added reliability and consistent results. Table 5 shows the data sources and descriptions.

Estimation techniques

Following Nathaniel et al. (2021b) and Ahmed et al. (2021), this study employs panel econometric approaches. These methods are appropriate for panels with a large number of cross-section and years. As noted earlier, the study's methodology consists of cross-sectional dependence (CSD) test, slope homogeneity test (SHT), second-generation panel unit root tests, Westerlund (2007) error-correction-based panel cointegration test (WECPT). Next, the estimation of long-run coefficients was conducted through the following estimators, i.e., mean group (MG), augmented mean group (AMG), and common correlated effects mean group (CCEMG) estimator. Finally, the causality was checked using the Dumitrescu and Hurlin (2012) panel causality test (DHPCT).

CSD test and SHT

Testing the cross-sectional dependence (CSD) among the series was the first step in the panel data analysis. This test was conducted to identify and deal with the problems of unit root and CSD in the data series. As the CSD is associated with economic unions, financial shocks, demand shocks, supply shocks, pandemic diseases, globalization, and trade wars, it must be dealt with accuracy and precision. If ignored, it could lead to biased cointegration and stationarity results (Khan et al., 2020). Based on prior recommendations (Ahmed et al. 2021; Nathaniel et al. 2021b), the Pesaran (2015) cross-sectional dependence test (PCSDT) was applied for addressing the CSD problem. The CSD statistics can be represented as follows:

$$CSD = \sqrt{\frac{2T}{N(N-1)}} \left(\sum_{i=0}^{N-1} \sum_{j=i+1}^{N-1} p_{ij} \right) N(0, 1), \quad (2)$$

where p_{ij} denotes the cross-sectional correlation of error between j and i . T and N represent time horizon and cross-sections, respectively. The selection of this approach is due to the dataset size, i.e., a smaller number of cross-sections compared to the time period (Nathaniel et al. 2021c).

Moreover, the Pesaran and Yamagata (2008) slope homogeneity test (SHT) was applied for addressing the homogeneity problems. As per the authors, the “slope homogeneity ($H_0: \beta_i = \beta$ for all i)” in the null hypothesis and “slope heterogeneity ($H_0: \beta_i \neq \beta$)” (Balsalobre-Lorente et al. 2020). The Pesaran and Yamagata (2008) SHT involve estimation of the following equations:

$$\tilde{\Delta} = \sqrt{N} \left(\frac{N^{-1} \tilde{S} - k}{\sqrt{2k}} \right) \quad (3)$$

$$\tilde{\Delta}_{adj} = \sqrt{N} \left(\frac{N^{-1} \tilde{S} - E(\tilde{z}_{iT})}{\sqrt{\text{Var}(\tilde{z}_{iT})}} \right) \quad (4)$$

where S depicts Swamy test statistic, N signifies the cross-sectional dimension, $E(\tilde{z}_{iT}) = k$, $\text{Var}(\tilde{z}_{iT}) = \frac{2k(T-k-1)}{T+1}$, and k represents finite positive constant.

Unit root testing

If the CSD problem is detected, the first-generation unit root approaches are not applicable because they cannot deal with the problem of CSD. Therefore, the second-generation tests—the Pesaran (2003) cross-sectionally augmented Dickey-Fuller (PCADF) and the Pesaran (2007) cross-sectionally augmented IPS (CIPS) unit root tests—are used to sort out CSD issues. Conventional or first-generation panel unit root tests are based on the hypothesis of cross-sectional independence (CSI). The second-generation unit root tests, however, allow for the assumption of CSD in the data series. With the results

Table 5 Data description and sources

Variables	Notation	Units	Source of data	Estimation technique	Expected signs
Electricity consumption	EC	Watt-hour	National Bureau of Statistics (2019)	Quadratic match-sum method	Positive
Foreign direct investment	FDI	Million yuan	National Bureau of Statistics (2019)	Quadratic match-sum method	Positive
Gross domestic product	GDP	100 million yuan	National Bureau of Statistics (2019)	Quadratic match-sum method	Positive
Population	POP	10,000 people	National Bureau of Statistics (2019)	Quadratic match-sum method	Positive
Research and development expenditures in the higher education sector	HEEXP	1000 yuan	National Bureau of Statistics (2019)	Quadratic match-sum method	Negative
Carbon dioxide emissions	CO ₂ e	10,000 tons	National Bureau of Statistics (2019)	Quadratic match-sum method	

of the second-generation tests providing strong evidence on the existence of CSD across the provinces in China, these tests were appropriate for estimating the order of integration. The PCADF test statistics can be estimated using the following generalized regression function:

$$\Delta y_{it} = \alpha_i + b_i y_{i,t-1} + c_i y_{i,t-1} + \sum_{j=0}^s d_{ij} \Delta y_{i,t-1} + \sum_{j=0}^s \delta_{ij} \Delta y_{i,t-j} + e_{it}, \quad (5)$$

where Δy indicates the averages of the cross-sectional outcome variables at first differences and y shows the averages of the cross-sectional outcome variables at lagged levels. The PCIPS statistic is then computed using the approximate t -statistic from Eq. (5), which can be defined as:

$$PCIPS = N^{-1} \sum_{i=1}^N CADF_i, \quad (6)$$

The null hypothesis of both PCIPS and PCADF indicates whether every panel's cross-section is stationary or nonstationary. For robustness check, the Clemente et al. (1998) unit root test (CMRURT) was applied with multiple structural breaks. After determining the order of integration among EC, FDI, GDP, POP, HEEXP, and CO₂e, it was important to look for the long-term nexus between them using a suitable cointegration method.

Cointegration testing

Westerlund (2007) error-correction-based panel cointegration test (WECPT) was employed to inspect the dynamic cointegration connection between EC, FDI, GDP, POP, HEEXP, and CO₂e. This test deals with the problem of common factor restriction (Nathaniel et al. 2021d). Westerlund (2007) proposed four cointegration tests to examine the presence of long-run cointegration in the panel data. These tests are based on the error-correction (EC) model and offer three distinct advantages: (1) allow unbalanced panels and unequal series length in units; (2) test heterogeneity that is permitted in the short- and long-run parameters of the error-correction model; and (3) obtain critical value using the bootstrap approach, if a correlation probability exists among units. The WECPT involves the following hypothesis:

H_0 : No cointegration exists among all panels

H_1 : Cointegration exists among all panels

The paper adopted three cointegration tests for checking robustness—Kao (1999) residual-based cointegration test (KRCPT), Pedroni (2004) cointegration test (PCT), and the Gregory and Hansen (1996) cointegration test (GHCT) (with structural breaks and regime shifts).

Long-run coefficients estimation

Several economic techniques have been introduced in the past decades for addressing the CSD and parameter heterogeneity problems. Some of the widely accepted methods include the M Hashem Pesaran and Smith (1995) mean group (MG) estimator, M Hashem Pesaran (2006) common correlated effects mean group (CCEMG) estimator, and the Eberhardt and Bond (2009) augmented mean group (AMG). Technically, the MG method separately applies times series ordinary least square (OLS) to each panel, including a linear trend to estimate time-variant unobservable (TVU) and an intercept to deal with fixed components. Then, this estimator averages the computed individual-specific slope (without or with wrights). For dynamic cases, this estimator proves to be reliable for large N and T if the coefficients exhibit heterogeneity in groups. This estimator, however, fails to offer information about common factors (CFs), which may exist in the panel data. The CFs are referred to as “time-specific effects,” which are common in provinces, countries, or regions. By incorporating the averages of the cross-sections of the independent and the dependent variables as surplus regressors (when applying OLS to specific units), the CCEMG method allows for TVU and CSD with heterogeneous effect in panel members. Identified by the averages of CS, the unobserved CFs can be any fixed digit. With superior small sample characteristics and short-run estimation properties, the CCEMG technique is relatively robust to non-cointegrated and nonstationary CF, structural breaks, and some serial correlations. As an alternate method, the AMG initially computes an augmented pooled model (with year dummies) through the first difference OLS. The calculated year dummies are then compiled to construct a new variable, representing the common dynamic process. This new variable is used as an extra regressor for single group-specific regressor model, along with an intercept for capturing the time-variant fixed impacts. Similar to the CCEMG technique, the AMG method helps in dealing with multifactor error terms and nonstationary variables, particularly considering CSD. The AMG estimator is superior to the CCEMG estimator in creating a set of unobservable CF as a common dynamic process. Dissimilar to a scenario in which the unobservable factors are considered a nuisance, the alternate treatment may offer helpful interpretations, depending on the context (Heshmati 2019). The AMG consists of the estimation of the following equations:

$$\text{Stage 1 : } \Delta y_{it} = \alpha_1 + b_i \Delta x_{it} + c_i f_t + \sum_{t=2}^T d_i \Delta D_t + e_{it} \quad (7)$$

$$\text{Stage 2 : } \hat{b}_{AMG} = N^{-1} \sum_{i=1}^N \hat{b}_i \quad (8)$$

where $\hat{b}_{AMG}$ is the AMG estimator, y_{it} denotes the observables, d_i signifies the coefficient of the time dummies, b_i is the country-specific estimates of coefficients, and f_t represents the unobserved common factor, while x_{it} and y_{it} show the observables.

The CCEMG introduced by Pesaran (2006) comprises the estimation of the following equations:

$$\hat{b}_i = (X_i' M_w X_i)^{-1} X_i' M_w Y_i \quad (9)$$

$$\hat{b}_{CCEMG} = \frac{1}{N} \sum_{j=1}^p \hat{b}_i \quad (10)$$

where $\hat{b}_{CCEMG}$ indicates the panel CCEMG estimator and $\hat{b}_i$ denotes the individual CCEMG estimation for each of the cross-sectional unit.

Panel causality testing

For panel data, Dumitrescu and Hurlin (2012) proposed a test to examine causal relationships between variables. This test outperforms the traditional causality tests by allowing for the hypothesis of causality existence in at least one cross-section against the nonexistence of the homogenous Granger-causality relationship. In this way, the Dumitrescu and Hurlin (2012) panel causality test (DHPCT) accounts for the CSD between the sample province or countries. Moreover, the DHPCT is insensitive to the variance among the cross-sections and the time difference in the panel. It generates efficient results, even if the size of the cross-sections and time series are smaller or larger than others (Ceyhun 2019). The DHPCT involves the estimation of the following standardized statistics:

$$y_{i,t} = \phi_i + \sum_{i=1}^p \xi_i^{(p)} y_{i,t-n} + \sum_{i=1}^p \pi_i^{(p)} x_{i,t-n} + \mu_{i,t} \quad (11)$$

where $\pi_i^{(p)}$ denotes the regression coefficient, $\xi_i^{(p)}$ shows the autoregressive parameter, ϕ_i is the intercept, and π_i represents the coefficient. $\pi_i = (\pi_i^{(1)}, \dots, \pi_i^{(p)})$ is constant. The DHPCT follows the testing of the following hypothesis:

$$H_0 : \beta_1 = 0$$

$$H_1 : \begin{cases} \beta_i = 0 \\ \beta_i \neq 0 \end{cases} \quad \forall i = 1, 2, \dots, N \text{ and } \forall i = N+1, N+2, \dots, N$$

Results and discussion

Table 6 depicts the results of PCSDT. As seen below, the null hypothesis of no CSD for the EC, FDI, GDP, POP, HEEXP, and CO₂e was rejected at 10, 5, and 1% significance levels, implying that all the provinces in China were interdependent, i.e., an economic shock in one region may affect other regions. As reported in Table 7, the SHT highlighted heterogeneity problems in the model.

Table 6 Results of the PCSDT

Variable	CD-statistic	P-value	Average joint T	Mean ρ	Mean obs (ρ)
CO ₂ e	148.205	0.000	80.00	0.77	0.86
EC	168.425	0.000	80.00	0.87	0.96
FDI	153.638	0.000	80.00	0.80	0.80
GDP	189.912	0.000	80.00	0.98	0.98
POP	56.194	0.000	80.00	0.29	0.48
HEEXP	150.963	0.000	80.00	0.78	0.81

Note. CO₂e, carbon dioxide emissions; EC, electricity consumption; FDI, foreign direct investment; GDP, gross domestic product; POP, population; HEEXP, higher education R&D expenditures

Table 8 displays the results of the PCADF and PCIPS unit root tests. These tests were used to check the integration order of all the study variables. The results confirmed that all the study variables were nonstationary at level but became stationary at the first difference, even though these tests could not deal with structural breaks in the data. Given that most global economies have experienced many structural changes, it was considered imperative to trace structural breaks in the data series for China. There was a high probability that the PCADF and PCIPS could have given bias results if structural changes were underestimated. This problem was addressed through the CMRURT that allowed for multiple structural breaks in the data.

Table 9 illustrates the results of the CMRURT. The test indicated that all variables were stationary at the first difference, with two break years in each series. The estimated structural breaks—often linked to global or local events—had potential positive or negative implications for the Chinese economy. In 2002, a deadly virus named SARS emerged in Guangdong and severely impacted industrial production (Wong and Zheng 2004). In 2004, China faced one of the worst historic inflationary pressures, partly triggered by real-estate speculations. With an increase in the costs of raw material and energy and over-investments in some industries, China raised interest rates and applied administrative control to abate the pace of investment in some sectors and industries (Morrison 2010). In 2005, the Lenovo Group acquired IBM's computer division for a hefty sum of USD1.75 billion, which was considered an economic breakthrough. Apart from gaining access to foreign facilities, operations, and R&D, China strengthened its presence in the USA (Morrison 2010). From 2008–2009, the global financial crisis pushed China to revisit its economic policies to sustain economic

growth. While the economic growth rate was disrupted in 2009 relative to the past years, this slowdown in growth was reasonably modest, especially compared to the total shrinkage in the world output (Lardy 2012). Although the incoming FDI experienced a sharp decline, the inbound foreign investments reached an all-time high in 2010, increasing by around two-third, i.e., USD185 billion. There was almost a 20% contraction in outbound FDI in 2009, but the outbound FDI increased by 37% and touched an all-time high of USD60 billion (Lardy 2012). Moreover, the inclusion and internationalization of RMB in the special drawing rights currency basket by the IMF in 2010 was another important milestone, which enabled China to expand its financial presence in the global financial markets (Cassis and Wójcik 2018). With all the study variables exhibiting the same integration order, the study applied the cointegration analysis, including the WECPT, KRCPT, PCT, and the GHCT.

Table 10 depicts the outcomes of the cointegration analysis without structural breaks. The first two columns (G_r , G_d) indicate the group means statistics for the total cointegration, whereas the remaining two columns (Pa, Pt) show panel statistics. The WECPT outputs confirmed a sustainable long-

Table 7 Results of the SHT

Statistics	Test value	P-value
Delta	82.524	0.000
Adjusted delta	86.391	0.000

Table 8 Results of the PCADF and the PCIPS unit root tests (without structural breaks)

Variable	At level		At first difference	
	PCADF	PCIPS	PCADF	PCIPS
CO ₂ e	0.588	−0.335	−9.307***	−3.942***
EC	3.226	−1.866	−3.374***	−4.161***
FDI	1.140	−0.727	−4.176***	−4.467***
GDP	2.028	−0.703	−16.727***	−3.186***
POP	20.072	−1.704	−23.227***	−3.222***
HEEXP	13.596	−1.295	−12.026***	−4.250***

Note. CO₂e, carbon dioxide emissions; EC, electricity consumption; FDI, foreign direct investment; GDP, gross domestic product; POP, population; HEEXP, higher education R&D expenditures. *** indicates 1% level of significance

Table 9 Unit root test with structural breaks

Variable	At level		At first difference	
	t-statistic	Breakpoints	t-statistic	Breakpoints
CO ₂ e	1.438	2002Q3, 2017Q3	−5.779***	2010Q4, 2016Q4
EC	0.842	2009Q2, 2012Q3	−2.287**	2006Q4, 2009Q4
FDI	1.360	2015Q1, 2017Q2	−4.722***	2001Q3, 2015Q1
GDP	1.442	2009Q3, 2010Q3	−4.337***	2003Q1, 2008Q4
POP	0.050	2004Q4, 2005Q3	−8.438***	2003Q4, 2004Q4
HEEXP	0.916	2008Q1, 2011Q3	4.187***	2010Q4, 2011Q4

Note. CO₂e, carbon dioxide emissions; EC, electricity consumption; FDI, foreign direct investment; GDP, gross domestic product; POP, population; HEEXP, higher education R&D expenditures. ** and *** indicate 5% and 1% level of significance, respectively

term association among all the study variables. In Table 11, the results of the cointegration analysis (with structural break and regime shifts) were found to be consistent with the WECPT, KRCPT, and PCT.

Table 12 displays the long-run coefficients based on three different econometric methods, including the MG, AMG, and CCMEG. The main findings are as follows. First, the estimates showed a significant negative linkage between HEEXP and CO₂e—a 1% increase in HEEXP predicted a decline of 0.29

(MG), 0.24 (AMG), and 0.30% (CCMEG) in CO₂e. As expected, this result supported that spending on research and development spending in higher education has helped mitigate CO₂e in China. A feasible explanation is that academic institutions have been a central part of the national research framework in developing green technology, innovation, and eco-urban systems in China. In 2011 alone, the faculty and staff from HEIs constituted 11.3% of the overall research and development population. Using almost 8.5% of the total national R&D spending, these researchers have shown impressive results. These individuals conducted 62.2% of all research projects and activities, received 28.8% of the total patents, applied for 21.6% of the total patents, and produced 64.4% of all scientific publications.

Following the “new normal” of fostering the nation with education, science, innovation, and developing a green economy, the Chinese government has focused on green and sustainable technology research. Currently, Chinese scholars are leading global research related to green production, sustainability, green technology, environmental science, and green energy. More so, the government has been allocating a considerable amount of funds for sustainability-oriented R&D projects. From 2000–2009, these funds have increased from just RMB7.67 billion to RMB46.7 billion, constituting almost 8% of the total national spending on R&D. A total of RMB14.5 billion was allocated to basic research, accounting for nearly 53% of the total national research budget (Hu et al. 2017).

Table 10 Cointegration analysis without structural breaks

Test statistics	CO ₂ e→EC	CO ₂ e→FDI	CO ₂ e→GDP	CO ₂ e→POP	CO ₂ e→HEEXP
WEPCT					
Gt	−2.098**	−2.059**	−12.575***	−5.554***	−4.362***
Ga	−116.59***	−44.50***	−43.088***	−29.438***	−128.47***
Pt	−3.411***	1.449	−2.087**	−1.750**	0.861
Pa	−7.055***	1.738	−1.534*	−1.148	0.011
KRCPT					
MDF _t	4.57***	−18.94***	−0.21	−1.23	1.59*
DF _t	5.60***	−10.94***	−4.02***	0.07	−1.85**
ADF _t	−2.27**	−13.20***	−7.08***	−3.32***	−6.26***
UMDF _t	5.53***	−9.65***	1.47***	−0.9653	2.17**
UDF _t	8.18***	−11.15***	−3.04***	0.23	−1.35*
PCT					
MDF _t	4.66***	3.92***	3.57***	−3.24***	2.64***
PP _t	9.10***	1.65*	7.87***	−2.78***	6.01***
ADF _t	21.11***	2.89***	21.29***	3.76***	14.52***

Note: WEPCT, Westerlund (2007) error-correction-based panel cointegration tests; KRCPT, Kao (1999) residual-based tests for cointegration in panel data; MDF_t, modified Dickey-Fuller t; DF_t, Dickey-Fuller t; ADF_t, augmented Dickey-Fuller t; UMD_t, unadjusted modified Dickey-Fuller t; UDF_t, unadjusted Dickey-Fuller t; PCT, Pedroni (2004) cointegration test; PP_t, Phillips-Perron t; ADF_t, augmented Dickey-Fuller t; CO₂e, carbon dioxide emissions; EC, electricity consumption; FDI, foreign direct investment; GDP, gross domestic product; POP, population; HEEXP, higher education R&D expenditures

*, **, and *** indicate 10%, 5% and 1% level of significance, respectively

Table 11 Cointegration analysis with structural break and regime shifts

Test statistics	CO ₂ e→EC	CO ₂ e→FDI	CO ₂ e→GDP	CO ₂ e→POP	CO ₂ e→HEEXP
<i>Change in level</i>					
ADF	−6.11***	−32.14***	−6.53***	−9.41***	−8.72***
Breakpoint	54	36	52	56	38
Break year	2013Q2	2009Q1	2012Q4	2013Q4	2009Q2
Critical values (1%)	−5.13	−5.13	−5.13	−5.13	−5.13
Critical values (5%)	−4.61	−4.61	−4.61	−4.61	−4.61
Critical values 10%)	−4.34	−4.34	−4.34	−4.34	−4.34
<i>Change in regime</i>					
ADF	−5.56***	−5.80***	−9.54***	−8.73***	−8.92***
Breakpoint	55	61	36	36	45
Break year	2013Q3	2015Q1	2008Q4	2008Q4	2011Q1
Critical values (1%)	−5.47	−5.47	−5.47	−5.47	−5.47
Critical values (5%)	−4.95	−4.95	−4.95	−4.95	−4.95
Critical values 10%)	−4.68	−4.68	−4.68	−4.68	−4.68

Note: CO₂e, carbon dioxide emissions; EC, electricity consumption; FDI, foreign direct investment; GDP, gross domestic product; POP, population; HEEXP, higher education R&D expenditures

***indicates a 1% level of significance

Next, China initiated the 211 Project and 985 Project to uplift the HEI standard. These projects focused on developing globally competitive first-class universities, programs, and scientific disciplines to promote sustainable and green socio-economic development in China. Hu et al. (2017) argued that the 15 years of the 211 Projects have been extremely fruitful in setting the foundations for green innovation in education, research and service, and transitioning to a green economy. China spends around 2% of its total GDP on research, an

amount that is increasing at the rate of 20% per year (Chung 2015). Under the government's guidance, Chinese HEIs have dedicated time, resources, and money to research green energy, economy, technology, education, and innovation to realize a green revolution (Liu et al. 2012). These factors have played an instrumental role in indirectly mitigating CO₂e by raising awareness, green technology development, green urbanization, and green education.

In the same vein, China has been investing heavily in the green university/campus project. Many top-ranking and globally recognized universities have joined hands with the government to realize the Sustainable Development Goals. For instance, Tsinghua University has been championing the idea of green campus (GC), green technology, and green education. Peking University initiated the Green University project in April 2009. As an initial step, the planning department was rebranded as the Campus Planning and Sustainable Development Office. Beijing University has set four key objectives for achieving the GC and educational goals: (1) spatial design augmentations of the university; (2) improved and continued excellence of scientific research and teaching; (3) propagation and restoration of culture and environmental heritage; and (4) establishment of zero-carbon campus (Morgan et al. 2017).

Lee and Efrid (2014) further explained the idea of green universities by identifying some key attributes. Firstly, these universities emphasize environmental education and integrate environmental aspects in the teaching, research, and curriculum. Secondly, the student and faculty master the knowledge, skills, and expertise on topics related to environmental protection, sustainable development, and environmental awareness.

Table 12 Long-run coefficients

Variables	MG	AMG	CCEMG
HEEXP	−0.294*** (−4.91) [0.059]	−0.242*** (−4.63) [0.052]	−0.303*** (−3.87) [0.078]
FDI	0.427*** (6.59) [0.067]	0.118*** (2.78) [0.042]	0.341*** (6.16) [0.055]
GDP	0.445*** (3.19) [0.139]	0.748*** (8.67) [0.086]	0.637*** (6.57) [0.097]
POP	0.686*** (4.53) [0.151]	0.922*** (3.98) [0.232]	0.683*** (3.58) [0.191]
EC	0.522*** (3.48) [0.1444]	0.383*** (6.15) [0.062]	0.308*** (3.14) [0.098]
C	1.169*** (3.85) [0.304]	2.6223*** (9.10) [0.288]	32.551*** (13.31) [2.126]

Note. CO₂e, carbon dioxide emissions; EC, electricity consumption; FDI, foreign direct investment; GDP, gross domestic product; POP, population; HEEXP, higher education R&D expenditures. ()= t-statistic; []= standard error; MG, mean group; AMG, augmented mean group; CCEMG, common correlated effect mean group

***indicates a 1% level of significance

Table 13 Parallel fluctuations in HEEXP and CO₂e

Province	Year	Quarter	HEEXP (%)	CO ₂ e (%)
Beijing	2002	I	0.03↑	0.485↓
Beijing	2008	II	0.306↑	0.399↓
Tianjin	2003	I	0.498↑	0.266↓
Tianjin	2016	IV	0.002↑	0.078↓
Hebei	2006	I	2.151↑	0.209↓
Hebei	2009	I	0.373↑	0.177↓
Shanxi	2006	I	0.146↑	0.245↓
Shanxi	2013	II	0.093↑	0.117↓
Inner Mongolia	2003	I	0.842↑	1.319↓
Inner Mongolia	2013	I	0.126↑	0.607↓
Liaoning	2000	I	0.881↑	2.189↓
Liaoning	2019	I	0.714↑	0.655↓
Jilin	2012	I	0.070↑	0.261↓
Heilongjiang	2004	IV	1.012↑	0.946↓
Heilongjiang	2016	III	0.187↑	0.188↓
Shanghai	2011	I	0.504↑	0.121↓
Shanghai	2014	I	0.354↑	0.548↓
Jiangsu	2017	II	0.178↑	0.139↓
Jiangsu	2018	I	0.806↑	0.992↓
Zhejiang	2017	III	0.0081↑	0.268↓
Zhejiang	2019	I	0.522↑	0.686↓
Anhui	2004	I	0.832↑	0.303↓
Anhui	2018	I	1.414↑	1.071↓
Fujian	2015	IV	0.357↑	0.183↓
Fujian	2018	II	0.189↑	0.817↓
Jiangxi	2012	I	0.113↑	0.604↓
Jiangxi	2014	I	0.212↑	0.390↓
Shandong	2006	I	0.888↑	0.191↓
Shandong	2019	I	1.136↑	0.133↓
Henan	2012	I	0.744↑	0.317↓
Henan	2015	I	0.055↑	0.184↓
Hubei	2008	I	0.101↑	0.222↓
Hubei	2018	I	2.135↑	1.042↓
Hunan	2004	I	0.650↑	0.168↓
Hunan	2013	II	0.112↑	0.104↓
Guangdong	2013	I	0.472↑	0.137↓
Guangdong	2018	I	0.638↑	1.117↓
Guangxi	2002	I	3.644↑	0.388↓
Guangxi	2015	I	0.080↑	0.444↓
Hainan	2015	IV	1.253↑	0.185↓
Chongqing	2003	II	0.744↑	0.253↓
Chongqing	2013	III	0.449↑	0.131↓
Sichuan	2006	I	0.814↑	0.205↓
Sichuan	2017	II	0.159↑	0.154↓
Guizhou	2004	I	1.6099↑	0.142↓
Guizhou	2010	I	0.795↑	0.211↓
Yunnan	2003	III	0.484↑	0.307↓
Yunnan	2010	I	0.779↑	0.135↓
Xizang	2006	II	0.489↑	0.105↓

Table 13 (continued)

Province	Year	Quarter	HEEXP (%)	CO ₂ e (%)
Xizang	2016	III	0.125↑	0.191↓
Shanxi	2009	I	0.839↑	0.171↓
Shanxi	2019	I	1.722↑	0.763↓
Gansu	2011	I	0.849↑	0.182↓
Gansu	2016	I	0.284↑	0.194↓
Qinghai	2013	I	2.716↑	0.114↓
Qinghai	2017	I	3.029↑	0.379↓
Ningxia	2004	II	0.293↑	0.459↓
Ningxia	2016	I	0.668↑	0.713↓
Xinjiang	2012	I	1.439↑	0.607↓
Xinjiang	2017	II	0.111↑	0.303↓

Thirdly, the members of the green universities actively engage in society-focused programs for environmental publicity, evaluation, and education. Fourthly, the environment becomes an important part of the campus culture, and it is integrated into all campus policies to develop a clean and green campus environment. Gou (2019) added that green campus operations are linked to all areas, including labs, classrooms, transportation, dormitories, and other facilities. Thus, the idea of green campus and green education entails several economic benefits, especially for a massively populated country like China. The GC can help to save energy, water, and other precious resources in China, particularly if the consumption of energy and water among HEIs is higher than that among the residential consumers.

Apart from enabling the generation of new ideas and patents for green production, innovation, technology, and economy, the macro impact of the GC resides in improved efficiency and social fairness in the usage of natural resources. For ecological advantages, all HEIs need to revisit their effects on energy efficiency by transforming their facilities to preserve the environment. Beyond that, the social benefits of the GC include the conversion of students and teachers into conscious and eco-friendly consumers. Thus, the GC holds the potential to reduce deprivation and poverty among regions or provinces, enhance fairness, and expand the sustainable growth concept in Chinese society. All these measures, if implemented correctly, can decrease CO₂-related energy consumption and increase the use of clean technologies across China. Table 13 exhibits the parallel fluctuations in HEEXP and CO₂e.

Second, the long-run coefficients indicated a significant positive linkage between FDI and CO₂e, offering empirical evidence for the acceptance of the PHH in China. A 1% increase in FDI caused a rise in CO₂e by 0.42 (MG), 0.12 (AMG), and 0.34% (CCMG). This result suggested that some cities, provinces, and municipalities in China, with less

stringent regulations, have become pollution havens in an attempt to attract FDI and pollution-intensive industries. This result validated the previous studies conducted for China (Ur Rahman et al. 2019); OECD (Manzoor Ahmad et al. 2020); newly industrialized nations (Destek and Okumus 2019); Cote d'Ivoire (Assamoi et al. 2020); ASEAN (Guzel and Okumus 2020); MINT countries (Balsalobre-Lorente et al. 2019); Pakistan (Nadeem et al. 2020; Naz et al. 2019); MIKTA economies (Bakirtas and Cetin 2017); BRICS (Khan et al. 2020); Arab countries (Abdo et al. 2020); Asian countries (Khan and Ozturk 2020); and European countries (Mert et al. 2019). However, this result contradicts the previous studies conducted for coastal Mediterranean countries (S. Nathaniel et al. 2020); OECD (Ahmad et al. 2019a); Turkey (Mert and Caglar 2020); China (Ayamba et al. 2019; Hao et al. 2020); and Kyoto Annex countries (Mert and Bölük 2016).

Third, the current estimations revealed a positive association between GDP and CO₂e—a 1% increase in GDP led to a rise in CO₂e by 0.44 (MG), 0.75 (AMG), and 0.64% (CCEMG). This result suggested that GDP growth—driven by low energy efficiency and coal consumption—had enhanced CO₂e in China. This result is consistent with the previous findings for India (Dar and Asif 2017); Pakistan (Chandia et al. 2018; Ur Rahman et al. 2019); China (Ahmad et al. 2018a; Mushtaq et al. 2020; Wei 2020; Zhou et al. 2018); the USA (Alola and Alola 2019); Liberia (Moutinho et al. 2020); Qatar (Mrabet et al. 2017); selected 72 countries (Inekwe et al. 2019); developing countries (Wawrzyniak and Doryń 2020); NAFTA and BRIC (Rahman et al. 2019a); SEE countries (Obradović and Lojanica 2017); and Asian economies (Qingquan et al. 2020).

Fourth, the long-term coefficients demonstrated a positive connection between population and CO₂e—a 1% increase in population contributed to a rise in CO₂e by 0.69 (MG), 0.92 (AMG), and 0.68% (CCEMG). This finding implied that although the growing aging populace would lower the rate of future CO₂e, it would also create the need to develop alternative models of economic growth for a smooth transition into a green economy. Nonetheless, this result supported the previous results for China (Khan et al. 2019b; Zhou et al. 2018); Asian economies (Khoshnevis Yazdi and Dariani 2019; Qingquan et al. 2020); developing economies (Martínez-zarzoso et al. 2007); MENA countries (Al-mulali et al. 2013); newly industrialized nations (Sharif Hossain 2011); and the EU nations (Kasman and Duman 2015).

Fifth, the results revealed a positive electricity use-CO₂e nexus, implying that the irresponsible electricity consumption (by educational, residential, and industrial consumers) had significantly enhanced CO₂e in China. This finding points toward the heavy reliance on carbon-intensive energy sources (e.g., coal and oil) for domestic and industrial consumers by the power generation sector. That said, the new energy policies and installed capacity forecast suggest that the

Table 14 Results of the DHPCT

Relationship	W-Stat	Zbar-Stat
EC→CO ₂ e	15.5470***	35.5125***
CO ₂ e→EC	11.0489***	23.6718***
FDI→CO ₂ e	8.90131***	18.0186***
CO ₂ e→FDI	14.9115***	33.8397***
GDP→CO ₂ e	15.3180***	34.9098***
CO ₂ e→GDP	13.8654***	31.0861***
POP→CO ₂ e	16.9784***	39.2807***
CO ₂ e→POP	18.1091***	42.2570***
HEEXP→CO ₂ e	7.11697***	13.3215***
CO ₂ e→HEEXP	12.0309***	26.2569***

Note: CO₂e, carbon dioxide emissions; EC, electricity consumption; FDI, foreign direct investment; GDP, gross domestic product; POP, population; HEEXP, higher education R&D expenditures. *** indicates a 1% level of significance

overdependency on fossil fuels will reduce significantly in the future, thereby decreasing CO₂e. The commercial sector (e.g., tech companies) is also setting the foundations for responsible energy consumption by switching from conventional to renewable energy sources. As some tech companies have started using solar and wind for power generation, other sectors will also follow this campaign to reduce their carbon footprint. This result validates the previous studies conducted for China (Akadiri et al. 2020; Munir and Riaz 2020; Xu et al. 2015; Zhang 2019); Spain (Zarco-Soto et al. 2020); South Asian economies (Munir and Riaz 2019); Bangladesh (Shahbaz et al. 2014); ASEAN countries (Lean and Smyth 2010); Pakistan (Rehman et al. 2019); and BRICS (Haseeb et al. 2019).

Finally, Table 14 exhibits the results of the DHPCT. The causality estimates revealed a bidirectional causality between EC and CO₂e; FDI and CO₂e; GDP and CO₂e; POP and CO₂e; and HEEXP and CO₂e. These results suggested that government policies that target EC, FDI, GDP, POP, and HEEXP have, directly and indirectly, led to an increase or decrease in CO₂e.

Conclusion and policy implications

The main objective of this study was to explore potential long-run connections between the HEEXP and CO₂e for thirty-one provinces in China from 2000(Q1) to 2019(Q4). The panel data were analyzed using the multiple econometric techniques. First, the results of the WECPT, KRCPT, and PCT indicated that a long-term cointegration existed between all the study variables. Second, the MG, AMG, and CCEMG

supported that the HEEXP had disrupted CO₂e, while EC, FDI, POP, and GDP had a positive interaction with CO₂e in the long run. Third, the DHPCT reflected that a two-way causal relationship existed between CO₂e and all other study variables—FDI, EC, GDP, POP, and HEEXP.

The following important implications were drawn from the current findings. First, the current findings assert the need for the policymakers to design specific policies for green education, green campus, and green economy. Chinese government should extend financial support to encourage its academic institutions for developing green patents and conducting research on projects related to energy efficiency, sustainable production, green consumption, and preservation of land, soil, and environment. With the nascent awareness of environmental standards and norms, an extensive capacity building is across all academic institutions to align these institutions with global standards, eco-innovation, and sustainability practices. Second, the current results also require the need for the adjustment of research themes with the national energy and sustainable development plans. For this purpose, the HEEXP policy should be designed in a manner that the rewards, incentives, bonuses, and funding for academic institutions are based on the quality and quantity of eco-related patents and research. These institutions should be directed to develop matrices aligned with national themes and sustainability targets, including but not limited to clean and efficient transport technologies, solar thermal technology, solar cells, wind power, new nuclear power systems, carbon capture and sequestration, clean coal, ecological conservation, grassland development, recycling economy, biofuels, bioproducts, and integrated gasification combined systems.

Third, the acceptance of the PHH in this study has strengthened the previous argument that FDI in developing countries have enhanced dirty technologies. Thus, policymakers are expected to tighten the environmental regulations, ensure that foreign enterprises transfer clean technologies, and improve green investment. Fourth, the positive connection between CO₂e and electricity use calls for not only revisiting the existing energy mix but also asserts the need for devising energy efficiency strategies to curb CO₂e. Policymakers should, therefore, continue to clean and expand the energy mix with more renewables for electricity generation to meet future demand. While encouraging and supporting the commercial sector to deploy solar and wind for power generation, the government should formulate energy efficiency policies for resources management, regardless of its types, i.e., nonrenewable or renewable energy. If inefficiently managed, these resources face the risk of depletion. Thus, the future policies for a green economy should incorporate efficient resources management, solar and wind energy development, technology improvements, carbon-taxing, and green urbanization. Of

particular significance, all these policies should be designed, integrated, and coordinated with multiple stakeholders (i.e., community, government, academia, and administration) for effective execution and results.

Fifth, the current findings concerning the adverse effect of the population on the environment assert the need for developing a responsible and eco-driven aging sector. This argument stems from the fact that a significant majority of the existing population in China is predicted to experience aging, leaving a wide gap in the workforce in the future. While this phenomenon may decrease the level of CO₂e, it necessitates the need policies that guarantee better healthcare, social justice, social security, and other related facilities across all provinces. If this issue is underestimated, the socially deprived and unsatisfied populace may contribute to CO₂e, thereby disrupting the green transformation. Thus, policymakers should devise policies to encourage investments in the aging sector to address the potential future disruption in economic growth. That said, this new sector should be built on the foundations of energy-saving, responsible consumption, social equality, income equality, old-age security, and equal access to quality healthcare for all provinces.

This study has some limitations that open new doors for future research. First, this study had only focused on China. The same model can be used for other developing and developed economies. Second, this study applied linear econometric techniques (MG, AMG, and CCEMG) to explore the relationship between HEEXP and CO₂e. Perhaps, some nonlinear models (e.g., NARDL) can be used to explore the same relationship and variables in a unified framework. Third, the current study has adopted the EKC framework for examining different relationships. Researchers are encouraged to tests the current findings using the STIRPAT framework for new insights.

Author contribution Sun YAWEN: Conceptualization; data curation; formal analysis

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Data availability The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

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Consent for publication Not applicable

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References

- Abbasi MA, Parveen S, Khan S, Kamal MA (2020) Urbanization and energy consumption effects on carbon dioxide emissions: evidence from Asian-8 countries using panel data analysis. *Environ Sci Pollut Res* 27(15):18029–18043. <https://doi.org/10.1007/s11356-020-08262-w>
- Abdo A-B, Li B, Zhang X, Lu J, Rasheed A (2020) Influence of FDI on environmental pollution in selected Arab countries: a spatial econometric analysis perspective. *Environ Sci Pollut Res* 27(22):28222–28246. <https://doi.org/10.1007/s11356-020-08810-4>
- Adebayo TS, Beton Kalmaz D (2021) Determinants of CO₂ emissions: empirical evidence from Egypt. *Environ Ecol Stat* 28:239–262. <https://doi.org/10.1007/s10651-020-00482-0>
- Adeyuyi AO, Awodumi OB (2020) Environmental pollution, energy import, and economic growth: evidence of sustainable growth in South Africa and Nigeria. *Environ Sci Pollut Res* 28:14434–14468. <https://doi.org/10.1007/s11356-020-11446-z>
- Ahmad M, Khattak SI (2020) Is aggregate domestic consumption spending (ADCS) per capita determining CO₂ emissions in South Africa? A new perspective. *Environ Resour Econ* 75(3):529–552. <https://doi.org/10.1007/s10640-019-00398-9>
- Ahmad M, Zhao Z-Y (2018) Empirics on linkages among industrialization, urbanization, energy consumption, CO₂ emissions and economic growth: a heterogeneous panel study of China. *Environ Sci Pollut Res* 25(30):30617–30632. <https://doi.org/10.1007/s11356-018-3054-3>
- Ahmad M, Ur Rahman Z, Hong L, Khan S, Khan Z, Naeem Khan M (2018a) Impact of environmental quality variables and socio-economic factors on human health: empirical evidence from China. *Pollution* 4(4):571–579. <https://doi.org/10.22059/POLL.2018.252214.391>
- Ahmad M, Khan Z, Ur Rahman Z, Khan S (2018b) Does financial development asymmetrically affect CO₂ emissions in China? An application of the nonlinear autoregressive distributed lag (NARDL) model. *Carbon Manag* 9(6):631–644. <https://doi.org/10.1080/17583004.2018.1529998>
- Ahmad M, Khan Z, Rahman ZU, Khattak SI, Khan ZU (2019a) Can innovation shocks determine CO₂ emissions (CO_{2e}) in the OECD economies? A new perspective. *Econ Innov New Technol* 30:89–109. <https://doi.org/10.1080/10438599.2019.1684643>
- Ahmad M, Ul Haq Z, Khan Z, Khattak SI, Ur Rahman Z, Khan S (2019b) Does the inflow of remittances cause environmental degradation? Empirical evidence from China. *Econ Res-Ekon Istraž* 32(1):2099–2121. <https://doi.org/10.1080/1331677X.2019.1642783>
- Ahmad M, Khattak SI, Khan A, Rahman ZU (2020) Innovation, foreign direct investment (FDI), and the energy–pollution–growth nexus in OECD region: a simultaneous equation modeling approach. *Environ Ecol Stat* 27:203–232. <https://doi.org/10.1007/s10651-020-00442-8>
- Ahmad M, Işık C, Jabeen G, Ali T, Ozturk I, Atchike DW (2021a) Heterogeneous links among urban concentration, non-renewable energy use intensity, economic development, and environmental emissions across regional development levels. *Sci Total Environ* 765:144527. <https://doi.org/10.1016/j.scitotenv.2020.144527>
- Ahmad M, Jabeen G, Irfan M, Işık C, Rehman A (2021b) Do inward foreign direct investment and economic development improve local environmental quality: aggregation bias puzzle. *Environ Sci Pollut Res*. <https://doi.org/10.1007/s11356-021-12734-y>
- Ahmad M, Jabeen G, Wu Y (2021c) Heterogeneity of pollution haven/halo hypothesis and environmental Kuznets Curve hypothesis across development levels of Chinese provinces. *J Clean Prod* 285:124898. <https://doi.org/10.1016/j.jclepro.2020.124898>
- Ahmed Z, Nathaniel SP, Shahbaz M (2021) The criticality of information and communication technology and human capital in environmental sustainability: evidence from Latin American and Caribbean countries. *J Clean Prod* 286:125529. <https://doi.org/10.1016/j.jclepro.2020.125529>
- Akadiri SS, Alola AA, Bekun FV, Etokakpan MU (2020) Does electricity consumption and globalization increase pollutant emissions? Implications for environmental sustainability target for China. *Environ Sci Pollut Res* 27(20):25450–25460. <https://doi.org/10.1007/s11356-020-08784-3>
- Akkaya Ş, Hepsag A (2021) Does fuel tax decrease carbon dioxide emissions in Turkey? Evidence from an asymmetric nonlinear cointegration test and error correction model. *Environ Sci Pollut Res*. <https://doi.org/10.1007/s11356-021-12907-9>
- Ali HS, Abdul-Rahim AS, Ribadu MB (2017) Urbanization and carbon dioxide emissions in Singapore: evidence from the ARDL approach. *Environ Sci Pollut Res* 24(2):1967–1974. <https://doi.org/10.1007/s11356-016-7935-z>
- Ali S, Yusop Z, Kaliappan SR, Chin L (2020) Dynamic common correlated effects of trade openness, FDI, and institutional performance on environmental quality: evidence from OIC countries. *Environ Sci Pollut Res* 27(11):11671–11682. <https://doi.org/10.1007/s11356-020-07768-7>
- Al-mulali U, Fereidouni HG, Lee JYM, Sab CNBC (2013) Exploring the relationship between urbanization, energy consumption, and CO₂ emission in MENA countries. *Renew Sust Energ Rev* 23:107–112. <https://doi.org/10.1016/j.rser.2013.02.041>
- Alola AA, Alola AA (2019) Carbon emissions and the trilemma of trade policy, migration policy and health care in the US. *Carbon Manag* 10(2):209–218. <https://doi.org/10.1080/17583004.2019.1577180>
- Anser MK, Khan MA, Nassani AA, Aldakhil AM, Voo XH, Zaman K (2020) Relationship of environment with technological innovation, carbon pricing, renewable energy, and global food production. *Econ Innov New Technol*:1–37. <https://doi.org/10.1080/10438599.2020.1792607>
- Anser MK, Ahmad M, Khan MA, Zaman K, Nassani AA, Askar SE, Abro MMQ, Kabbani A (2021) The role of information and communication technologies in mitigating carbon emissions: evidence from panel quantile regression. *Environ Sci Pollut Res* 28:21065–21084. <https://doi.org/10.1007/s11356-020-12114-y>
- Arshad Z, Robaina M, Shahbaz M, Veloso AB (2020) The effects of deforestation and urbanization on sustainable growth in Asian countries. *Environ Sci Pollut Res* 27(9):10065–10086. <https://doi.org/10.1007/s11356-019-07507-7>
- Asghar MM, Wang Z, Wang B, Zaidi SAH (2020) Nonrenewable energy—environmental and health effects on human capital: empirical evidence from Pakistan. *Environ Sci Pollut Res* 27(3):2630–2646. <https://doi.org/10.1007/s11356-019-06686-7>
- Assamoi GR, Wang S, Liu Y, Gnangoin YTB (2020) Investigating the pollution haven hypothesis in Cote d’Ivoire: evidence from autoregressive distributed lag (ARDL) approach with structural breaks. *Environ Sci Pollut Res* 27(14):16886–16899. <https://doi.org/10.1007/s11356-020-08246-w>
- Ayamba EC, Haibo C, Ibn Musah A-A, Ruth A, Osei-Agyemang A (2019) An empirical model on the impact of foreign direct investment on China’s environmental pollution: analysis based on simultaneous equations. *Environ Sci Pollut Res* 26:1–10. <https://doi.org/10.1007/s11356-019-04991-9>
- Aziz N, Mihardjo LWW, Sharif A, Jermisittiparsert K (2020) The role of tourism and renewable energy in testing the environmental Kuznets curve in the BRICS countries: fresh evidence from methods of moments quantile regression. *Environ Sci Pollut Res* 27:39427–39441. <https://doi.org/10.1007/s11356-020-10011-y>
- Baek J (2016) A new look at the FDI–income–energy–environment nexus: dynamic panel data analysis of ASEAN. *Energy Policy* 91:22–27. <https://doi.org/10.1016/j.enpol.2015.12.045>

- Bakirtas I, Cetin MA (2017) Revisiting the environmental Kuznets curve and pollution haven hypotheses: MIKTA sample. *Environ Sci Pollut Res* 24(22):18273–18283. <https://doi.org/10.1007/s11356-017-9462-y>
- Baloch MA, Danish, Meng F, Zhang J, Xu Z (2018) Financial instability and CO2 emissions: the case of Saudi Arabia. *Environ Sci Pollut Res* 25(26):26030–26045. <https://doi.org/10.1007/s11356-018-2654-2>
- Balsalobre-Lorente D, Shahbaz M, Roubaud D, Farhani S (2018) How economic growth, renewable electricity and natural resources contribute to CO2 emissions? *Energy Policy* 113:356–367. <https://doi.org/10.1016/j.enpol.2017.10.050>
- Balsalobre-Lorente D, Gokmenoglu KK, Taspinar N, Cantos-Cantos JM (2019) An approach to the pollution haven and pollution halo hypotheses in MINT countries. *Environ Sci Pollut Res* 26(22):23010–23026. <https://doi.org/10.1007/s11356-019-05446-x>
- Balsalobre-Lorente D, Driha OM, Shahbaz M (2020) Strategies in sustainable tourism, economic growth and clean energy. Springer Nature, Switzerland. <https://books.google.com/books?id=cx8MEAAQBAJ>
- Bélaïd F, Youssef M (2017) Environmental degradation, renewable and non-renewable electricity consumption, and economic growth: assessing the evidence from Algeria. *Energy Policy* 102:277–287. <https://doi.org/10.1016/j.enpol.2016.12.012>
- Ben Jebli M, Ben Youssef S (2019) Combustible renewables and waste consumption, agriculture, CO₂ emissions and economic growth in Brazil. *Carbon Manag* 10(3):309–321. <https://doi.org/10.1080/17583004.2019.1605482>
- Cassidy Y, Wójcik D (2018) International financial centres after the global financial crisis and Brexit. OUP, Oxford. <https://books.google.co.il/books?id=ig5jDwAAQBAJ>
- Centre OD, Kiichiro F, Masahiro KGPM, Alexandra TD (2005) Development centre studies policy coherence towards East Asia development challenges for OECD countries: development challenges for OECD countries. OECD, Japan
- Ceyhan GÇ (2019). Handbook of research on the applications of international transportation and logistics for world trade. IGI Global, Hershey
- Chandia KE, Gul I, Aziz S, Sarwar B, Zulfiqar S (2018) An analysis of the association among carbon dioxide emissions, energy consumption and economic performance: an econometric model. *Carbon Manag* 9(3):227–241. <https://doi.org/10.1080/17583004.2018.1457930>
- Chen T, Gozgor G, Koo CK, Lau CKM (2020) Does international cooperation affect CO2 emissions? Evidence from OECD countries. *Environ Sci Pollut Res* 27(8):8548–8556. <https://doi.org/10.1007/s11356-019-07324-y>
- Chung JH (2015) Assessing China's power. Palgrave Macmillan, US <https://books.google.co.il/books?id=ImreCgAAQBAJ>
- Clemente J, Montañés A, Reyes M (1998) Testing for a unit root in variables with a double change in the mean. *Econ Lett* 59(2):175–182. [https://doi.org/10.1016/s0165-1765\(98\)00052-4](https://doi.org/10.1016/s0165-1765(98)00052-4)
- Cowan WN, Chang T, Inglesi-Lotz R, Gupta R (2014) The nexus of electricity consumption, economic growth and CO2 emissions in the BRICS countries. *Energy Policy* 66:359–368. <https://doi.org/10.1016/J.ENPOL.2013.10.081>
- Dar JA, Asif M (2017) Is financial development good for carbon mitigation in India? A regime shift-based cointegration analysis. *Carbon Manag* 8(5–6):435–443. <https://doi.org/10.1080/17583004.2017.1396841>
- Destek MA, Okumus I (2019) Does pollution haven hypothesis hold in newly industrialized countries? Evidence from ecological footprint. *Environ Sci Pollut Res* 26(23):23689–23695. <https://doi.org/10.1007/s11356-019-05614-z>
- Dietz T, Rosa EA (1997) Effects of population and affluence on CO2 emissions. *Proc Natl Acad Sci U S A* 94(1):175–179. <https://doi.org/10.1073/pnas.94.1.175>
- Du J, Sun Y (2021) The nonlinear impact of fiscal decentralization on carbon emissions: from the perspective of biased technological progress. *Environ Sci Pollut Res*. <https://doi.org/10.1007/s11356-021-12833-w>
- Dumitrescu E-I, Hurlin C (2012) Testing for Granger non-causality in heterogeneous panels. *Econ Model* 29(4):1450–1460. <https://doi.org/10.1016/J.ECONMOD.2012.02.014>
- Eberhardt M, Bond S (2009) Cross-section dependence in nonstationary panel models: a novel estimator. MPRA Paper 17692, University Library of Munich, Germany
- El Menyari Y (2021) The effects of international tourism, electricity consumption, and economic growth on CO2 emissions in North Africa. *Environ Sci Pollut Res*. <https://doi.org/10.1007/s11356-021-13818-5>
- Consumption-based carbon emissions and trade nexus: Evidence from nine oil exporting countries. *Energy Econ* 89:104806. <https://doi.org/10.1016/j.eneco.2020.104806>
- Etokakpan MU, Osundina OA, Bekun FV, Sarkodie SA (2020) Rethinking electricity consumption and economic growth nexus in Turkey: environmental pros and cons. *Environ Sci Pollut Res* 27(31):39222–39240. <https://doi.org/10.1007/s11356-020-09612-4>
- Godil DI, Sharif A, Afshan S, Yousuf A, Khan SAR (2020) The asymmetric role of freight and passenger transportation in testing EKC in the US economy: evidence from QARDL approach. *Environ Sci Pollut Res* 27(24):30108–30117. <https://doi.org/10.1007/s11356-020-09299-7>
- Gou Z (2019) Green building in developing countries: policy, strategy and technology. Springer Nature, Switzerland
- Gregory AW, Hansen BE (1996) Residual-based tests for cointegration in models with regime shifts. *J Econ* 70(1):99–126. [https://doi.org/10.1016/0304-4076\(96\)01685-7](https://doi.org/10.1016/0304-4076(96)01685-7)
- Grossman G, Krueger A (1991) Environmental impacts of a North American free trade agreement. NBER Working Papers 3914, National Bureau of Economic Research, Inc. Available at <https://ideas.repec.org/p/nbr/nberwo/3914.html>
- Guo Y, You W, Lee CC (2020) CO₂ emissions, income inequality, and country risk: some international evidence. *Environ Sci Pollut Res*. <https://doi.org/10.1007/s11356-020-09501-w>
- Guzel AE, Okumus İ (2020) Revisiting the pollution haven hypothesis in ASEAN-5 countries: new insights from panel data analysis. *Environ Sci Pollut Res* 27(15):18157–18167. <https://doi.org/10.1007/s11356-020-08317-y>
- Hao Y, Wu Y, Wu H, Ren S (2020) How do FDI and technical innovation affect environmental quality? Evidence from China. *Environ Sci Pollut Res* 27:7835–7850
- Harper S (2013) Population-environment interactions: European migration, population composition and climate change. *Environ Resour Econ* 55(4):525–541. <https://doi.org/10.1007/s10640-013-9677-4>
- Haseeb A, Xia E, Saud S, Ahmad A, Khurshid H (2019) Does information and communication technologies improve environmental quality in the era of globalization? An empirical analysis. *Environ Sci Pollut Res* 26(9):8594–8608. <https://doi.org/10.1007/s11356-019-04296-x>
- Heshmati A (2019). Economic transformation for poverty reduction in Africa: a multidimensional approach. Routledge, New York
- Hu Y, Liang W, Tang Y (2017) Evaluating research efficiency of Chinese universities. Springer, Singapore <https://books.google.co.il/books?id=dhNhDgAAQBAJ>
- Hussain I, Rehman A (2021) Exploring the dynamic interaction of CO2 emission on population growth, foreign investment, and renewable energy by employing ARDL bounds testing approach. *Environ Sci Pollut Res*. <https://doi.org/10.1007/s11356-021-13502-8>
- Iheonu CO, Anyanwu OC, Odo OK, Nathaniel SP (2021) Does economic growth, international trade, and urbanization uphold environmental

- sustainability in sub-Saharan Africa? Insights from quantile and causality procedures. *Environ Sci Pollut Res* 28:28222–28233. <https://doi.org/10.1007/s11356-021-12539-z>
- Inekwe J, Maharaj EA, Bhattacharya M (2019) Drivers of carbon dioxide emissions: an empirical investigation using hierarchical and non-hierarchical clustering methods. *Environ Ecol Stat* 27:1–40. <https://doi.org/10.1007/s10651-019-00433-4>
- Isiksal AZ (2021) Testing the effect of sustainable energy and military expenses on environmental degradation: evidence from the states with the highest military expenses. *Environ Sci Pollut Res* 28: 20487–20498. <https://doi.org/10.1007/s11356-020-11735-7>
- Isiksal AZ, Samour A, Resatoglu NG (2019) Testing the impact of real interest rate, income, and energy consumption on Turkey's CO2 emissions. *Environ Sci Pollut Res* 26(20):20219–20231. <https://doi.org/10.1007/s11356-019-04987-5>
- Jiang P, Yang H, Ma X (2019) Coal production and consumption analysis, and forecasting of related carbon emission: evidence from China. *Carbon Manag* 10(2):189–208. <https://doi.org/10.1080/17583004.2019.1577177>
- Jiang Q, Khattak SI, Ahmad M, Lin P (2021a) Mitigation pathways to sustainable production and consumption: examining the impact of commercial policy on carbon dioxide emissions in Australia. *Sustain Prod Consum* 25:390–403. <https://doi.org/10.1016/j.spc.2020.11.016>
- Jiang Q, Khattak SI, Rahman ZU (2021b) Measuring the simultaneous effects of electricity consumption and production on carbon dioxide emissions (CO2e) in China: new evidence from an EKC-based assessment. *Energy* 229:120616. <https://doi.org/10.1016/j.energy.2021.120616>
- Kao C (1999) Spurious regression and residual-based tests for cointegration in panel data. *J Econ* 90(1):1–44. [https://doi.org/10.1016/S0304-4076\(98\)00023-2](https://doi.org/10.1016/S0304-4076(98)00023-2)
- Kasman A, Duman YS (2015) CO2 emissions, economic growth, energy consumption, trade and urbanization in new EU member and candidate countries: a panel data analysis. *Econ Model* 44:97–103. <https://doi.org/10.1016/j.econmod.2014.10.022>
- Khan MA, Ozturk I (2020) Examining foreign direct investment and environmental pollution linkage in Asia. *Environ Sci Pollut Res* 27(7):7244–7255. <https://doi.org/10.1007/s11356-019-07387-x>
- Khan A, Chenggang Y, Hussain J, Bano S (2019a) Does energy consumption, financial development, and investment contribute to ecological footprints in BRI regions? *Environ Sci Pollut Res* 26:36952–36966. <https://doi.org/10.1007/s11356-019-06772-w>
- Khan Z, Shahbaz M, Ahmad M, Rabbi F, Siqun Y (2019b) Total retail goods consumption, industry structure, urban population growth and pollution intensity: an application of panel data analysis for China. *Environ Sci Pollut Res* 26:32224–32242. <https://doi.org/10.1007/s11356-019-06326-0>
- Khan ZU, Ahmad M, Khan A (2020) On the remittances-environment led hypothesis: empirical evidence from BRICS economies. *Environ Sci Pollut Res* 27(14):16460–16471. <https://doi.org/10.1007/s11356-020-07999-8>
- Khattak SI, Ahmad M, Khan S, Li H (2021) The cyclical and asymmetrical impact of green and sustainable technology research (GSTR) on carbon dioxide emissions (CO2) in BRICS economies: role of renewable energy consumption, foreign direct investment, and exports. <https://doi.org/10.21203/RS.3.RS-280754/V1>
- Khoshnevis Yazdi S, Dariani AG (2019) CO2 emissions, urbanisation and economic growth: evidence from Asian countries. *Econ Res-Ekon Istraž* 32(1):510–530. <https://doi.org/10.1080/1331677X.2018.1556107>
- Lardy NR (2012) Sustaining China's economic growth after the global financial crisis. Peterson Institute for International Economics, Washington
- Lean HH, Smyth R (2010) CO2 emissions, electricity consumption and output in ASEAN. *Appl Energy* 87(6):1858–1864. <https://doi.org/10.1016/j.apenergy.2010.02.003>
- Lee JCK, Efrid R (2014) Schooling for sustainable development across the Pacific. Springer, Netherlands <https://books.google.co.il/books?id=6HMBAAQBAJ>
- Li Q, Wu S, Lei Y, Li S, Li L (2019) China's provincial CO2 emissions and interprovincial transfer caused by investment demand. *Environ Sci Pollut Res* 26(1):312–325. <https://doi.org/10.1007/s11356-018-3332-0>
- Li H, Khattak SI, Ahmad M (2021) Measuring the impact of higher education on environmental pollution: new evidence from thirty provinces in China. *Environ Ecol Stat* 28:1–31. <https://doi.org/10.1007/s10651-020-00480-2>
- Liddle B (2013) Population, affluence, and environmental impact across development: Evidence from panel cointegration modeling. *Environ Model Softw* 40:255–266. <https://doi.org/10.1016/j.envsoft.2012.10.002>
- Liu X, Strangway DW, Feng Z (2012) Environmental innovation in China. WIT Press, Southampton
- Mao Y (2018) Does democratic transition reduce carbon intensity? Evidence from Indonesia using the synthetic control method. *Environ Sci Pollut Res* 25(20):19908–19917. <https://doi.org/10.1007/s11356-018-2165-1>
- Martínez-zarzoso I, Bengochá-Martínez-zarzoso I, Bengochea-moranco A, Morales-lage R, Lavoie NDI, Eni F, Mattei E (2007) The impact of population on CO2 emissions: evidence from European countries. *Environ Resour Econ* (38):497–512
- Meirun T, Mihadjo LWW, Haseeb M, Khan SAR, Jermisittiparsert K (2021) The dynamics effect of green technology innovation on economic growth and CO2 emission in Singapore: new evidence from bootstrap ARDL approach. *Environ Sci Pollut Res* 28(4):4184–4194. <https://doi.org/10.1007/s11356-020-10760-w>
- Melnik LG, Kubatko OV, Kubatko OV (2016) Were Ukrainian regions too different to start interregional confrontation: economic, social and ecological convergence aspects? *Econ Res-Ekon Istraž* 29(1): 573–582. <https://doi.org/10.1080/1331677X.2016.1174387>
- Mert M, Bölük G (2016) Do foreign direct investment and renewable energy consumption affect the CO2 emissions? New evidence from a panel ARDL approach to Kyoto Annex countries. *Environ Sci Pollut Res* 23(21):21669–21681. <https://doi.org/10.1007/s11356-016-7413-7>
- Mert M, Çağlar AE (2020) Testing pollution haven and pollution halo hypotheses for Turkey: a new perspective. *Environ Sci Pollut Res* 27:32933–32943. <https://doi.org/10.1007/s11356-020-09469-7>
- Mert M, Bölük G, Çağlar AE (2019) Interrelationships among foreign direct investments, renewable energy, and CO2 emissions for different European country groups: a panel ARDL approach. *Environ Sci Pollut Res* 26:21495–21510. <https://doi.org/10.1007/s11356-019-05415-4>
- Morgan WJ, Gu Q, Li F (2017) Handbook of education in china. Edward Elgar Publishing, Northampton
- Morrison WM (2010). China's economic conditions. DIANE Publishing Corporation, Washington, D.C
- Moutinho V, Madaleno M, Bento JP (2020) Cointegration and causality: considering Iberian economic activity sectors to test the environmental Kuznets curve hypothesis. *Environ Ecol Stat* 27(2):363–413. <https://doi.org/10.1007/s10651-020-00449-1>
- Mrabet Z, AlSamara M, Hezam Jarallah S (2017) The impact of economic development on environmental degradation in Qatar. *Environ Ecol Stat* 24(1):7–38. <https://doi.org/10.1007/s10651-016-0359-6>
- Munir K, Riaz N (2019) Energy consumption and environmental quality in South Asia: evidence from panel non-linear ARDL. *Environ Sci Pollut Res* 26(28):29307–29315. <https://doi.org/10.1007/s11356-019-06116-8>

- Munir K, Riaz N (2020) Asymmetric impact of energy consumption on environmental degradation: evidence from Australia, China, and USA. *Environ Sci Pollut Res* 27(11):11749–11759. <https://doi.org/10.1007/s11356-020-07777-6>
- Murshed M, Nurmakhanova M, Elheddadi M, Ahmed R (2020) Value addition in the services sector and its heterogeneous impacts on CO2 emissions: revisiting the EKC hypothesis for the OPEC using panel spatial estimation techniques. *Environ Sci Pollut Res* 27:1–23. <https://doi.org/10.1007/s11356-020-09593-4>
- Mushtaq A, Chen Z, Din NU, Ahmad B, Zhang X (2020) Income inequality, innovation and carbon emission: perspectives on sustainable growth. *Econ Res-Ekon Istraž* 33(1):769–787. <https://doi.org/10.1080/1331677X.2020.1734855>
- Nadeem AM, Ali T, Khan MTI, Guo Z (2020) Relationship between inward FDI and environmental degradation for Pakistan: an exploration of pollution haven hypothesis through ARDL approach. *Environ Sci Pollut Res* 27(13):15407–15425. <https://doi.org/10.1007/s11356-020-08083-x>
- Nathaniel SP (2020) Modelling urbanization, trade flow, economic growth and energy consumption with regards to the environment in Nigeria. *GeoJournal* 85(6):1499–1513. <https://doi.org/10.1007/s10708-019-10034-0>
- Nathaniel SP (2021) Environmental degradation in ASEAN: assessing the criticality of natural resources abundance, economic growth and human capital. *Environ Sci Pollut Res* 28(17):21766–21778. <https://doi.org/10.1007/s11356-020-12034-x>
- Nathaniel SP, Adeleye N (2021) Environmental preservation amidst carbon emissions, energy consumption, and urbanization in selected african countries: Implication for sustainability. *J Clean Prod* 285: 125409. <https://doi.org/10.1016/j.jclepro.2020.125409>
- Nathaniel SP, Iheonu CO (2019) Carbon dioxide abatement in Africa: the role of renewable and non-renewable energy consumption. *Sci Total Environ* 679:337–345. <https://doi.org/10.1016/J.SCITOTENV.2019.05.011>
- Nathaniel S, Agueboh E, Iheonu C, Sharma G, Shah M (2020) Energy consumption, FDI, and urbanization linkage in coastal Mediterranean countries: re-assessing the pollution haven hypothesis. *Environ Sci Pollut Res* 27:35474–35487. <https://doi.org/10.1007/s11356-020-09521-6>
- Nathaniel SP, Nwulu N, Bekun F (2021a) Natural resource, globalization, urbanization, human capital, and environmental degradation in Latin American and Caribbean countries. *Environ Sci Pollut Res* 28(5): 6207–6221. <https://doi.org/10.1007/s11356-020-10850-9>
- Nathaniel SP, Alam MS, Murshed M, Mahmood H, Ahmad P (2021b) The roles of nuclear energy, renewable energy, and economic growth in the abatement of carbon dioxide emissions in the G7 countries. *Environ Sci Pollut Res*. <https://doi.org/10.1007/s11356-021-13728-6>
- Nathaniel SP, Barua S, Ahmed Z (2021c) What drives ecological footprint in top ten tourist destinations? Evidence from advanced panel techniques. *Environ Sci Pollut Res*. <https://doi.org/10.1007/s11356-021-13389-5>
- Nathaniel SP, Murshed M, Bassim M (2021d) The nexus between economic growth, energy use, international trade and ecological footprints: the role of environmental regulations in N11 countries. *Energy, Ecology and Environment*. <https://doi.org/10.1007/s40974-020-00205-y>
- Nathaniel SP, Yalçiner K, Bekun FV (2021e) Assessing the environmental sustainability corridor: linking natural resources, renewable energy, human capital, and ecological footprint in BRICS. *Res Policy* 70:101924. <https://doi.org/10.1016/j.resourpol.2020.101924>
- National Bureau of Statistics. (2019). China energy statistical yearly book. http://www.stats.gov.cn/tjsj/tjcbw/201806/t20180612_1604117.html
- Naz S, Sultan R, Zaman K, Aldakhil AM, Nassani AA, Abro MMQ (2019) Moderating and mediating role of renewable energy consumption, FDI inflows, and economic growth on carbon dioxide emissions: evidence from robust least square estimator. *Environ Sci Pollut Res* 26(3):2806–2819. <https://doi.org/10.1007/s11356-018-3837-6>
- Obradović S, Lojanica N (2017) Energy use, CO2 emissions and economic growth – causality on a sample of SEE countries. *Econ Res-Ekon Istraž* 30(1):511–526. <https://doi.org/10.1080/1331677X.2017.1305785>
- Ou X, Xiaoyu Y, Zhang X (2011) Life-cycle energy consumption and greenhouse gas emissions for electricity generation and supply in China. *Appl Energy* 88(1):289–297. <https://doi.org/10.1016/j.apenergy.2010.05.010>
- Özcan B, Öztürk I (2019) Environmental Kuznets curve (EKC): a manual. Academic Press, London
- Pedroni P (2004) Panel cointegration: asymptotic and finite sample properties of pooled time series tests with an application to the PPP hypothesis. *Economet Theor* 20(03):597–625. <https://doi.org/10.1017/S0266466604203073>
- Pesaran MH (2003) A simple panel unit root test in the presence of cross section dependence. Cambridge Working Papers in Economics 0346, Faculty of Economics, University of Cambridge. Available at <https://ideas.repec.org/p/cam/camdae/0346.html>
- Pesaran MH (2006) Estimation and inference in large heterogeneous panels with a multifactor error structure. *Econometrica* 74:967–1012. <https://doi.org/10.1111/j.1468-0262.2006.00692.x>
- Pesaran MH (2007) A simple panel unit root test in the presence of cross-section dependence. *J Appl Econ* 22(2):265–312. <https://doi.org/10.1002/jae.951>
- Pesaran MH (2015) Testing weak cross-sectional dependence in large panels testing weak cross-sectional dependence in large panels. *Econ Rev* 34:1089–1117. <https://doi.org/10.1080/07474938.2014.956623>
- Pesaran MH, Smith R (1995) Estimating long-run relationships from dynamic heterogeneous panels. *J Econ* 68(1):79–113. [https://doi.org/10.1016/0304-4076\(94\)01644-F](https://doi.org/10.1016/0304-4076(94)01644-F)
- Pesaran MH, Yamagata T (2008) Testing slope homogeneity in large panels. *J Econ* 142(1):50–93. <https://doi.org/10.1016/J.JECONOM.2007.05.010>
- Qingquan J, Khattak SI, Ahmad M, Ping L (2020) A new approach to environmental sustainability: assessing the impact of monetary policy on CO 2 emissions in Asian economies. *Sustain Dev* 28:1331–1346. <https://doi.org/10.1002/sd.2087>
- Raggad B (2018) Carbon dioxide emissions, economic growth, energy use, and urbanization in Saudi Arabia: evidence from the ARDL approach and impulse saturation break tests. *Environ Sci Pollut Res* 25(15):14882–14898
- Rahman ZU, Cai H, Khattak SI, Hasan MM (2019a) Energy production-income-carbon emissions nexus in the perspective of N.A.F.T.A. and B.R.I.C. nations: a dynamic panel data approach. *Econ Res-Ekon Istraž* 32(1):3378–3391. <https://doi.org/10.1080/1331677X.2019.1660201>
- Rahman, Z. U., Chongbo, W., Ahmad, M. (2019b). An (a)symmetric analysis of the pollution haven hypothesis in the context of Pakistan: a non-linear approach. *Carbon Manag*, (0), 1–13. <https://doi.org/10.1080/17583004.2019.1577179>, 10
- Raza SA, Shah SH, Yousufi SQ (2021) The impact of public-private partnerships investment in energy on carbon emissions: evidence from nonparametric causality-in-quantiles. *Environ Sci Pollut Res* 28:23182–23192. <https://doi.org/10.1007/s11356-020-12306-6>
- Rehman A, Rauf A, Ahmad M, Chandio AA, Deyuan Z (2019) The effect of carbon dioxide emission and the consumption of electrical energy, fossil fuel energy, and renewable energy, on economic performance: evidence from Pakistan. *Environ Sci Pollut Res* 26(21): 21760–21773. <https://doi.org/10.1007/s11356-019-05550-y>

- Ren Y-S, Ma C-Q, Apergis N, Sharp B (2021) Responses of carbon emissions to corruption across Chinese provinces. *Energy Econ* 98:105241. <https://doi.org/10.1016/j.eneco.2021.105241>
- Salahuddin M, Alam K, Ozturk I, Sohag K (2018) The effects of electricity consumption, economic growth, financial development and foreign direct investment on CO₂ emissions in Kuwait. *Renew Sust Energ Rev* 81:2002–2010. <https://doi.org/10.1016/j.rser.2017.06.009>
- Salahuddin M, Ali MI, Vink N, Gow J (2019) The effects of urbanization and globalization on CO₂ emissions: evidence from the sub-Saharan Africa (SSA) countries. *Environ Sci Pollut Res* 26(3):2699–2709. <https://doi.org/10.1007/s11356-018-3790-4>
- Sbia R, Shahbaz M, Hamdi H (2014) A contribution of foreign direct investment, clean energy, trade openness, carbon emissions and economic growth to energy demand in UAE. *Econ Model* 36:191–197. <https://doi.org/10.1016/j.econmod.2013.09.047>
- Shahbaz M, Salah Uddin G, Ur Rehman I, Imran K (2014) Industrialization, electricity consumption and CO₂ emissions in Bangladesh. *Renew Sust Energ Rev* 31:575–586. <https://doi.org/10.1016/j.rser.2013.12.028>
- Shahbaz M, Van Hoang TH, Mahalik MK, Roubaud D (2017) Energy consumption, financial development and economic growth in India: new evidence from a nonlinear and asymmetric analysis. *Energy Econ* 63:199–212. <https://doi.org/10.1016/j.eneco.2017.01.023>
- Sharif Hossain M (2011) Panel estimation for CO₂ emissions, energy consumption, economic growth, trade openness and urbanization of newly industrialized countries. *Energy Policy* 39(11):6991–6999. <https://doi.org/10.1016/j.enpol.2011.07.042>
- Sharif A, Afshan S, Chrea S, Amel A, Khan SAR (2020) The role of tourism, transportation and globalization in testing environmental Kuznets curve in Malaysia: new insights from quantile ARDL approach. *Environ Sci Pollut Res* 27(20):25494–25509. <https://doi.org/10.1007/s11356-020-08782-5>
- Shi A (2003) The impact of population pressure on global carbon dioxide emissions, 1975–1996: evidence from pooled cross-country data. *Ecol Econ* 44(1):29–42. [https://doi.org/10.1016/S0921-8009\(02\)00223-9](https://doi.org/10.1016/S0921-8009(02)00223-9)
- Sohail MT, Ullah S, Majeed MT, Usman A, Andlib Z (2021) The shadow economy in South Asia: dynamic effects on clean energy consumption and environmental pollution. *Environ Sci Pollut Res* 28:29265–29275. <https://doi.org/10.1007/s11356-021-12690-7>
- Solarin SA, Nathaniel SP, Bekun FV, Okunola AM, Alhassan A (2021) Towards achieving environmental sustainability: environmental quality versus economic growth in a developing economy on ecological footprint via dynamic simulations of ARDL. *Environ Sci Pollut Res* 28(14):17942–17959. <https://doi.org/10.1007/s11356-020-11637-8>
- Tan H, Chen S, Shi Q, Wang L (2014) Development of green campus in China. *J Clean Prod* 64:646–653. <https://doi.org/10.1016/j.jclepro.2013.10.019>
- Uddin MMM (2021) Revisiting the impacts of economic growth on environmental degradation: new evidence from 115 countries. *Environ Ecol Stat* 28(1):153–185. <https://doi.org/10.1007/s10651-020-00479-9>
- Ullah S, Ozturk I, Usman A, Majeed MT, Akhtar P (2020) On the asymmetric effects of premature deindustrialization on CO₂ emissions: evidence from Pakistan. *Environ Sci Pollut Res* 27(12):13692–13702. <https://doi.org/10.1007/s11356-020-07931-0>
- Ur Rahman Z, Chongbo W, Ahmad M (2019) An (a)symmetric analysis of the pollution haven hypothesis in the context of Pakistan: a non-linear approach. *Carbon Manag* 10(3):227–239. <https://doi.org/10.1080/17583004.2019.1577179>
- Vo XV, Zaman K (2020) Relationship between energy demand, financial development, and carbon emissions in a panel of 101 countries: “go the extra mile” for sustainable development. *Environ Sci Pollut Res* 27(18):23356–23363. <https://doi.org/10.1007/s11356-020-08933-8>
- Wawrzyniak D, Doryń W (2020) Does the quality of institutions modify the economic growth-carbon dioxide emissions nexus? Evidence from a group of emerging and developing countries. *Econ Res-Ekon Istraž* 33(1):124–144. <https://doi.org/10.1080/1331677X.2019.1708770>
- Wei, L. (2020). EKC test study on the relationship between carbon dioxide emission and regional economic growth. *Carbon Manag*, (0), 1–11. <https://doi.org/10.1080/17583004.2020.1768776>, 11
- Wendt K, Söder I, Leppälähti A (2015) A guide to understanding higher education R&D statistics in the Nordic countries. Nordic Institute for Studies in Innovation, Research and Education (NIFU) Working Paper No. 9/2015. Available at <http://hdl.handle.net/11250/282893>
- Westerlund J (2007) Testing for error correction in panel data. *Oxf Bull Econ Stat* 69(6):709–748. <https://doi.org/10.1111/j.1468-0084.2007.00477.x>
- Wong J, Zheng Y (2004) The SARS epidemic: challenges to China’s 1568 crisis management. World Scientific, Singapore
- Xiaosan Z, Qingquan J, Shoukat Iqbal K, Manzoor A, Zia Ur R (2021) Achieving sustainability and energy efficiency goals: assessing the impact of hydroelectric and renewable electricity generation on carbon dioxide emission in China. *Energy Policy* 155:112332. <https://doi.org/10.1016/j.enpol.2021.112332>
- Xu C, Hong J, Ren Y, Wang Q, Yuan X (2015) Approaches for controlling air pollutants and their environmental impacts generated from coal-based electricity generation in China. *Environ Sci Pollut Res* 22(16):12384–12395. <https://doi.org/10.1007/s11356-015-4539-y>
- Yorucu V, Varoglu DE (2020) Empirical investigation of relationships between energy consumption, industrial production, CO₂ emissions, and economic growth: the case of small island states. *Environ Sci Pollut Res* 27:14228–14236. <https://doi.org/10.1007/s11356-020-07838-w>
- Zarco-Soto IM, Zarco-Periñán PJ, Sánchez-Durán R (2020) Influence of climate on energy consumption and CO₂ emissions: the case of Spain. *Environ Sci Pollut Res* 27(13):15645–15662. <https://doi.org/10.1007/s11356-020-08079-7>
- Zhang H (2019) Effects of electricity consumption on carbon intensity across Chinese manufacturing sectors. *Environ Sci Pollut Res* 26(26):27414–27434. <https://doi.org/10.1007/s11356-019-05955-9>
- Zhou W y, Yang W l, Wan W x, Zhang J, Zhou W, Yang H s, Yang H, Xiao H, Deng S h, Shen F, Wang Y j (2018) The influences of industrial gross domestic product, urbanization rate, environmental investment, and coal consumption on industrial air pollutant emission in China. *Environ Ecol Stat* 25(4):429–442. <https://doi.org/10.1007/s10651-018-0412-8>
- Zhu H, Xia H, Guo Y, Peng C (2018) The heterogeneous effects of urbanization and income inequality on CO₂ emissions in BRICS economies: evidence from panel quantile regression. *Environ Sci Pollut Res* 25(17):17176–17193. <https://doi.org/10.1007/s11356-018-1900-y>

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