Environmental Science and Pollution Research (2022) 29:23779–23793
https://doi.org/10.1007/s11356-021-17261-4

RESEARCH ARTICLE

Determinants of ecological footprint in OCED countries: do environmental-related technologies reduce environmental degradation?

Lan Khanh Chu[1]

Received: 5 August 2021 / Accepted: 25 October 2021 / Published online: 23 November 2021

Abstract
The world is in a clash between the perspectives of economic expansion and sustainable environment. The high pace of technological progress opens space for fostering economic growth but at the same time, it creates a big dilemma for humans in protecting the environmental quality. The environmentally specific technologies are expected to help human beings to achieve dual objectives of economic prosperity and environmental sustainability. Despite its importance, attention to the role of environmental-related technologies in reducing environmental degradation is limited. This paper, therefore, intends to discover the impact of environmental-related technologies on the ecological footprint for 20 OECD from 1990 to 2015. The results endorse a long-run relationship between ecological footprint and green technologies, renewable energy, international trade, energy intensity, and real income. Environmental-related technologies and renewable energy consumption are found to be impetuous to sustainable development. The study provides relevant implications for policymakers to support the development and adoption of green technologies.

Keywords CS-ARDL · Ecological footprint · Environmental-related technologies · OECD countries · Panel data

Introduction

Human history indicates that all industrial revolutions, from the first to the fourth, are related to the adoption of creative and destructive technologies for efficient production and then, for more responsible consumption. The ongoing Fourth Industrial Revolution, characterized by advanced manufacturing and distributing models, has been changing the world dramatically (Cheng et al. 2021; Ikram et al. 2021). In the environmental aspect, such technological advancements are expected to transform the traditional methods of natural resource exploitation and emissions management to more efficient and cleaner ones (An et al. 2021; Dhanwani et al. 2021; Khan et al. 2021; Zhang and Li 2020). Therefore, the world has made a strong effort to promote the achievements of the Fourth Industrial Revolution to realize higher economic growth while still sustaining environmental quality (Bilgili et al. 2021).

At the same time, environmental degradation has been one of the biggest challenges for humans. Nature is being changed and destroyed at an unprecedented in history, threatening human well-being. On the one hand, many side effects of the industrial revolution have been proved unpreventable and irreversible. On the other hand, the integration of the industrial revolution into environmental management and protection is potential for promoting de-carbonization, bio-diversity conservation, food and water security, to name a few (Shao et al. 2021). On an empirical aspect, while several studies indicate the detrimental effects of innovation on environmental quality (Danish et al. 2018; Kocak and Ulucak 2019; Park et al. 2018), most claim that innovation minimizes the harmful environmental impacts of human activities. However, the majority of studies attempt to explore this relationship by relying on the overall innovation (Chu and Hoang 2021; Khattak et al. 2020). To have a precise conclusion, the innovation used in such research should be environmentally specific. According to Hussain et al. (2020), environmental sustainability could be realized with environmental-related technologies. There are some

Responsible Editor: Ilhan Ozturk

✉ Lan Khanh Chu
lanck@hvnh.edu.vn

[1] Banking Research Institution, Vietnam Banking Academy, Hanoi, Vietnam

channels through which environmental technologies can minimize the pollution generated from production and consumption (Ahmed 2020). For example, advanced technologies can increase the efficiency of existing energy sources (significantly reduce the amount of energy needed for producing a unit of good) or they can promote the development and adoption of new cleaner energy sources (solar, wind, hydro, and tidal). In addition, some environmental-related technologies can deal effectively with wastes discharged by human activities.

However, the technological advance may act as a double-edged sword where the progress in technology increases environmental degradation through the rebound effect (Bentzen 2004; Bessec and Fouquau 2008). While energy efficiency improvement is achieved at the micro-level, it may lead to more energy consumption at the macro level (Yang and Li 2017). If the rebound effect exists, the concentration of environmental-related technologies should be shifted from energy efficiency to reducing ecosystem damage such as capture, storage, disposal of polluted air or wastes. In addition, the discovery and exploitation of cleaner and more available energies reduce energy prices, encouraging both production and consumption activities. Consequently, they lead to greater pollution and faster depletion of natural resources (Ali et al. 2021). Wang and Wei (2020) indicate that the high levels of technological progress when combined with the heterogeneous characteristics of OECD countries make the effect of many environmental policies inter-wined and complex. Thus, an important question to be answered is whether higher environmental-related technologies (or green technologies for short) lead to environmental sustainability or not.

Recently, the ecological footprint has been introduced as a more inclusive benchmark of environmental externalities. In essence, it quantifies the amount of biologically productive land and water area needed to supply the resources that a community consumes and to dissolve the waste generated. Since the calculation and publication of data on ecological footprint by the Global Footprint Network, there have been numerous studies employing this indicator to proxy for environmental quality (Altintas and Kassouri 2020; Chu and Le 2021; Danish and Wang 2019; Danish et al. 2020).

Based on the premises above, this study's primary motive is to analyze the potential impact of green technologies on ecological footprint while considering the role of energy intensity, renewable energy, trade openness, and real income. The reviewed literature indicates that the role of green technologies in the protecting environment, especially in OCED countries, is still limited. The scope of this research is bounded within 20 OECD countries. We decide to focus on OECD countries due to several reasons. First, OECD countries have being exposed to environmental hazards. For example, nearly two-thirds of people are facing dangerous levels of air pollution, according to OECD (2020). In addition, renewable energies still account for a minor proportion of the total primary energy supply although the share is still higher than the rest of the world. The data show that the average carbon footprint per capita has been on a declining trend since 2010 (OECD 2020). The second reason relies on the fact that advanced countries, like OECD members, are witnessing the increasing role of knowledge as a key factor of production (Chu 2021; Wang and Wei 2020). Because of huge investment in research and development, the production and diffusion of technologies have become prominent in OECD countries. The third reason is the data availability of green technologies from the OECD statistics database.

The contribution of this paper to the current literature is three folds. We first examine the long-term connection between ecological footprint and its determining factors, including environmental-related technologies, trade openness, energy intensity, renewable energy, and real income. The reviewed literature indicates that while there have been many studies on the environmental effects of technologies in OECD context, the number of studies exploring the role of environmental-related technologies in the ecological footprint is limited and should be further investigated. Moreover, previous literature often uses carbon emissions for measuring environmental degradation while the ecological footprint is considered a more comprehensive measure (Danish and Wang 2019; Destek and Sarkodie 2019; Chu and Le 2021; Ulucak and Bilgili 2018). Accordingly, this paper connects a series of sustainable development goals (SDG) such as SDG 7 (affordable and clean energy) and SDG 9 (industry, innovation, and infrastructure) to other aspects of the ecological system such as SDG 6 (clean water and sanitation), SDG 13 (climate change), SDG 14 (life below water), and SDG 15 (life on land).

Second, the latest econometric techniques such as second-generation econometric approaches (Pesaran (2015)'s unit root, Westerlund (2005)'s co-integration) and cross-sectional augmented autoregressive distributive lag (Chudik and Pesaran 2015) are adopted to discover the aforementioned nexus. These techniques deal rigorously with the potential existence of cross-sectional dependence and heterogeneity in panel data. It is because the socio-economic activities of OECD countries are integrated due to increasing cross-border trade, investment, and environmental commitments.

Third, the beneficial impact of environmental-related technologies on footprint over the long-run is firmly identified by empirical results. However, such a desirable effect of green technologies on ecological footprint is not found in the short-run. The empirical results also posit that rather than addressing the issues related to environment, technology, and economic growth separately, a co-integrated approach that cover these interrelated factors is necessary to achieve a sustainable environment. Based on these findings, some policy implications are suggested to facilitate the development and deployment of green technologies to achieve sustainable development goals.

The paper's structure is divided into five parts. The next section provides a review of the literature. The "Methodology" section describes the data, model specification, and methodological issues. The "Results and discussion" section reports and discusses empirical results. The last section wraps up the paper and suggests recommendations.

Literature review

The topic of potential determinants of environmental quality, especially ecological footprint among other indicators, and the role of environmental-related technologies have been extensively examined in the literature. The existing literature, while is inconsistent in the empirical findings, could be classified into three broad categories.

The first collection focuses on the association between environmental-related technologies and the popular environmental quality indicators such as carbon and greenhouse gas emissions (hereafter GHG). Ahmed (2020) studies the nexus between environmental policy stringency, green technologies, and carbon emissions in 20 OECD nations from 1999 to 2015. The empirical results indicate that both environmental regulation and innovation reduce CO_2 in the long-run. Similarly, Mensah et al. (2019) find that eco-patents and trademarks alleviate carbon emissions in OECD economies from 1990 to 2015. Alvarez-Herranz et al. (2017) and Balsalobre et al., (2015) explore the impact of research and development on energy on GHG emissions for OECD economies over. The results suggest the beneficial environmental effect of energy innovation and technical innovation can correct the harmful effect of energy intensity. In a smaller context, the study by Wang et al. (2020) analyzes the impact of eco-innovation and export diversification on CO_2 emissions in G7 countries from 1990 to 2017. The empirical results show that while ecological innovation reduces CO_2 emissions, export diversification magnifies CO_2 emissions. Nevertheless, the drawback effect of export diversification gets weakened with the increase in the level of innovation. Other studies indicate insignificant or harmful effects of technological innovations on environmental sustainability. Wang and Wei (2020) find evidence that OECD countries are at a level of excessive technological progress, which causes a rebound effect on carbon emissions. A similar result is discovered by Ahmad et al. (2020a, b) who criticize innovation as the main culprit of carbon emissions in 24 OECD countries. Sohag et al. (2019) analyze the role of scale, composite, and technology effects in OECD countries and find that technological progress has a marginal role in limiting carbon emissions through energy efficiency.

With regard to emerging countries, Danish and Ulucak (2020) examine the long-run relationship between green innovations, renewable, non-renewable energy, and green growth in the context of BRIC countries. The empirical estimations based on panel data from 1992 to 2016 confirm the crucial roles of environmental technologies and renewable energy in promoting green growth. Hussain et al. (2020) evaluate the contribution of environmental-related technologies on controlling CO_2 and GHG emissions in E7 countries. The findings significantly confirm the supportive roles of environmental-related technologies and renewable energy sources in achieving sustainable targets. Shao et al. (2021) address the literature gap on the influence of green technology innovations, renewable energy on carbon levels in Next-11 countries. By employing a dataset from 1980 to 2018, authors find that, in the long-run, both green technologies and renewable energies significantly lessen CO_2 emissions. However, such beneficial effect of green technology innovations does not occur in the short-run. In the context of a single country, Shahbaz et al. (2020) examine the nexus between public–private partnership investment in the energy sector and CO_2 emissions in China taking into consideration the role of technological innovations. The empirical results indicate that while public–private partnership investment substantially degrades environmental quality, the advancement in technologies helps to lower the environmental externalities. In contrast, Su and Moaniba (2017) investigate how innovation reacts to climate change in 70 countries from 1976 to 2014. Empirical results show that a country's innovation and climate change technology depends on CO_2 and other GHG emissions. The government interventions on factors that determining environmental quality such as energy, telecom, transport, and environmental-related projects do not necessarily lead to the development of climate technologies.

Second, the recent literature has shifted attention from traditional measures of environmental quality to a much broader measure, namely ecological footprint. Destek et al. (2018) examine the presence of the Environmental Kuznets Curve (hereafter EKC) hypothesis for 15 European countries. The empirical findings based on two econometric methods of Fully Modified Ordinary Least Squares and Dynamic Ordinary Least Squares are quite different. Specifically, the estimation results from the former approach propose a U-shaped relationship between income and ecological footprint in some countries but those from the latter one suggest that is the case of others. Altintas and Kassouri (2020) check the validity of the EKC hypothesis for a group of 14 European nations over the period from 1990 to 2014. The two authors provide a new perception regarding the relevance of ecological footprint as a useful indicator of environmental quality. Specifically, the empirical results endorse the existence of the EKC hypothesis together with the beneficial environmental effect of renewable energy.

There are several studies with the aim of exploring the causes of ecological footprint in emerging economies. Danish et al. (2020) investigate the factors influencing ecological footprint in BRICS economics. All three factors, including renewable energy, natural resources rent, and urbanization, are found to have a beneficial impact on the environment. The EKC hypothesis is also empirically documented. Similarly, Destek and Sarkodie (2019) test the validity of the EKC hypothesis in the context of 11 newly industrialized countries. The panel data from 1977 to 2013 confirms an inverted U-shaped association between economic expansion and ecological footprint. Similarly, Chardeffine and Mrabet (2017) find that real income displays an inverted U-shaped connection with ecological footprint in eight oil-exporting countries in the Middle East and North African countries. Interestingly, seven non-oil exporting countries observe a U-shaped relationship between real income and ecological footprint. Danish and Wang (2019) investigate the effect of energy consumption, urbanization, and economic growth on the ecological footprint of the Next-11 countries. While higher level of urbanization leads to environmental degradation in most countries, the moderation between income and urbanization significantly reduces environmental degradation. Danish et al. (2019) examine the relationship between economic growth, bio-capacity, and ecological footprint in Pakistan. The data reveal that both factors significantly contribute to environmental deprivation in terms of ecological footprint. In a larger sample, Ulucak and Bilgili (2018) analyze the EKC hypothesis for different groups of high-, middle-, and low-income economies. The ecological footprint is found to increase at the initial level of income and decrease through economic development.

The third group combines two strands of literature by exploring the environmental impact of green technology on ecological footprint. However, to our best knowledge, the role of environmental-related technology, as an effective tool in controlling ecological footprint has not been well studied, particularly in OECD countries. Hussain and Dogan (2021) use a panel dataset of BRICS countries from 1992 to 2016 to estimate the long- and short-run effects of environmental-related technologies and institutional quality on the ecological footprint. The findings suggest that, on the one hand, the governments in BRICS countries improve institutions to moderate environmental impacts. On the other hand, they should encourage the investment in environmental-related technologies, which may facilitate the reduction in ecological footprint. Ahmad et al. (2020a, b) employ a panel dataset from 1984 to 2016 for a group of 22 emerging countries to examine the dynamic link between ecological footprint, natural resources rent, technological innovation, and economic activities. The findings imply that technological innovation is an efficient way to abate the environmental damage. In another interesting research, Destek and Manga (2021) aim at determining the impact of technological innovation on both carbon emissions and ecological footprint for big emerging markets. While technological innovation is found to curb CO_2 emissions, it proves ineffective in controlling ecological footprint.

The above summary of the recent literature suggests that the studies on the role of green technologies in controlling ecological footprint are relatively scant. Furthermore, such a limited number of studies disregard advanced economies such as OECD countries. To fill this literature gap, this on-hand study focuses on the nexus between environmental-related technologies in 20 OECD countries.

Methodology

Data

The sample comprises a panel data covering 20 OECD countries. It makes use of data spanning over the period from 1990 to 2015. The choices of countries and time coverage are subjected to the availability of data (see Appendix 1). The dataset includes the variables of ecological footprint, environmental-related technologies, trade openness, energy intensity, renewable energy consumption, and real income.

This study employs ecological footprint as a measure of environmental degradation, which is different from previous studies which mostly focus on carbon emissions (Ahmed, 2020; Alvarez-Herranz et al. 2017; Danish and Ulucak 2020; Hussain et al. 2020; Shao et al. 2021; Wang et al. 2020). The ecological footprint of consumption is defined as the area used to produce the materials consumed and the area need to absorb the emissions (Rees 1992). The ecological footprint increases with the surge in production and consumption activities, which unavoidably utilize a high amount of ecological resources, especially traditional fuels. The data are expressed in global hectares per capita and borrowed from Global Footprint Network.

To measure eco-innovation, we use patents in environmental-related technologies that are filed under the Patent Co-operation Treaty. An advantage of using this definition over the use of overall patents lies in the fact that the former directly help achieve a wide range of environmental control objectives. The data on environmental-related technologies are collected from the OECD Statistics database.

Trade openness quantifies the economic integration of a country into the global economy. It is measured as the sum of export and import as a percentage of gross domestic products. Energy intensity indicates the efficiency of energy used to produce a unit of product. Renewable energy is the proportion of total final consumed energies that are generated by renewable sources such as biomass, hydropower, geothermal, wind, and solar. The data on trade openness, energy intensity, renewable energy consumption, and gross domestic products per capita are taken from the World Bank's database. The measurement and sources of all variables are presented in Table 1.

Model and method

This study seeks to explore the nexus between environmental-related technologies and ecological footprint while taking into account the effects of economic integration, energy usage efficiency, and renewable energy. Dietz and Rosa (1994, 1997) and Rosa and Dietz (1998) propose the Stochastic Impacts by Regression on Population, Affluence, and Technology model) (STIRPAT) for understanding the complex relationship between the human system and the ecosystem upon which they depend. Based on the STIRPAT model, we design a model in which ecological footprint represents ecosystem degradation, income, and international trade refer to affluence, while energy intensity, renewable energy, and environmental-related technologies account for technology. The population factor is incorporated into the model by using per capita measurement of variables such as ecological footprint and gross domestic products. The model for the relationship between interested variables is proposed as follow:

$$EFC = f(ERT, OPE, ENE, REN, GDP) \quad (1)$$

where EFC is ecological footprint per capita, ERT is environmental-related technologies, OPE is trade openness, ENE is energy intensity, REN is renewable energy, GDP is gross domestic product per capita.

The model (1) is transformed into an economic form as below:

$$EFC_{i,t} = \alpha_0 + \alpha_1 ERT_{i,t} + \alpha_2 OPE_{i,t} + \alpha_3 ENE_{i,t} + \alpha_4 REN_{i,t} + \alpha_5 GDP_{i,t} + \varepsilon_{i,t} \quad (2)$$

where ε remains the error terms. Subscript i (i = 1,…, N) denotes the country in the sample with N being equal to 20. Subscript t (t = 1990,…, 2015) denotes the time period.

The coefficient of interest is α_1. It sign and significance indicate whether a larger number of environmental-related technologies substantially reduces environmental degradation in OECD countries or not. All variables are transformed into natural logarithm to make them consistent with the theoretical framework. The interpretation of the estimated coefficient is in terms of the percentage change.

Due to the high level of socio-economic integration among OECD economies, the possibility of cross-sectional dependence among variables should be expected. Hence, the study starts by testing cross-sectional dependence. The Pesaran (2015)'s test for cross-sectional dependency under the null hypothesis that errors are weakly cross-sectionally dependent is employed. It is also essential to verify the cross-sectional heterogeneity issue since each OECD member has its own characteristics. The on-hand study relies on Pesaran and Yamagata (2008) test to evaluate the null hypothesis of homogeneous slopes. Given the presence of cross-sectional dependence and heterogeneity, the cross-sectionally augmented Im, Pesaran and Shin unit root test is employed to check the stationary of variables (Pesaran, 2021). To conclude whether the long-run connection between variables is established, the Pedroni (1991, 2001)'s and Westerlund (2005)'s tests are utilized. The latter approach is more suitable because it circumvents the presence of cross-sectional dependence.

If the co-integration is statistically confirmed, this study relies on three economic methods of fixed effect with Driscoll-Kay standard errors (hereafter fixed effect with D-KSE), Feasible Generalized Least Squares (hereafter FGLS), Panel Corrected Standard Error (hereafter PCSE) to estimate the long-run elasticities between environmental-related technologies and ecological footprint. Moreover, due to the heterogeneity among individual OECD countries, it is suitable to apply the pooled mean group (hereafter PMG) estimation for our panel data. The PMG estimation can be applied in the case of co-integration between $I(0)$ and $I(1)$ variables. It relies on an ARDL model, which can be expressed in the following equation:

Table 1 Variable description

Variables	Symbol	Measurement	Sources
Ecological footprint	*EFC*	global hectares per capita	Global Footprint Network
Environmental-related technologies	*ERT*	number of patents related to environment	OECD Statistics
Trade openness	*OPE*	Sum of exports and imports to GDP	World Development Indicators
Energy intensity	*ENE*	kg of oil equivalent per capita	World Development Indicators
Renewable energy consumption	*REN*	% of total final energy consumption	World Development Indicators
Gross domestic per capita	*GDP*	constant 2010 US$	World Development Indicators

$$EFC_{i,t} = \sum_{j=1}^{p} \lambda_{i,j} EFC_{i,t-j} + \sum_{j=0}^{q} \delta'_{ij} X_{i,t-j} + \beta_i + \mu_{i,t} \tag{3}$$

where λ is a scalar of coefficients of the lagged value of the ecological footprint. X is a vector of independent variables with the corresponding vector of coefficients, δ. β is the specific individual country. μ is the error term.

It is likely to be problematic to use the traditional panel ARDL in the context of high interdependency among countries, especially those that are found within a particular region or have a high level of socio-economic integration (Dimnwobi et al. 2021; Kim et al. 2016; Sharma et al. 2021). Thus, we step further by using the cross-sectional augmented distributed lag approach (hereafter CS-ARDL) proposed by Chudik and Pesaran (2015). In this approach, the cross-sectional means of dependent and explanatory variables are added into the model to control for cross-sectional dependency. The Eq. (3) can be transformed to the style of error correction model as follows:

$$\begin{aligned}\Delta EFC_{i,t} &= \theta_i\left(EFC_{i,t-1} - \zeta' X_{i,t-1}\right) + \sum\nolimits_{j=1}^{p-1} \lambda^*_{i,t} \Delta EFC_{i,t-j} \\ &+ \sum\nolimits_{j=0}^{q-1} \zeta'^*_{i,t} X_{i,t-j} + \sum\nolimits_{j=1}^{p} \omega_j \overline{EFC_{t-j}} \\ &+ \sum\nolimits_{j=0}^{q} \varphi_j \overline{X_{t-j}} + \sum\nolimits_{j=1}^{p-1} \rho_j \overline{\Delta EFC_{t-j}} + \sum\nolimits_{j=0}^{q-1} \vartheta_j \overline{\Delta X_{t-j}} + \alpha_i + \mu_{i,t}\end{aligned} \tag{4}$$

where the cross-sectional averages of ecological footprint and all independent variables are expressed in the form of $\overline{EFC}$ and $\overline{X}$. $\overline{\Delta EFC_{t-j}}$ and $\overline{\Delta X_{t-j}}$ are the averages of the differences of the lagged dependent variable and other regressors, respectively. θ is the error-correction term, or the speed of correction from the short-term divergence to the long-term steady state. It is expected that the error-correction term is negative and statistically significant if the variables of interest show a long-run equilibrium relationship.

The CS-ARDL is favored over the PMG, mean group, common correlated mean group, and augmented mean group as it can deal rigorously with both heterogeneity and cross-sectional dependence issues. It is also able to produce both long- and short-term coefficients, which enrich our discussions on the relationship between interested variables. A variety of studies has employed this approach to exploring the determinants of environmental quality (Ahmad et al. 2020a, b; Atsu and Adams 2021; Dimnwobi et al. 2021; Hussain and Dogan 2021; Sharma et al. 2021).

Results and discussion

For a basic understanding of the variables, the descriptive statistics, cross-sectional dependence, slope homogeneity, stationary, and co-integration tests are reported in Tables 2, 3, 4 and 5. Table 2 shows that ecological footprint consumption per capita has a mean value of 1.765 and a standard deviation of 0.255. Although the United States ranks first in terms of ecological footprint, its level has been on the decrease. A similar pattern also occurs in France, Germany, Italy, Spain, Switzerland, and the UK (see Appendix 2). With regard to environmental-related technologies, most countries witness sustainable increases in the number of patents filed under the Patent Co-operation Treaty. Countries that have the highest number of environmental-related patents are Germany, Japan, and the USA (see Appendix 3). The last column in Table 2 shows that the null hypothesis of cross-sectional independence or weak cross-sectional dependence is rejected at 1% significance level. It means that all variables are inter-related. Table 3 reports the Pesaran and Yamagata (2008)'s slope homogeneity test result, which significantly rejects the null hypothesis of homogeneous slope coefficients.

The existence of cross-sectional dependence and slope homogeneity suggest the application of cross-sectionally augmented Im, Pesaran, and Shin unit root test. Table 4 reports the unit root test in two cases, with and without a

Table 3 Slope homogeneity test

	Statistical value
Δ tilde	10.854***
Δ tilde adjusted	12.748***

***, **, * denotes rejection of null hypothesis of slope homogenous at the 1%, 5%, and 10% significance level, respectively

Table 2 Descriptive statistics and cross-sectional dependence test

Variables	No. obs	Mean	Std. Dev	Min	Max	CD-test
EFC	509	1.765	0.255	0.846	2.350	26.999***
ERT	509	5.257	1.912	-1.109	9.244	33.395***
OPE	509	4.165	0.503	2.773	5.371	81.540***
ENE	509	8.250	0.427	6.884	9.043	69.969***
REN	509	2.285	1.079	-0.497	4.117	30.137***
GDP	509	10.544	0.452	8.838	11.425	41.658***

***, **, * denotes rejection of null hypothesis of cross-sectional independence at the 1%, 5%, and 10% significance level, respectively

Table 4 Unit root test

	No trend			Trend		
Lags	0	1	2	0	1	2
Level						
EFC	-3.967***	-1.132	0.535	-5.211***	-1.430*	0.183
ERT	-6.820***	-6.113***	-3.527***	-4.370***	-3.685***	-0.046
OPE	-0.178	-4.305***	-1.547*	3.351	-1.066	0.979
ENE	-1.925**	-2.058**	0.372	-3.784***	-3.602***	-0.846
REN	-2.637***	-0.370	1.459	-6.599***	-3.759***	-3.122***
GDP	1.237	-0.574	-0.385	0.126	0.302	1.139
First difference						
EFC	-16.855***	-9.477***	-5.209***	-15.497***	-6.846***	-2.501***
ERT	-15.996***	-12.860***	-6.139***	-14.068***	-10.718***	-4.087***
OPE	-7.469***	-4.779***	-2.401***	-6.420***	-3.253***	0.413
ENE	-15.671***	-11.329***	-5.762***	-14.325***	-9.309***	-3.704***
REN	-18.228***	-10.525***	-5.868***	-16.641***	-8.447***	-3.138***
GDP	-6.799***	-3.782***	-1.454*	-4.018***	-1.676**	0.484

***, **, * denotes rejection of null hypothesis of nonstationary at the 1%, 5%, and 10% significance level, respectively

Table 5 Co-integration test. Pedroni test

Statistic	Panel	Group
v	-1.524	
rho	0.506	2.057**
t	-8.171***	-8.841***
adf	-1.264	-0.527

***, **, * denotes rejection of null hypothesis of no co-integration at the 1%, 5%, and 10% significance level, respectively

Table 6 Co-integration test. Westerlund test

Statistic	Value	*Z*-value	*P*-value
Gt	-3.627	-6.619	0.000
Ga	-11.953	-0.398	0.345
Pt	-18.010	-8.915	0.000
Pa	-14.050	-4.495	0.000

***, **, * denotes rejection of null hypothesis of no co-integration at the 1%, 5%, and 10% significance level, respectively

time trend. According to the results, most variables are stationary at level, except for trade openness and gross domestic products. Nevertheless, after taking the first difference, all variables turn to be stationary at the conventional significance level. This finding supports the use of CS-ARDL in the subsequent analysis.

We step further to check the co-integration or the long-term relationship between variables. As indicated in Tables 5 and 6, both Pedroni (1991, 2001)'s and Westerlund (2005)'s tests significantly reject the null hypothesis of no co-integration. It implies that a long-run relationship between ecological footprint, environmental-related technologies, and other control variables exists.

The core findings involve the long- and short-run relationship between ecological footprint and green technologies. Table 7 proceeds with the fixed effect with D-KSE, FGLS, and PCSE in columns (1) to (3). The long-run coefficient of environmental-related technologies variable is negative at 1% significance level. Specifically, 1% increase in environmental-related technologies in terms of patents (per capita) significantly yields a 0.025%, 0.036%, or 0.045% reduction in ecological footprint (per capita). With regard to the CS-ARDL approach, the findings are summarized in Table 7 columns (4) and (5). The magnitude of long-run coefficient is 0.015% and statistically significant at 5% level. This negative long-run relationship is consistent with the finding of Hussain and Dogan (2021) and Ahmad et al. (2020a, b) on the beneficial impact of environmental-related technologies on ecological footprint. It is also supported by the empirical works on the nexus between green technologies and carbon emissions (Ahmed 2020; Alvarez-Harranz et al. 2017; Danish and Ulucak 2020; Wang, et al. 2020). However, it is found that the short-run connection between ecological footprint and environmental-related technologies is not statistically established although the sign of the coefficient is negative. This outcome is similar to the conclusion of Shao et al. (2021) who find that technologies only affect carbon emissions in the long-run. Briefly, an accumulation in the number of patents related to the environment will help OECD countries to achieve sustainable environmental

Table 7 Main results

	(1)	(2)	(3)	(4)	(5)
	D-KSE	FGLS	PCSE	CS-ARDL	
				Long-run	Short-run
ERT	-0.045***	-0.025***	-0.036***	-0.015**	-0.018
	(0.007)	(0.004)	(0.003)	(0.007)	(0.024)
OPE	-0.045**	0.014	-0.053***	-0.044*	0.147***
	(0.021)	(0.019)	(0.011)	(0.025)	(0.036)
ENE	0.642***	0.426***	0.476***	0.815***	-0.142
	(0.046)	(0.026)	(0.010)	(0.082)	(0.102)
REN	-0.018**	-0.053***	-0.050***	-0.044**	-0.034
	(0.007)	(0.006)	(0.004)	(0.018)	(0.058)
GDP	0.154***	0.157***	0.157***	0.308***	0.345**
	(0.038)	(0.027)	(0.011)	(0.084)	(0.166)
ECT					-0.872***
					(0.072)
Constant	-4.693***	-3.235***	-3.300***		-1.042
	(0.538)	(0.135)	(0.0		

***, **, * denotes statistically significant at the 1%, 5%, and 10%, respectively. Robust standard errors in parentheses

goals over the long-term. Therefore, not only do enterprises and research institutes invest in research and development activities related to green technologies but the governments should implement policies that encourage such activities as well as the adoption of such innovations in practice.

The coefficient for the error correction term is both negative (-0.872) and significant at 99% confidence level. It implies that there is 87.2% adjustment from a short-run divergence to the long-run equilibrium between interested variables. This speed of correction is much higher than those in the case of 20 OECD countries (Ahmed 2020) and of BRICS countries (Hussain and Dogan 2021) but similar to those in the case of G7 countries (Wang et al. 2020) and 22 emerging countries (Ahmad et al. 2020a, b). Such differences rely on the different measures of environmental quality (carbon emissions in Admed (2020) and different samples (BRICS countries in Hussain and Dogan (2021)).

With regard to other control variables, higher trade openness and renewable energy lessen the environmental externalities while higher energy intensity and income per capita degrade the quality of environment. A 1% rise in trade openness leads to 0.04 to 0.05% corresponding reduction in ecological footprint in the long-run. Similarly, a 1% higher proportion of renewable energy consumption mitigates ecological footprint by 0.02 to 0.05%. These two findings are similar to those of Danish and Ulucak (2020)), Hussain et al (2020), and Shao et al. (2021). However, in the short-run, higher economic integration causes harmful environmental impact. To mitigate the environmental degradation, all stakeholders in OECD countries such as the governments, enterprises, households are advised to shift their reliance from non-renewable to renewable energy sources. Moreover, the impact of trade on environmental quality must be scrutinized to avoid the case that OECD countries export pollution to their trading partners.

Energy efficiency exerts a statistical impact on environmental pollution. A 1% increase energy intensity causes 0.6 to 0.8% surges in ecological footprint. The literature is consistent with this outcome (Chu 2021; Danish et al. 2020; Pham et al. 2020). It is worth mentioning that higher income per capita is identified as a key element of the footprint both in the short- and long-run. Ahmed (2020) and Hussain et al. (2021) find a similar pattern.

The study checks the sensitivity of the main findings by substituting environmental related technologies by its two sub-indicators, including patents related to environmental management and climate change mitigation. The same methods are applied for two substituting variables and are posted in Table 8. While the signs and magnitude of independent variables' coefficients are similar to those of the main findings, there are two remarkable points. First, environmental-related technologies, measured by both sub-indicators, significantly increase ecological footprint in the short-run. Specifically, in a standalone basis, a 1% rise in each sub-indicator leads to a growth by 0.014 to 0.016% in ecological footprint. It signifies the rebound effect of technological advance as discovered by Wang and Wei (2020). Only by combining two types of technology, the beneficial effects of environmental-related technologies are achieved. Second, the speed of adjustment to permit convergence among the variables in the long-run is significantly lower in the case of two sub-indicators of patents (about 56%) than in the case of total patents. This finding is intuitive because the synergy of two types of technological advances will bring more benefits for the ecosystem.

To be assured of our main results in terms of estimation method, we employ a system-generalized method of moments (hereafter system-GMM). This estimation approach is chosen because it deals rigorously with heterogeneity and autocorrelation. The results reported in Table 9 reveal that the environmental-related technologies lead to a reduction in ecological footprint.

With regard to model specification, this study challenges Eq. (2) by adding the square of gross domestic products per capita to take into consideration the EKC. The EKC hypothesis suggests the existence of an inverted U-shaped connection between per capita income and per capita pollution. The output (not shown here to save space) indicate that the nexus between environmental technologies and ecological footprint is robust even when we control for the EKC. In sum, the outcomes of three robustness tests validate the statistically negative impact of green technologies on the ecological footprint in the long-run.

Table 8 Environmental management and climate change mitigation patents estimation

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
	Environmental management					Climate change mitigation				
	D-KSE	FGLS	PCSE	CS-ARDL		D-KSE	FGLS	PCSE	CS-ARDL	
				Long-run	Short-run				Long-run	Short-run
ERT	-0.034***	-0.023***	-0.039***	-0.035**	0.014**	-0.039***	-0.021***	-0.033***	-0.031**	0.016**
	(0.008)	(0.004)	(0.003)	(0.014)	(0.007)	(0.006)	(0.005)	(0.003)	(0.013)	(0.008)
OPE	-0.059**	0.016	-0.060***	-0.040	0.022	-0.044**	0.019	-0.048***	-0.043	0.043
	(0.026)	(0.019)	(0.011)	(0.047)	(0.044)	(0.021)	(0.019)	(0.010)	(0.048)	(0.041)
ENE	0.645***	0.443***	0.490***	0.624***	0.103	0.631***	0.419***	0.471***	0.610***	0.106
	(0.056)	(0.025)	(0.009)	(0.088)	(0.072)	(0.048)	(0.026)	(0.010)	(0.087)	(0.072)
REN	-0.026***	-0.053***	-0.053***	0.006	-0.006	-0.016**	-0.052***	-0.048***	0.010	-0.005
	(0.009)	(0.006)	(0.004)	(0.017)	(0.030)	(0.007)	(0.007)	(0.004)	(0.018)	(0.030)
GDP	0.100***	0.133***	0.158***	0.200***	0.635***	0.152***	0.153***	0.155***	0.199***	0.621***
	(0.036)	(0.028)	(0.011)	(0.072)	(0.104)	(0.041)	(0.028)	(0.012)	(0.071)	(0.107)
ECT					-0.560***				-0.423	-0.559***
					(0.039)				(0.972)	(0.039)
Constant	-4.144***	-3.152***	-3.383***		0.451	-4.631***	-3.184***	-3.282***		-0.423
	(0.570)	(0.161)	(0.063)		(1.079)	(0.561)	(0.144)	(0.064)		(0.972)

***, **, * denotes statistically significant at the 1%, 5%, and 10%, respectively. Robust standard errors in parentheses

Table 9 System GMM estimation

	(1)	(2)	(3)
	Environmental related technologies	Environmental management	Climate change mitigation
Lag.EFC	0.363***	0.362***	0.395***
	(0.123)	(0.125)	(0.134)
ERT	-0.028*	-0.025*	-0.027**
	(0.017)	(0.014)	(0.013)
OPE	-0.034	-0.034	-0.025
	(0.037)	(0.038)	(0.039)
ENE	0.304***	0.323***	0.288***
	(0.096)	(0.095)	(0.095)
REN	-0.032**	-0.032**	-0.025
	(0.015)	(0.015)	(0.017)
GDP	0.130	0.099	0.128
	(0.141)	(0.102)	(0.139)
Constant	-2.397**	-2.255***	-2.362**
	(1.062)	(0.760)	(0.990)

***, **, * denotes statistically significant at the 1%, 5%, and 10%, respectively. Robust standard errors in parentheses

Conclusion and policy implications

This study relates two important issues, one is the wake of Industrial revolution 4.0 and the second is the increasing high pressures of human activities on environmental quality. The main question to be answered is whether cutting-edge environmental technologies are effective in protecting and sustaining the environment. Based on such premises, this on-hand study employs recently developed data to empirically examine both long- and short-run relationships between environmental related technologies and ecological footprint for 20 OECD countries. Specifically, it provides new understandings about the dynamic impacts of environmental-related technologies, energy intensity, renewable energy, and trade openness on ecological footprint from 1990 to 2015. The Peasaran (2015)'s cross-sectional dependence, Pesaran and Yamagata (2008)'s slope heterogeneity, Pesaran (2021)'s stationary, and Westerlund (2005)'s co-integration tests are employed to check the long-run connection between studied variables. Finally, a series of estimation techniques such as fixed effects with D-KSE, FGLS, PCSE, CS-ARDL, and system-GMM are conducted to provide robust empirical results.

The primary tests first confirm that all cross-sectional variables are co-integrated. Second, all estimation techniques reveal that ecological footprint is significantly related to environmental-related technologies over the long-run.

However, the result of CS-ARDL indicates that the environmental influence of green technologies is not significant in the short-run. In addition, it takes more than one year for a short-term deviation to converge to the long-run equilibrium. This finding is intuitive because the adoption of green technologies is a long-term process that demands huge investment and associates with high uncertainties related to many legal and socio-economic factors such as environmental regulations and consumption habitats (Shabalov et al. 2021; Wada et al., 2021). Thus, the environmental evaluation of green technologies should be conducted and evaluated on a long-term perspective, which considers all the possible externalities. Renewable energy and international trade help control the ecosystem degradation in OECD countries (Anwar et al. 2021; Chen and Lei 2018; Cheng et al. 2021; Chu and Hoang 2021; Qi et al. 2019). Similarly, the efficient use of energy should mitigate environmental degradation (Xie et al. 2021; Salman et al. 2019).

Based on empirical results, this study proposes several relevant policies related to technological innovation and environmental quality. First, there is an urgent need for research focusing on ecological footprint as a benchmark of environmental quality besides a huge existing literature on the determining factors such as carbon and GHG emissions (Danish and Wang 2019; Destek and Sarkodie 2019; Sharif et al. 2020). This new strand of literature will contribute to the achievement of several sustainable development goals related to good health and well-being (SDG 3), water and sanitation (SDG 6), life below water (SDG 14), and life on land (SDG 15).

Second, both governments and enterprises in OCED countries should be able to take advantage of innovations from the Industrial revolution 4.0 on the development of environmental-related technologies. To facilitate such a process, the policymakers are advised to introduce standards for green technologies together with the stricter environmental regulations (Aichele and Felbermayr 2013; de Angelis et al. 2019; Danish et al. 2020; Korhonen et al. 2015; Wang et al. 2019; Zhang 2016). Environmental regulation can affect environmental sustainability through the idea that stringent policies make activities that negatively affect the environment more costly to change the behaviors of economic agents. The government can also design policies to inspire the invention and adoption of environmentally friendly technologies, which effectively limit environmental deprivation. Moreover, they must consider sponsoring the research and development of green technologies through both public and public–private programs or introduce tax cuts on these activities (Bekun et al. 2021). The establishment of a market for such patents to be traded is also essential for the diffusion of green technologies.

Third, at the end of the day, the success of green technologies in sustaining environmental quality depends on the enterprises that adopt them in producing goods and services. The investment cost of adopting clean technologies should be shared between all stakeholders, the governments, enterprises, and consumers through an appropriate mechanism. It is also the objective of SDG 17 which requires the global partnership for accelerating sustainable solutions to all the world's biggest challenges. The governments and international donors should actively engage with private sectors to help catalyze their business investment and to ensure their responsibility, sustainability, and inclusivity of business activities.

Last, given the fact that both environmental-related technologies and renewable energy are powerful in dealing with environmental degradation, environmental-related technologies should be treated as a valuable instrument to boost the share of renewable energy production and consumption (Adedoyin et al. 2021; Sharif et al. 2020). Raising the carbon price on traditional energy sources and using the revenue to sponsor renewable energy projects should in made in parallel to optimize the coordination of the two strategies (Khan et al. 2021).

There are several potential ways to extend this study in the future. Future work directed toward a larger sample of high-income countries or smaller samples such as G7 or E7 countries would contribute to a more consolidated understanding of the technology-environmental quality nexus. It would be also excited to explore the connection between green technologies and ecological footprint while taking into account the role of institutional quality (Li 2019; Ouyang et al. 2019), economic policy uncertainty (Akadiri et al. 2020), or green finance (Shahbaz et al. 2016), for example Table 10, Figs. 1 and 2.

Appendix 1

Table 10 List of countries

Austria	Germany	Portugal	United Kingdom
Belgium	Greece	Spain	United States
Canada	Ireland	Sweden	Italy
Denmark	Netherlands	Switzerland	Japan
France	Norway	Turkey	Finland

Appendix 2

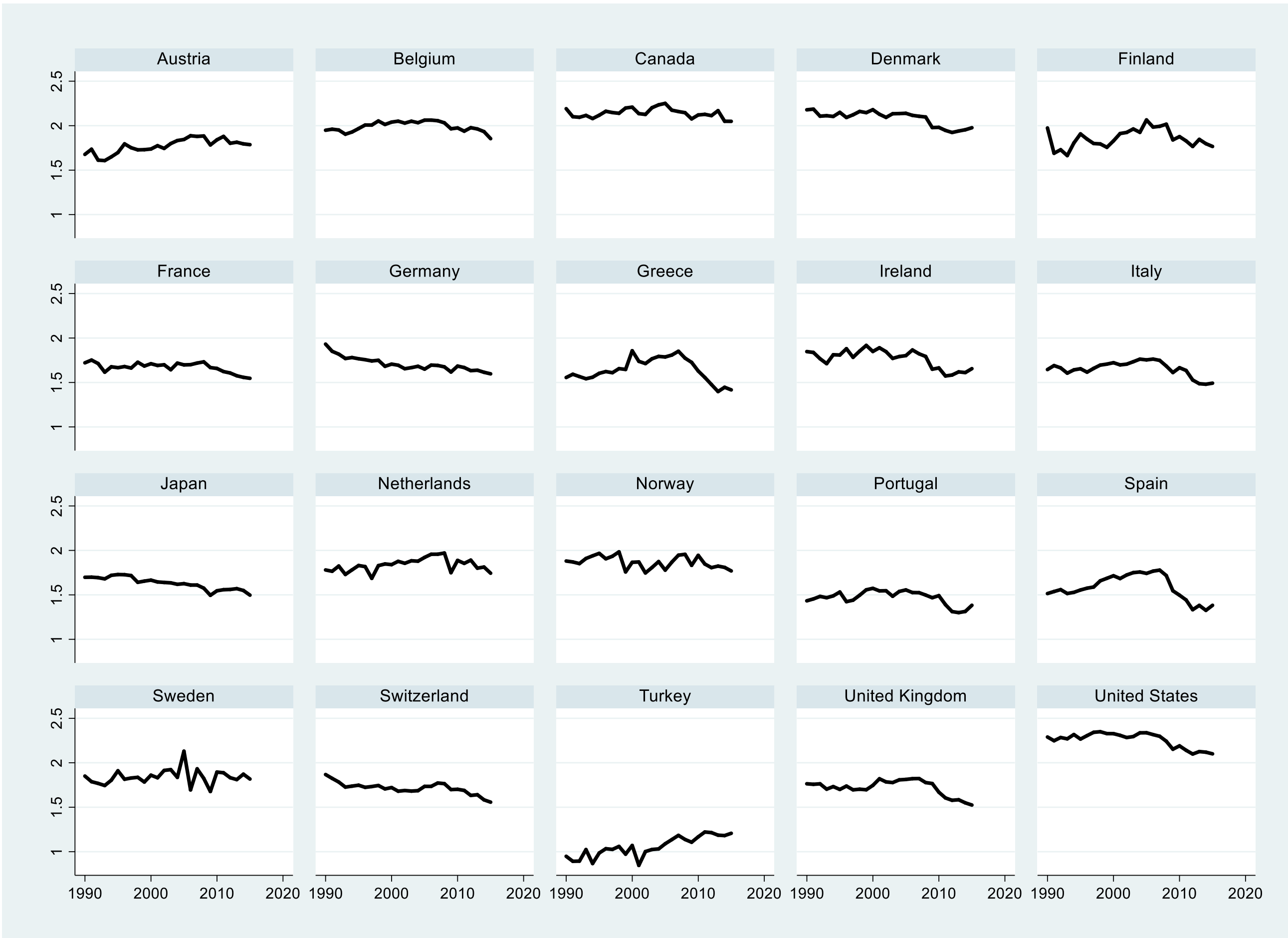

Fig. 1 The ecological footprint of 20 OECD countries. Note: the dark line represents the global hectares per capita in logarithm form

Appendix 3

Fig. 2 Environmental-related technologies of 20 OECD countries. Note: the dark line represents the numbers of environmental-related patents in logarithm form

Author contribution Lan Khanh Chu: Conceptualization, Introduction, Literature review, Methodology, Result, Discussion, Conclusion, Data curation, Software, Review and Editing.

Data availability All data analyzed during this study are available and freely collected from public sources.

Code availability Not applicable.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The author declares no competing interests.

References

Adedoyin FF, Ozturk I, Agboola MO, Agboola PO, Bekun FV (2021) The implications of renewable and non-renewable energy generating in Sub-Saharan Africa: The role of economic policy uncertainties. Energy Policy, 150(December 2020), 112115. https://doi.org/10.1016/j.enpol.2020.112115

Ahmad M, Jiang P, Majeed A, Umar M, Khan Z, Muhammad S (2020a) The dynamic impact of natural resources, technological innovations and economic growth on ecological footprint: An advanced panel data estimation. Resour Policy 69(July):101817. https://doi.org/10.1016/j.resourpol.2020.101817

Ahmad M, Khattak SI, Khan A, Rahman ZU (2020b) Innovation, foreign direct investment (FDI), and the energy–pollution–growth nexus in OECD region: a simultaneous equation modeling approach. Environ Ecol Stat 27(2):203–232. https://doi.org/10.1007/s10651-020-00442-8

Ahmed K (2020) Environmental policy stringency, related technological change and emissions inventory in 20 OECD countries. J Environ Manage 274(July):111209. https://doi.org/10.1016/j.jenvman.2020.111209

Aichele R, Felbermayr G (2013) Estimating the effects of kyoto on bilateral trade flows using matching econometrics. The World Economy 36(3):303–330. https://doi.org/10.1111/twec.12053

Akadiri SS, Alola AA, Uzuner G (2020) Economic policy uncertainty and tourism: evidence from the heterogeneous panel. Current Issues in Tourism 23(20):2507–2514. https://doi.org/10.1080/13683500.2019.1687662

Ali U, Li Y, Yánez Morales VP, Hussain B (2021) Dynamics of international trade, technology innovation and environmental sustainability: evidence from Asia by accounting for cross-sectional dependence. J Environ Planning Manage 64(10):1864–1885. https://doi.org/10.1080/09640568.2020.1846507

Altıntaş H, Kassouri Y (2020) Is the environmental Kuznets Curve in Europe related to the per-capita ecological footprint or CO2 emissions? Ecological Indicators, 113(January). https://doi.org/10.1016/j.ecolind.2020.106187

Álvarez-Herránz A., Balsalobre D, Cantos JM, Shahbaz M (2017) Energy innovations-GHG emissions Nexus: fresh empirical evidence from OECD countries. Energy Policy, 101(June 2016), 90–100. https://doi.org/10.1016/j.enpol.2016.11.030

An H, Razzaq A, Haseeb M, Mihardjo LWW (2021) The role of technology innovation and people's connectivity in testing environmental Kuznets curve and pollution heaven hypotheses across the Belt and Road host countries: new evidence from Method of Moments Quantile Regression. Environ Sci Pollut Res 28(5):5254–5270. https://doi.org/10.1007/s11356-020-10775-3

Anwar A, Siddique M, Dogan E, Sharif A (2021) The moderating role of renewable and non-renewable energy in environment-income nexus for ASEAN countries: Evidence from Method of Moments Quantile Regression. Renewable Energy 164:956–967. https://doi.org/10.1016/j.renene.2020.09.128

Atsu F, Adams S (2021) Energy consumption, finance, and climate change: Does policy uncertainty matter? Economic Analysis and Policy 70:490–501. https://doi.org/10.1016/j.eap.2021.03.013

Balsalobre D, Álvarez A, Cantos JM (2015) Public budgets for energy RD&D and the effects on energy intensity and pollution levels. Environ Sci Pollut Res 22(7):4881–4892. https://doi.org/10.1007/s11356-014-3121-3

Bekun FV, Alola AA, Gyamfi BA, Ampomah AB (2021) The environmental aspects of conventional and clean energy policy in sub-Saharan Africa: is N-shaped hypothesis valid? Environ Sci Pollut Res. https://doi.org/10.1007/s11356-021-14758-w

Bentzen J (2004) Estimating the rebound effect in US manufacturing energy consumption. Energy Economics 26(1):123–134. https://doi.org/10.1016/S0140-9883(03)00047-1

Bessec M, Fouquau J (2008) The non-linear link between electricity consumption and temperature in Europe: A threshold panel approach. Energy Economics 30(5):2705–2721. https://doi.org/10.1016/j.eneco.2008.02.003

Bilgili F, Nathaniel SP, Kuşkaya S, Kassouri Y (2021) Environmental pollution and energy research and development: an Environmental Kuznets Curve model through quantile simulation approach. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-021-14506-0

Charfeddine L, Mrabet Z (2017) The impact of economic development and social-political factors on ecological footprint: A panel data analysis for 15 MENA countries. Renew Sustain Energy Rev 76(March):138–154. https://doi.org/10.1016/j.rser.2017.03.031

Chen W, Lei Y (2018) The impacts of renewable energy and technological innovation on environment-energy-growth nexus: New evidence from a panel quantile regression. Renewable Energy 123:1–14. https://doi.org/10.1016/j.renene.2018.02.026

Cheng C, Ren X, Dong K, Dong X, Wang Z (2021) How does technological innovation mitigate CO2 emissions in OECD countries? Heterogeneous analysis using panel quantile regression. J Environ Manag, 280(November 2020), 111818. https://doi.org/10.1016/j.jenvman.2020.111818

Chu KL, Le TMN (2021). Environmental quality and the role of economic policy uncertainty, economic complexity, renewable energy, energy intensity: the case of G7 countries. Environ Sci Pollut Res

Chu LK (2021) Economic structure and environmental Kuznets curve hypothesis: new evidence from economic complexity. Appl Econ Lett 28(7):612–616. https://doi.org/10.1080/13504851.2020.1767280

Chu LK, Hoang DP (2021) The complementarity of income equalization and innovation for more effective emission reduction. J Environ Manage 284(January):112007. https://doi.org/10.1016/j.jenvman.2021.112007

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

Danish, Ulucak R (2020) How do environmental technologies affect green growth? Evidence from BRICS economies. Science of the Total Environment, 712, 136504. https://doi.org/10.1016/j.scitotenv.2020.136504

Danish, Wang Z (2019) Investigation of the ecological footprint's driving factors: What we learn from the experience of emerging economies. Sustainable Cities and Society, 49(March), 101626. https://doi.org/10.1016/j.scs.2019.101626

Danish, Hassan ST, Baloch MA, Mahmood N, Zhang JW (2019). Linking economic growth and ecological footprint through human capital and biocapacity. Sustainable Cities and Society, 47(March), 101516. https://doi.org/10.1016/j.scs.2019.101516

Danish, Khan N, Baloch MA, Saud S, Fatima T (2018) The effect of ICT on CO2 emissions in emerging economies: does the level of income matters? Environ Sci Pollut Res, 25(23), 22850–22860. https://doi.org/10.1007/s11356-018-2379-2

Danish, Ulucak R, Khan SUD (2020) Determinants of the ecological footprint: Role of renewable energy, natural resources, and urbanization. Sustainable Cities and Society, 54(December 2019), 101996. https://doi.org/10.1016/j.scs.2019.101996

de Angelis EM, Di Giacomo M, Vannoni D (2019) Climate change and economic growth: The role of environmental policy stringency. Sustainability (switzerland) 11(8):1–15. https://doi.org/10.3390/su11082273

Destek MA, Manga M (2021) Technological innovation, financialization, and ecological footprint: evidence from BEM economies. Environ Sci Pollut Res 28(17):21991–22001. https://doi.org/10.1007/s11356-020-11845-2

Destek MA, Sarkodie SA (2019) Investigation of environmental Kuznets curve for ecological footprint: The role of energy and financial development. Sci Total Environ 650:2483–2489. https://doi.org/10.1016/j.scitotenv.2018.10.017

Destek MA, Ulucak R, Dogan E (2018) Analyzing the environmental Kuznets curve for the EU countries: the role of ecological footprint. Environ Sci Pollut Res 25(29):29387–29396. https://doi.org/10.1007/s11356-018-2911-4

Dhanwani R, Prajapati A, Dimri A, Varmora A, Shah M (2021) Smart Earth Technologies: a pressing need for abating pollution for a better tomorrow. Environ Sci Pollut Res 28(27):35406–35428. https://doi.org/10.1007/s11356-021-14481-6

Dietz T, Rosa EA (1994) Rethinking the environmental impacts of population, affluence and technology. Hum Ecol Rev 1:277–300

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

Dimnwobi SK, Ekesiobi C, Madichie CV, Asongu SA (2021) Population dynamics and environmental quality in Africa. Sci Total Environ 797:149172. https://doi.org/10.1016/j.scitotenv.2021.149172

Hashem Pesaran M, Yamagata T (2008) Testing slope homogeneity in large panels. Journal of Econometrics 142(1):50–93. https://doi.org/10.1016/j.jeconom.2007.05.010

Hussain M, Dogan E (2021) The role of institutional quality and environment-related technologies in environmental degradation for BRICS. J Clean Prod 304:127059. https://doi.org/10.1016/j.jclepro.2021.127059

Hussain M, Mir GM, Usman M, Ye C, Mansoor S (2020) Analysing the role of environment-related technologies and carbon emissions in emerging economies: a step towards sustainable development. Environmental Technology (United Kingdom), 0(0), 1–9. https://doi.org/10.1080/09593330.2020.1788171

Ikram M, Ferasso M, Sroufe R, Zhang Q (2021) Assessing green technology indicators for cleaner production and sustainable investments in a developing country context. J Clean Prod 322(March):129090. https://doi.org/10.1016/j.jclepro.2021.129090

Khan MK, Babar SF, Oryani B, Dagar V, Rehman A, Zakari A, Khan MO (2021) Role of financial development, environmental-related technologies, research and development, energy intensity, natural resource depletion, and temperature in sustainable environment in Canada. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-021-15421-0

Khattak SI, Ahmad M, Khan ZU, Khan A (2020) Exploring the impact of innovation, renewable energy consumption, and income on CO2 emissions: new evidence from the BRICS economies. Environ Sci Pollut Res 27(12):13866–13881. https://doi.org/10.1007/s11356-020-07876-4

Kim DH, Lin SC, Suen YB (2016) Trade, growth and growth volatility: New panel evidence. Int Rev Econ Financ 45(32):384–399. https://doi.org/10.1016/j.iref.2016.07.006

Koçak E, Ulucak ZŞ (2019) The effect of energy R&D expenditures on CO 2 emission reduction: estimation of the STIRPAT model for OECD countries. Environ Sci Pollut Res 1. https://doi.org/10.1007/s11356-019-04712-2

Korhonen J, Pätäri S, Toppinen A, Tuppura A (2015) The role of environmental regulation in the future competitiveness of the pulp and paper industry: The case of the sulfur emissions directive in Northern Europe. J Clean Prod 108:864–872. https://doi.org/10.1016/j.jclepro.2015.06.003

Levin A, Lin C-F, James Chu C-S (2002) Unit root tests in panel data: asymptotic and finite-sample properties. Journal of Econometrics 108(1):1–24. https://doi.org/10.1016/S0304-4076(01)00098-7

Li C (2019) How does environmental regulation affect different approaches of technical progress?—Evidence from China's industrial sectors from 2005 to 2015. J Clean Prod 209:572–580. https://doi.org/10.1016/j.jclepro.2018.10.235

Ouyang X, Shao Q, Zhu X, He Q, Xiang C, Wei G (2019) Environmental regulation, economic growth and air pollution: Panel threshold analysis for OECD countries. Sci Total Environ 657:234–241. https://doi.org/10.1016/j.scitotenv.2018.12.056

OECD (2020) How's Life? 2020. OECD. https://doi.org/10.1787/9870c393-en

Park Y, Meng F, Baloch MA (2018) The effect of ICT, financial development, growth, and trade openness on CO2 emissions: an empirical analysis. Environ Sci Pollut Res 25(30):30708–30719. https://doi.org/10.1007/s11356-018-3108-6

Pedroni P (1999) Critical Values for Cointegration Tests in Heterogeneous Panels with Multiple Regressors. Oxford Bull Econ Stat 61(s1):653–670. https://doi.org/10.1111/1468-0084.0610s1653

Pedroni P (2001) Purchasing power parity tests in cointegrated panels. Rev Econ Stat 83(4):727–731. https://doi.org/10.1162/003465301753237803

Pesaran MH (2015) Testing weak cross-sectional dependence in large panels. Economet Rev 34(6–10):1089–1117. https://doi.org/10.1080/07474938.2014.956623

Pesaran MH (2021) General diagnostic tests for cross-sectional dependence in panels. Empirical Economics 60(1):13–50. https://doi.org/10.1007/s00181-020-01875-7

Pham NM, Huynh TLD, Nasir MA (2020) Environmental consequences of population, affluence and technological progress for European countries: A Malthusian view. J Environ Manag, 260(December 2019), 110143. https://doi.org/10.1016/j.jenvman.2020.110143

Qi S, Peng H, Zhang X, Tan X (2019) Is energy efficiency of Belt and Road Initiative countries catching up or falling behind? Evidence from a panel quantile regression approach. Appl Energy 253(July):113581. https://doi.org/10.1016/j.apenergy.2019.113581

Rosa EA, Dietz T (1998) Climate change and society. Int Sociol 13(4):421–455. https://doi.org/10.1177/026858098013004002

Rees WE (1992) Ecological footprints and appropriated carrying capacity: what urban economics leaves out. Environ Urban 4(2):121–130. https://doi.org/10.1177/095624789200400212

Salman M, Long X, Dauda L, Mensah CN, Muhammad S (2019) Different impacts of export and import on carbon emissions across 7 ASEAN countries: A panel quantile regression approach. Sci Total Environ 686:1019–1029. https://doi.org/10.1016/j.scitotenv.2019.06.019

Shabalov MY, Zhukovskiy YL, Buldysko AD, Gil B, Starshaia VV (2021) The influence of technological changes in energy efficiency on the infrastructure deterioration in the energy sector. Energy Reports 7:2664–2680. https://doi.org/10.1016/j.egyr.2021.05.001

Shahbaz M, Shahzad SJH, Ahmad N, Alam S (2016) Financial development and environmental quality: The way forward. Energy Policy 98:353–364. https://doi.org/10.1016/j.enpol.2016.09.002

Shahbaz M, Raghutla C, Song M, Zameer H, Jiao Z (2020) Public-private partnerships investment in energy as new determinant of CO2 emissions: The role of technological innovations in China. Energy Economics 86:104664. https://doi.org/10.1016/j.eneco.2020.104664

Shahzad U, Radulescu M, Rahim S, Isik C, Yousaf Z, Ionescu SA (2021) Do environment-related policy instruments and technologies facilitate renewable energy generation? Exploring the contextual evidence from developed economies. Energies, 14(3). https://doi.org/10.3390/en14030690

Shao X, Zhong Y, Liu W, Yi R, Li M (2021) Modeling the effect of green technology innovation and renewable energy on carbon neutrality in N-11 countries ? Evidence from advance panel estimations. J Environ Manage 296(June):113189. https://doi.org/10.1016/j.jenvman.2021.113189

Sharif A, Baris-Tuzemen O, Uzuner G, Ozturk I, Sinha A (2020) Revisiting the role of renewable and non-renewable energy consumption on Turkey's ecological footprint: Evidence from Quantile ARDL approach. Sustain Cities Soc 57(March):102138. https://doi.org/10.1016/j.scs.2020.102138

Sharma R, Sinha A, Kautish P (2021) Does renewable energy consumption reduce ecological footprint? Evidence from eight developing countries of Asia. J Clean Prod 285:124867. https://doi.org/10.1016/j.jclepro.2020.124867

Sohag K, Kalugina O, Samargandi N (2019) Re-visiting environmental Kuznets curve: role of scale, composite, and technology factors in OECD countries. Environ Sci Pollut Res 26(27):27726–27737. https://doi.org/10.1007/s11356-019-05965-7

Su HN, Moaniba IM (2017) Does innovation respond to climate change? Empirical evidence from patents and greenhouse gas emissions. Technol Forecast Soc Chang 122(May):49–62. https://doi.org/10.1016/j.techfore.2017.04.017

Ulucak R, Bilgili F (2018) A reinvestigation of EKC model by ecological footprint measurement for high, middle and low income countries. J Clean Prod 188:144–157. https://doi.org/10.1016/j.jclepro.2018.03.191

Wada I, Faizulayev A, Victor Bekun F (2021) Exploring the role of conventional energy consumption on environmental quality in Brazil: Evidence from cointegration and conditional causality. Gondwana Res 98:244–256. https://doi.org/10.1016/j.gr.2021.06.009

Wang H, Wei W (2020) Coordinating technological progress and environmental regulation in CO2 mitigation: The optimal levels for OECD countries & emerging economies. Energy Economics 87:104510. https://doi.org/10.1016/j.eneco.2019.104510

Wang K, Yan M, Wang Y, Chang CP (2020) The impact of environmental policy stringency on air quality. Atmos Environ 231(March):117522. https://doi.org/10.1016/j.atmosenv.2020.117522

Wang Q, Qu J, Wang B, Wang P, Yang T (2019) Green technology innovation development in China in 1990–2015. Sci Total Environ 696:134008. https://doi.org/10.1016/j.scitotenv.2019.134008

Westerlund J (2005) New Simple Tests for Panel Cointegration. Economet Rev 24(3):297–316. https://doi.org/10.1080/07474930500243019

Xie Z, Wu R, Wang S (2021) How technological progress affects the carbon emission efficiency? Evidence from national panel quantile regression. J Clean Prod 307:127133. https://doi.org/10.1016/j.jclepro.2021.127133

Yang L, Li Z (2017) Technology advance and the carbon dioxide emission in China – Empirical research based on the rebound effect. Energy Pol, 101(March 2016), 150–161. https://doi.org/10.1016/j.enpol.2016.11.020

Zhang H (2016) Exploring the impact of environmental regulation on economic growth, energy use, and CO2 emissions nexus in China. Nat Hazards 84(1):213–231. https://doi.org/10.1007/s11069-016-2417-7

Zhang W, Li G (2020) Environmental decentralization, environmental protection investment, and green technology innovation. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-020-09849-z