



# Does technology advancement reduce aggregate carbon dioxide emissions? Evidence from 66 countries with panel threshold regression model

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## Abstract

The influence of technology advancement on carbon dioxide (CO<sub>2</sub>) emissions is complex and controversial, yet existing literature ignores the level of economic development in regard to its influential effect. With the panel threshold regression model, this research investigates the marginal and non-linear impacts of technology advancement on CO<sub>2</sub> emissions along with the changes of economic development and presents the heterogeneity between different countries. The results are as follows: First, technology advancement and CO<sub>2</sub> emissions have a non-linear inverted U-shaped relationship, which is significantly affected by different levels of economic development. When economic development exceeds a certain threshold, the impact turns from positive to negative. Second, the impact varies remarkably among different countries. We provide evidence for inverted U-shaped and N-shaped correlations in the Organization for Economic Co-operation and Development (OECD) countries and high-income countries (non-OECD), respectively. Although technology advancement always promotes CO<sub>2</sub> emissions in middle- and low-income countries, its marginal effect is decreasing. This study not only indicates the dynamic impacts of technology advancement on CO<sub>2</sub> emissions in different countries, but also contributes to policymakers' understanding of the "common but differentiated responsibilities" involved in mitigating CO<sub>2</sub> emissions.

**Keywords** Technology advancement · CO<sub>2</sub> emissions · Threshold effects · Economic development stages

## Introduction

As the demand for energy grows around the world, climate change is increasingly exposing itself in many negative ways (Zhang et al. 2017; Lee and Chiu 2011; Hao et al. 2020; Lee et al. 2020). Carbon dioxide (CO<sub>2</sub>) emission reduction is now an important international issue (Youssef et al. 2016; Moutinho et al. 2017; Chen and Lee 2020), leading to dramatic discussions on the factors influencing such a reduction. In fact, greater attention is being paid to technology

advancement (Cheng et al. 2018; Du and Li 2019), as it not only is a process of continuous development, improvement, and replacement of environment-related technologies (Hayashi 2018), but also covers production efficiency improvement (Shapiro and Walker 2018; Chen et al. 2020; Yuan et al. 2020), which greatly contributes to economic prosperity. Technology advancement also closely relates to the levels and goals of economic development (Yuan et al. 2020). As for different economic development levels and goals, the impact of technology advancement on CO<sub>2</sub> emissions may exhibit a non-linear process and differ between countries (Chang and Lee 2008; Yang and Li 2017; Chen and Lee 2020).

Nearly all countries of the world emphasize that better technology can help reduce CO<sub>2</sub> emissions. Nonetheless, an obvious fact is that some countries, just like BRICS (Brazil, Russia, India, China, and South Africa), have experienced sharp increases in aggregate CO<sub>2</sub> emissions along with the industrialization as well as similarly significant progress in technology (Boden et al. 2015). Even in some developed

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countries, aggregate CO<sub>2</sub> emissions have recovered after a brief reduction (Li and Wang 2017), whereas France, Canada, and the USA are experiencing drops in CO<sub>2</sub> (Kasman and Duman 2015). This indicates that technology advancement might have different shocks on CO<sub>2</sub> emissions due to different economic development stages (Khattak et al. 2020). Therefore, it is necessary to gain insight into the non-linear changes of the impacts of technology advancement on CO<sub>2</sub> emissions during different economic development stages, because they can provide references for countries to formulate CO<sub>2</sub> emission reduction strategies. To this end, the present study aims to find evidence to identify different countries' marginal efforts and the non-linear process in order to shed light on the "common but differentiated responsibilities" of aggregate CO<sub>2</sub> emission reduction. This is the prime motivation of the research.

## Literature review

### Non-linear relationship between CO<sub>2</sub> emissions and economic growth

The environmental Kuznets curve (EKC) hypothesis postulates that economic growth and the environment share an inverted U-shaped relationship (Ang 2007), which was first proposed and tested by Grossman and Krueger (1995)—that is, when a country's economic development level is low, environmental quality sharply deteriorates along with economic growth. When economic development reaches a turning point, environmental quality achieves a notable improvement. Without considering international trade, the relationship is mainly reflected in three channels—namely, scale effect, structural effect, and technical effect (Grossman and Krueger 1995)—which closely relate to better technology (Apergis 2016). Thereafter, it is now very popular to study the effects of technology advancement and economic growth on environmental quality.

Research and development (R&D) investment theoretically can help promote environmentally friendly technologies that reduce greenhouse gas emissions (Bosetti et al. 2006; Chen and Lee 2020). In contrast, Berkhout et al. (2000) argued that technology advancement makes equipment more energy efficient and increases CO<sub>2</sub> emissions by boosting economic development. In other words, although countries may ameliorate economic development patterns and industrial structures, thus effectively reducing CO<sub>2</sub> emission intensity (Grubb 2006; Barrett 2006), they pay more attention on economic growth (Sánchez and Maldonado 2015). Considering different economies, for example, during the last few years, BRICS have experienced profound structural changes and technology advancement that continue to influence the evolution of CO<sub>2</sub> emissions, with potentially adverse consequences for global

mitigation strategies (Tamazian et al. 2009). In contrast, Jordaan et al. (2017) stated that investments in eco-innovation technologies have impacted CO<sub>2</sub> emission reduction among OECD economies. Although developing countries with rapid economic transitions and objectives of becoming developed nations, especially Malaysia and India, are on the same path that developed countries experienced, Saudi et al. (2019) argued that technological innovation could lead to a cleaner environment.

### Non-linear impact of technology advancement on CO<sub>2</sub> emissions

Grossman and Krueger (1995) noted that technologies generally receive little attention in the early days of economic development, but as the level of economic development improves, technological progress tends to reduce pollutant emissions. Ahmad et al. (2019) captured the positive and negative innovation shocks endogenously in the EKC equation. In other words, technological progress may be a double-edged sword, as it not only provides conditions for economic development and production but also causes ecological damage and environmental pollution (Yuan et al. 2020).

In terms of the degree of economic development, Du et al. (2019) confirmed that the income level matters for the effect of technology advancement, and that the impact of green technology innovations on CO<sub>2</sub> emissions presents a single-threshold effect regarding the income level. Yu and Du (2019) argued that the impact highly correlates to regional growth speed, and thus, the independent innovation of provinces with high-speed growth contributes greater toward promoting CO<sub>2</sub> emissions than it does for provinces with slower growth rates in China. Du and Li (2019) found that green technology innovations only influence high-income economies, and that it is difficult to find significant evidence that green technology innovations positively impact carbon productivity in less developed economies. Chen et al. (2020) presented that the nexus between technology advancement and CO<sub>2</sub> emissions depends on both environmental and production technological changes. Töbelmann and Wendler (2020) noted that environmental innovation contributes to the reduction of carbon dioxide emissions, while general innovative activity does not cause any decrease in emissions.

To sum up, most previous studies in the related literature have come to important and valuable conclusions, but there are still issues that need to be further addressed. The present study thus investigates the non-linear changes in the impacts of technology advancement on CO<sub>2</sub> emissions during economic development for the following reasons. First, this study emphasizes total factor productivity (TFP) rather than technological innovation as a form of technology advancement. As Cheng et al. (2018) and Chen et al. (2020) pointed out, technological innovation cannot essentially reflect the meaning of

technology advancement. In fact, technology advancement is not only reflected in specific technological innovations, such as R&D activities (Khattak et al. 2020), but also is particularly evident in production changes as well as efficiency changes, such as management and institution innovation (Chen et al. 2020). It is worth noting that the TFP based on the DEA (data envelopment analysis) -Malmquist model illustrates both connotations (Li and Lin 2016).

Second, considering the positive and negative effects of technology advancement on CO<sub>2</sub> emissions, this study provides a new perspective on the combination of technology advancement and economic development for explaining the formation of the EKC. In the early stages of economic development, technology advancement focuses on the scale of economic growth while ignoring pollutant emissions (Grossman and Krueger 1995). Moreover, as the level of economic development improves, it gradually tends to balance economic growth with CO<sub>2</sub> emission reduction (Lee et al. 2010; Sánchez and Maldonado 2015).

Third, this study combines the STIRPAT model and panel threshold regression model (PTR) to identify the marginal and non-linear impacts of technology advancement on CO<sub>2</sub> emissions (Wang et al. 2017). Although structural decomposition analysis (SDA) has been widely employed (Lin and Liu 2012; Andreoni and Galmarini 2016), it ignores changes to marginal effects. Thus, the efforts that developing and developed countries have made (if there are any) might be more keenly observed from the marginal change in technology advancement on CO<sub>2</sub> emission reduction (Cheng et al. 2018; Wang 2012). As such, it is crucial to improve the understanding and quantification of the threshold effect of technology advancement on CO<sub>2</sub> emissions according to different stages of economic development.

Finally, this paper studies 66 countries with different stages of economic development and thus provides additional reference for CO<sub>2</sub> emission reduction, especially in developing countries. More importantly, with the deepening of globalization, technology transfer is accelerating, which means that developing countries may have more opportunities to accept technological innovations from developed countries. Hence, the turning point of EKC may appear earlier to spur efforts at reducing global carbon emissions.

## The model and econometric methodology

To investigate the marginal and dynamic effects of technology advancement on CO<sub>2</sub> emissions, this study combines the STIRPAT model and the panel threshold regression model.

### STIRPAT framework

Ehrlich and Holdren (1971) first proposed the IPAT (influence, population, affluence, and technology) model, which is widely used to describe the effects of human activities on the

environment. Based on the IPAT model, the environmental impact ( $I$ ) is decomposed into three main driving factors: population size ( $P$ ), affluence ( $A$ ), and technology ( $T$ ) level. The model not only can examine the impacts of population, economic level, and technological progress on the environment but also be randomly expanded according to the specific situation of the country (Zhou et al. 2018; Chen and Lee 2020; Pham et al. 2020). The basic model runs as follows.

$$I = P \times A \times T \quad (1)$$

To analyze the stochastic impacts, this paper employs the STIRPAT framework (stochastic impacts by regression on population, affluence and technology) based on the IPAT model (Dietz and Rosa 1997). The STIRPAT model is the following equation:

$$I_{it} = \alpha_i P_{it}^{\beta_1} A_{it}^{\beta_2} T_{it}^{\beta_3} \varepsilon_{it} \quad (2)$$

In Eq. (2),  $\alpha$  is the constant term, and  $\beta_1$ ,  $\beta_2$ , and  $\beta_3$  are estimated parameters of  $P_{it}$ ,  $A_{it}$ , and  $T_{it}$ , respectively. Here,  $\varepsilon_{it}$  represents the error term,  $i$  ( $i = 1, 2, \dots, n$ ) refers to countries, and  $t$  ( $t = 1, 2, \dots, T$ ) refers to the time period. Equation (2) is generally processed by taking its logarithmic form as:

$$\ln I_{it} = \alpha + \beta_1 \ln P_{it} + \beta_2 \ln A_{it} + \beta_3 \ln T_{it} + \varepsilon_{it} \quad (3)$$

This paper mainly focuses on the variable  $T$  and its coefficient  $\beta_3$ . To investigate the influencing factors of CO<sub>2</sub> emissions, the extended model is presented as:

$$\begin{aligned} \ln \text{CO2}_{it} = & \alpha + \beta_1 \ln \text{pop}_{it} + \beta_2 \ln \text{pgdp}_{it} + \beta_3 \ln \text{tech}_{it} \quad (4) \\ & + \gamma_1 \ln \text{trade}_{it} + \gamma_2 \ln \text{service}_{it} + \gamma_3 \ln \text{energy}_{it} \\ & + \gamma_4 \ln \text{urban}_{it} + \gamma_5 \ln \text{fd}_{it} + \mu_i + \tau_t + \varepsilon_{it} \end{aligned}$$

Here,  $\mu_i$  and  $\tau_t$  capture the individual effect and time effect, respectively,  $\text{CO2}_{it}$  denotes carbon dioxide emissions,  $\text{pop}_{it}$  refers to population size,  $\text{pgdp}_{it}$  refers to GDP per capita, and  $\text{tech}_{it}$  refers to technology advancement. Extended from Chen and Lee (2020), this study includes influencing factors of CO<sub>2</sub> emissions, such as industrial structure, urbanization, trade openness, energy intensity, and financial development.

### Panel threshold model

The panel threshold regression (PTR) model proposed by Hansen (1999) can be used to both estimate the threshold value and to test the significance of the endogenous threshold effect. Based on Eq. (4), this paper employs the PTR model to investigate the impact from non-linear changes of technology advancement on CO<sub>2</sub> emissions via economic development. The expression is as follows:

$$\begin{aligned} \ln CO_{2it} = & \alpha + \beta_1 \ln pop_{it} + \beta_2 \ln pgdp_{it} + \theta_1 \ln tech_{it} \\ & \times \varphi(q_{it} \leq \delta) + \theta_2 \ln tech_{it} \times \varphi(q_{it} > \delta) \\ & + \gamma_1 \ln trade_{it} + \gamma_2 \ln service_{it} + \gamma_3 \ln energy_{it} \\ & + \gamma_4 \ln urban_{it} + \gamma_5 \ln fd_{it} + \mu_i + \varepsilon_{it} \end{aligned} \tag{5}$$

Equation (5) shows a single-threshold model, which needs a strong balanced data panel:  $\{CO_{2it}, X_{it} : 1 \leq i \leq n, 1 \leq t \leq T\}$ . Here,  $\varphi(\cdot)$  is the indicator function,  $q_{it}$  is the threshold variable, and  $\delta$  is the threshold estimator.

According to whether the threshold variable  $q_{it}$  is smaller or larger than the threshold estimator  $\delta$ , the samples are divided into two “regimes.” If  $q_{it} \leq \delta$ , then  $\varphi(q_{it} \leq \delta) = 1$ ; if not,  $\varphi(q_{it} \leq \delta) = 0$ . The difference between the two regimes is recognized by different regression slopes,  $\theta_1$  and  $\theta_2$ , respectively. Therefore, the hypothesis of no threshold effect can be expressed by the constraint  $H_0: \theta_1 = \theta_2$ , and if the null hypothesis is rejected, then there could be threshold  $\delta$ . Hence, the form of multiple thresholds can also be concluded if necessary.

### Description of variables and data

Considered that a balanced data panel is needed in the panel threshold model, the data involved in this study span from 1990 to 2014, and up to 66 countries are included, split into high-income countries (OECDs), high-income countries (non-OECDs), middle-income countries (merging upper middle-income countries and middle lower-income countries), and low-income countries. Appendix Table 11 provides the list. Data of CO<sub>2</sub> emissions come from the European Commission’s Global Climate Change Research Database (EDGAR), and the remaining indicators are from the World Bank database (see Appendix Table 11). The variables are constructed as follows.

#### Carbon dioxide emissions

Compared with carbon intensity, aggregate CO<sub>2</sub> emissions provide a more comprehensive picture of global climate change. Different from most literature employing carbon intensity as the dependent variable, this paper’s empirical model adopts aggregate CO<sub>2</sub> emissions to describe environmental changes, which is in line with the works of Li and Wang (2017), Wang et al. (2017), and Zhang et al. (2017).

#### Population

Impacts due to demographics are notable for our topic of concern (Zhang et al. 2017). Most studies found that population has a significant impact on the environment. The larger the

population is, the higher energy consumption is, resulting in more and more carbon emissions (Liddle 2013). Therefore, this study takes the number of total population into the STIRPAT framework.

#### Economic development

The threshold variable chosen in this study is GDP per capita (*pgdp*), which can directly affect the relationship between technology advancement and aggregate CO<sub>2</sub> emissions (Yu and Du 2019). As mentioned previously, the role of increased income at promoting environmental quality should be carefully interpreted in light of technological progress for environmental improvement. Therefore, it is of great significance to examine the non-linear relationship between technology advancement and CO<sub>2</sub> emissions under certain economic development levels. Additionally, as income greatly influences CO<sub>2</sub> emissions, this study also takes GDP per capita as an important explanatory variable.

#### Technology advancement

Based on the neoclassical economic growth model (Solow, 1957; Brock and Taylor 2010), the total factor productivity (TFP) index can be applied to represent technology advancement, which is in line with Cheng et al.’s (2018) and Chen et al.’s (2020) study. This study calculates TFP by the DEA-Malmquist index (Fare et al. 1994), which needs inputs like capital stock and labor force, as well as GDP output. Capital stock is measured by the perpetual inventory method, as in equation  $K_{it} = (1 - \delta) \times K_{i(t-1)} + I_{it}$ , where  $i$  is the country,  $t$  is the year,  $I$  refers to gross capital formation,  $K$  refers to capital stock, and  $\delta$  refers to a capital depreciation rate of 6% (Hall and Jones 1999). For the basic capital stock of 1990, this paper uses the formula  $K_{i1990} = I_{i1990}/10\%$ , dividing gross capital formation in 1990 by 10% (Shan 2008; Li and Wang 2017). Furthermore, to avoid any biased estimation, this study applies the bootstrap DEA method to get the bias-corrected TFP index and use it as a robustness test.

#### Control variables

**Trade openness** The impact of international trade on the environment has attracted a wide range of discussions in the trade policy literature. On the one hand, through international trade, pollutants from one country may be transferred to other countries along with goods and services (Ali et al. 2017). However, the impact of trade openness on carbon emissions varies from country to country, because of its technical and productivity effects (Shapiro and Walker 2018). For example, trade openness benefits the environment in developed countries (Managi et al. 2009), while it mostly boosts economic activities and consumes more energy and causes pollution in

developing countries. Therefore, this study incorporates trade openness into the model and further investigates its impact in countries with different development levels.

**Industrial structure** Along with the upgrading of industrial structure, economic activities gradually reduce energy consumption and thus will contribute to carbon emission mitigation (Zheng and Luo 2013). The present study uses the proportion of the service industry (*service*) to investigate the impact of industrialization on aggregate CO<sub>2</sub> emissions (Wang et al. 2017).

**Energy intensity** Energy consumption is another notable issue related to CO<sub>2</sub> emissions (Ang 2007; Li and Wang 2017). However, energy consumption closely also relates to urbanization and industrial structure, and it may have some uncertain and complex effects in the model (Ahmad et al. 2019; Liu and Lee 2020; Shahbaz et al. 2020).

**Urbanization** This issue covers the process of population shifting from rural areas to cities, which has led to a significant concentration of economic activities and energy consumption (Madlener and Sunak 2011). However, due to differences in industrial structure, public transportation, etc., the impacts on CO<sub>2</sub> emissions differ between different countries (Rafiq et al. 2016; Du et al. 2019).

**Financial development** A growing body of studies confirmed that the dramatical increase in CO<sub>2</sub> emissions is closely associated with the corresponding economic development (Le and Ozturk 2020; Nasir et al. 2019). As a crucial part of national economic growth, financial development may also have profound effects on CO<sub>2</sub> emissions (Zhao and Yang 2020). The development of financial sectors in developing countries possibly encourages new projects to be environmentally unfriendly and boosts energy consumption and CO<sub>2</sub> emissions. In contrast, it may also contribute to green development and reduce carbon emissions in developed countries.

## Data description

Table 1 lists the specific descriptions and statistics of the variables used for examining the nexus among carbon dioxide emission, economic growth, and technology advancement. It clearly shows the gap between the maximum and minimum of these values. First, carbon dioxide emissions vary from a minimum of 341.52 Kt to a maximum of  $1.07e + 07$  Kt, while the TFP index varies from a minimum of 0.0028 to a maximum of 23.38, and the same goes for economic development and population scales. It indicates that carbon dioxide emissions in different countries can vary greatly depending on the level of technology advancement. Economic growth, population, and technology

advancement also have potential impacts on carbon dioxide emissions. Second, for trade openness, industrial structure, energy intensity, urbanization, and financial development, these variables do not vary that much.

With regard to skewness and kurtosis, it is known that they measure symmetry and flatness of a data panel distribution, respectively. Skewness equal to 0 means that the data distribution shape is the same as that of a normal distribution; skewness  $> 0$  ( $< 0$ ) means that the data distribution shape is positively skewed (negatively skewed) compared with the normal distribution. The greater the absolute value is of skewness, the more serious the degree is of deviation in the distribution. Kurtosis equal to 0 indicates that the data distribution is as steep as a normal distribution; kurtosis  $> 0$  indicates that the data distribution is steeper than a normal distribution. Therefore, Table 1 shows that these variables are not distributed symmetrically. Almost all variables show right skewness, meaning that they are concentrated on the right and are unevenly distributed, especially carbon dioxide emissions, technology advancement, population scales, and energy intensity, while the variables of industrial structure and urbanization level are distributed slightly to the left. In terms of kurtosis, carbon dioxide emissions, technology advancement, population scales, and energy intensity exhibit leptokurtic and thick-tailed distributions. This indicates that these variables are not only mainly concentrated on the right side but also have a very high probability density.

Based on the skewness and kurtosis results, it is found that the above variables are not normally distributed. Furthermore, the Jarque-Bera test is conducted for the goodness of fit of the sample data with the skewness and kurtosis in line with the normal distribution. Table 1 shows that the Jarque-Bera test result of the above variables is significantly greater than 1, which means that it rejects the null hypothesis of normal distribution.

## Empirical results

### Multicollinearity testing

In order to eliminate the influence of a variable's dimension, all variables are processed logarithmically. This study conducts an ordinary least square regression to analyze the multicollinearity of all independent variables and to evaluate the variance inflation factor (VIF). The VIF values are far from the tolerance of 10 (Table 2), which indicates that there is no multicollinearity among the independent variables (Wang et al. 2017). Table 3 exhibits the unit-root tests of LLC and ADF-Fisher. The results indicate that all variables are at stationary level.

**Table 1** Description and summary statistics of variables

Symbol	Variable	Definition	Min	Max	Skewness	Kurtosis	JB test
<i>CO2</i>	Carbon dioxide emissions	Carbon dioxide emissions from fossil fuels and cement	341.52	1.07e+07	5.74	41.42	1.1e+05*** (0.000)
<i>tech</i>	Technology advancement	Total factor production index with the DEA-Malmquist index, taking 1990 as the base period	0.0028	23.38	3.33	14.45	1.2e+04*** (0.000)
<i>tech-bootstrap</i>	Technology advancement	Total factor production index with the bootstrap DEA model, taking 1990 as the base period	0.0034	19.73	3.23	13.51	1.0e+04*** (0.000)
<i>pop</i>	Population	Total population	254,826	1.36e+09	5.00	28.12	5.0e+04*** (0.000)
<i>pgdp</i>	GDP per capita	GDP divided by mid-year population (constant 2010)	161.83	111,968.3	1.47	5.19	922.1*** (6.e-201)
<i>trade</i>	Trade openness	Percentage of imports and exports in GDP, including goods and services	11.09	441.60	2.93	14.76	1.2e+04*** (0.000)
<i>service</i>	Industrial structure	Percentage of service value-added in GDP	18.91	87.64	-0.43	2.92	51.8*** (5.7e-12)
<i>energy</i>	Energy intensity	Energy use (kg of oil equivalent) per US\$1000 GDP (constant 2011)	47.60	1197.44	3.98	26.43	4.2e+04*** (0.000)
<i>urban</i>	Urbanization	Percentage of urban population in the total population	8.53	100.00	-0.48	2.41	86.35*** (1.8e-19)
<i>fd</i>	Financial development	Domestic credit to the private sector	0.81	357.32	1.35	5.03	788.6*** (6.e-172)

*p* values are in parentheses. \**p* < 0.1

\*\**p* < 0.05

\*\*\**p* < 0.01

**Table 2** Variance inflation factor

Variable	VIF	1/VIF
<i>lnpgdp</i>	3.09	0.323501
<i>lnfd</i>	2.43	0.412191
<i>lnservice</i>	2.04	0.490744
<i>lnurban</i>	1.94	0.514877
<i>lnpop</i>	1.85	0.541956
<i>lntrade</i>	1.57	0.638923
<i>lnenergy</i>	1.11	0.897581
<i>Intech</i>	1.02	0.982904
Mean VIF	1.88	

**Basic regression result**

Table 4 shows the basic regression result. Controlling a series of influencing factors, the result shows that technology advancement has no significant impact on CO<sub>2</sub> emissions, indicating that it does not accurately reflect the role of technology advancement on CO<sub>2</sub> emissions, but rather only focuses on technology advancement while at the same time ignoring changes in economic development stages (Du et al. 2019). On the other hand, although the impacts are not significant, the middle-income and low-income countries show a positive effect, while the high-income countries show a negative effect. This may mean that as the level of economic development increases, the impact of technology advancement on CO<sub>2</sub> emissions will change, which is a non-linear process. To that end, this study incorporates economic development levels into the indicator function and further employs the PTR model to explore the impact of technology advancement on carbon emissions with changes in economic development levels.

**Table 3** The panel unit-root tests' results at the level

Variable	LLC	ADF-Fisher
<i>lnCO2</i>	-2.1593***	5.5579***
<i>Intech</i>	-6.4305***	6.6160***
<i>lnpop</i>	-22.0996***	8.4566***
<i>lnpgdp</i>	-2.9560***	4.8287***
<i>lntrade</i>	-5.6187***	2.8415***
<i>lnservice</i>	-4.7145***	3.8101***
<i>lnenergy</i>	-6.0167***	4.9175***
<i>lnurban</i>	-6.6553***	18.6775***
<i>lnfd</i>	-2.4309***	5.7381***

\*\*\*Refers to significance at the 1% level

**Table 4** Results of the basic regression

Variable	(1) Full sample	(2) High-income (OECD)	(3) High-income (non-OECD)	(4) Middle-income	(5) Low-income
<i>Intech</i>	− 0.00689 (− 0.75)	− 0.00357 (− 0.58)	− 0.0146 (− 1.23)	0.00657 (0.44)	0.00321 (0.13)
<i>lnpop</i>	1.885*** (34.15)	1.281*** (19.37)	0.592*** (5.42)	1.070*** (11.62)	2.161*** (15.01)
<i>lnpgdp</i>	1.053*** (32.11)	1.025*** (28.39)	0.778*** (16.72)	1.427*** (26.78)	0.838*** (9.32)
<i>lntrade</i>	0.0230 (1.01)	− 0.0433* (− 1.76)	− 0.0173 (− 0.52)	− 0.0857** (− 2.28)	− 0.00415 (− 0.09)
<i>lnservice</i>	0.0353 (0.74)	− 0.134** (− 2.01)	− 0.319*** (− 3.34)	0.0869 (1.12)	− 0.117 (− 1.19)
<i>lnenergy</i>	0.703*** (20.98)	0.814*** (31.19)	0.833*** (13.41)	1.038*** (19.86)	0.410*** (5.16)
<i>lnurban</i>	0.227*** (3.12)	0.708*** (7.54)	0.0953 (0.46)	− 0.851*** (− 9.49)	0.213 (1.21)
<i>lnfd</i>	0.0123 (1.16)	− 0.0923*** (− 7.97)	− 0.00210 (− 0.08)	0.0207* (1.75)	0.144*** (5.54)
Individual	Yes	Yes	Yes	Yes	Yes
Time	Yes	Yes	Yes	Yes	Yes
_cons	− 34.44*** (− 33.43)	− 25.73*** (− 22.63)	− 9.339*** (− 3.78)	− 20.72*** (− 11.40)	− 36.24*** (− 12.70)
<i>N</i>	1650	625	175	350	500
<i>R</i> <sup>2</sup>	0.805	0.847	0.928	0.941	0.830

*t* statistics are in parentheses

\**p* < 0.1

\*\**p* < 0.05

\*\*\**p* < 0.01

### Panel threshold effect test

As shown in Table 5, it is first found that there are significant triple thresholds of economic development level, and the threshold estimates and confidence interval appear in Table 6. Within the 95% confidence interval, the threshold estimates are 6.5373, 7.4191, and 9.2710 and refer to

US\$690, US\$1667, and US\$10625 per capita (in 2010 prices), respectively. Furthermore, all countries are divided into four regimes by three thresholds, as shown in Fig. 1. This indicates that the impacts vary under different regimes. At the same time, countries have transformed over different threshold regimes along with economic development changes from 1990 to 2014.

**Table 5** Results of panel threshold testing

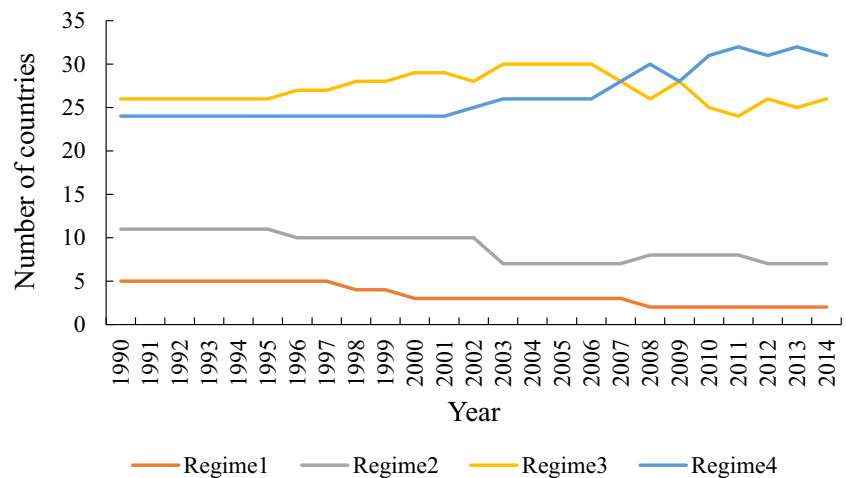
Model	<i>F</i> value	<i>p</i> value	<i>F</i> critical value		
			1%	5%	10%
Single threshold	80.9523***	0.0000	6.5462	4.1543	2.8690
Double thresholds	28.5316***	0.0000	6.5289	3.7547	2.6153
Triple thresholds	10.1291***	0.0000	5.2783	− 0.0735	− 2.1689

Note: *p* value and *F* critical value are the results of Bootstrap sampling for 1000 times

**Table 6** Results of threshold estimates

Threshold	Threshold estimate	95% confid. interval of threshold
$\theta_1$	6.5373	[6.4932, 6.5814]
$\theta_2$	7.4191	[7.2869, 7.6837]
$\theta_3$	9.2710	[9.0946, 9.9765]

**Fig. 1** Different groups divided by estimated thresholds. Notes: Regime1,  $\lnpgdp \leq 6.5373$ ; Regime2,  $6.5373 < \lnpgdp \leq 7.4191$ ; Regime3,  $7.4191 < \lnpgdp \leq 9.2710$ ; Regime4,  $\lnpgdp \geq 9.2710$



**Panel threshold regression results**

The results shown in Table 7 illustrate that technology advancement has a non-linear inverted U-shaped impact on CO<sub>2</sub> emissions. Adding control variables step by step, the regression results presented are robust. With continuous economic growth, technology advancement increases CO<sub>2</sub> emissions significantly. However, when per capita GDP exceeds US\$690 (in 2010 prices), technology advancement significantly reduces CO<sub>2</sub> emissions. On the one hand, the result above verifies the different impacts under various economic development stages (Du et al. 2019). On the other hand, the result above also shows the gradual changing of marginal effects, which is consistent with the research findings of Ang (2007) and Apergis and Payne (2009). Therefore, technology advancement is not conducive to environmental improvement. At the early stage of economic development, technology advancement can contribute to the improvement of economic scale and productivity, but little attention gets paid to environmental protection (Grossman and Krueger 1995). When economic development reaches a certain level, technology advancement shows a remarkable contribution to CO<sub>2</sub> emission mitigation, in which environmental friendly technologies play great roles (Chen et al. 2020).

Table 7 also shows the impacts of population, economic abundance, trade openness, industrial structure, energy intensity, and urbanization on CO<sub>2</sub> emissions. First, this study concludes that population and economic scale have positive effects on CO<sub>2</sub> emissions, which are consistent with the findings of Ali et al. (2017), Zhang et al. (2017), and Wang et al. (2017). With an increase in population and economic scale, people will consume more resources to meet overall demand and produce more outputs as well as more CO<sub>2</sub>. In terms of international trade, the present study finds a significantly negative impact on CO<sub>2</sub> emissions, which runs in contrast to Zhang et al. (2017). The effects of trade openness on CO<sub>2</sub> emissions are negative following the pollution-halo

hypothesis (Nguyen et al. 2020). Although international trade brings about the flow of goods and embodies carbon effects, it also accelerates technological transfer and spillover among countries (Huang et al. 2018), which can mitigate CO<sub>2</sub> emissions to some extent.

As for industrial structural upgrading, there is a negative effect on CO<sub>2</sub> emissions, but not significantly. As Jaforullah and King (2017) emphasized, energy intensity can cause systematic volatility in the model’s coefficients. On the other hand, energy consumption highly correlates to the manufacturing industrial structure. Therefore, regardless of the internal structure of the manufacturing industry, the index for the proportion of service value-added only can reflect industrial structural upgrading and cannot indicate optimization of the industrial structure (Cheng et al. 2018). Urbanization also shows no significant impact on CO<sub>2</sub> emissions, indicating a certain gap in the quality of urbanization for different countries (Li and Lin 2015). Financial development stimulates CO<sub>2</sub> emissions, but not significantly, which is consistent with the full sample result of Table 4. The main reason is that the maturity of financial sectors of developing countries possibly encourages new projects and activities, but is unable to reach achievements in allocating finance for environment-friendly projects, thus boosting energy consumption and CO<sub>2</sub> emissions (Le and Ozturk 2020).

**Thresholds in different groups**

As for countries with different economic development levels, this study further investigates the marginal effects of technology advancement in different groups, shown in Table 8. The result is still robust, and there are three thresholds. The research also draws a clearer conclusion in different countries for the impacts of technology advancement on CO<sub>2</sub> emissions, which show a diverse non-linear process.

Table 8 presents in the initial development stage of high-income countries (OECD and non-OECD) that technology



**Table 7** Results of the panel threshold regression for the full sample

Variable	(1)	(2)	(3)	(4)	(5)	(6)
<i>Intech</i> ( $lnpgdp \leq \theta_1$ )	0.0336*** (4.50)	0.0349*** (3.26)	0.0327*** (3.06)	0.0382*** (3.72)	0.0378*** (3.68)	0.0374*** (3.64)
<i>Intech</i> ( $\theta_1 < lnpgdp \leq \theta_2$ )	- 0.0045** (- 1.97)	- 0.0062** (- 2.58)	- 0.0071*** (- 2.93)	- 0.0068*** (- 2.92)	- 0.0068*** (- 2.91)	- 0.0068*** (- 2.91)
<i>Intech</i> ( $\theta_2 < lnpgdp \leq \theta_3$ )	- 0.0479*** (- 10.41)	- 0.0489*** (- 14.27)	- 0.0462*** (- 13.87)	- 0.0326*** (- 11.76)	- 0.0323*** (- 11.85)	- 0.0325*** (- 11.53)
<i>Intech</i> ( $lnpgdp > \theta_3$ )	- 0.0239*** (- 7.72)	- 0.0234*** (- 8.38)	- 0.0229*** (- 8.43)	- 0.0144*** (- 7.05)	- 0.0146*** (- 7.23)	- 0.0148*** (- 7.14)
<i>Inpop</i>	1.5893*** (36.19)	1.6153*** (21.82)	1.5832*** (21.58)	1.4978*** (21.72)	1.4672*** (20.12)	1.4666*** (20.04)
<i>lnpgdp</i>	0.4930*** (19.31)	0.5144*** (16.29)	0.5707*** (17.61)	0.9059*** (31.32)	0.8876*** (26.61)	0.8861*** (26.06)
<i>Intrade</i>		- 0.0668** (- 2.47)	- 0.0656** (- 2.56)	- 0.0550** (- 2.35)	- 0.0590** (- 2.54)	- 0.0597** (- 2.57)
<i>Inservice</i>			- 0.2849*** (- 5.31)	- 0.0601 (- 1.09)	- 0.0702 (- 1.25)	- 0.0771 (- 1.36)
<i>lnenergy</i>				0.7247*** (16.02)	0.7121*** (15.28)	0.7134*** (15.46)
<i>lnurban</i>					0.1214 (1.60)	0.1240 (1.61)
<i>lnfd</i>					0.0047 (0.35)	
<i>F</i>	20.65***	20.73***	18.33***	15.97***	15.07***	15.14***
<i>N</i>	1650	1650	1650	1650	1650	1650

*t* statistics are in parentheses

\**p* < 0.1

\*\**p* < 0.05

\*\*\**p* < 0.01

**Table 8** Thresholds in different groups

Countries	Regimes ( <i>lnpgdp</i> )	Coefficient ( <i>Intech</i> )	<i>t</i> statistics	<i>p</i> value
High-income (OECD)	(− ∞, 8.9871)	0.0659***	(4.07)	0.0001
	(8.9871, 9.9027)	0.0214***	(3.14)	0.0018
	(9.9027, 11.0295)	− 0.0160***	(− 7.92)	0.0000
	(11.0295, +∞)	0.0079	(1.50)	0.1345
High-income (non-OECD)	(− ∞, 9.1272)	0.0621***	(6.55)	0.0000
	(9.1272, 10.1745)	0.0097	(0.93)	0.3514
	(10.1745, 10.4317)	− 0.0223***	(− 3.19)	0.0017
	(10.4317, +∞)	0.0239*	(1.70)	0.0917
Middle-income	(− ∞, 7.9037)	0.1310***	(5.03)	0.0000
	(7.9038, 8.7297)	0.0485***	(7.79)	0.0000
	(8.7297, 9.1230)	0.0072	(0.68)	0.4945
	(9.1230, +∞)	0.0844***	(2.62)	0.0093
Low-income	(− ∞, 6.4053)	0.0920***	(4.99)	0.0000
	(6.4053, 6.5072)	0.3084***	(3.54)	0.0004
	(6.5072, 7.4040)	0.0581***	(6.27)	0.0000
	(7.4040, +∞)	0.0173**	(2.41)	0.0161

*t* statistics are in parentheses

\**p* < 0.1

\*\**p* < 0.05

\*\*\**p* < 0.01

advancement has increased CO<sub>2</sub> emissions, indicating that the goal of technological progress at this time is dominated by scale effects, and insufficient attention has been paid to environmental governance. When the level of economic development exceeds the threshold, the impact of technology advancement on CO<sub>2</sub> emissions begins to manifest as an intensity effect and to reduce CO<sub>2</sub> emissions significantly.

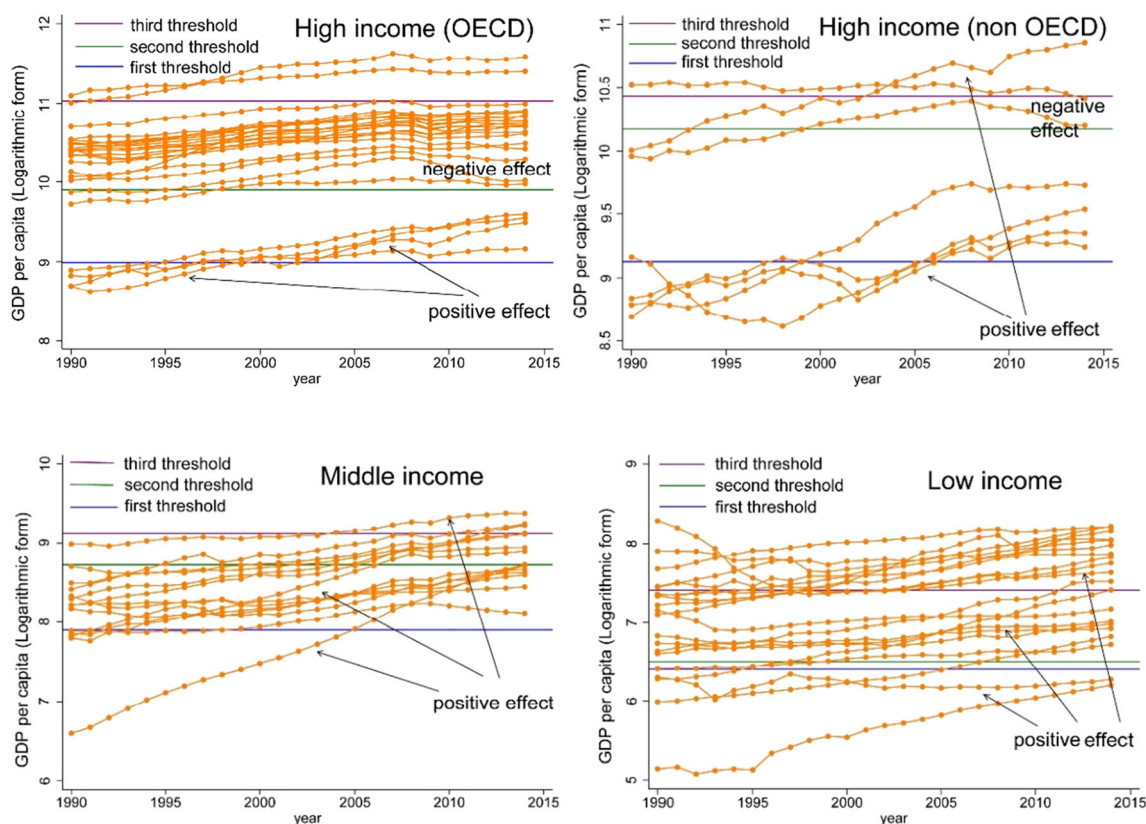
Technology advancement and CO<sub>2</sub> emissions have a significantly inverted U-shaped relationship in OECD countries. Under US\$19,984 GDP per capita (in 2010 prices), technology advancement increases CO<sub>2</sub> emissions significantly, but the marginal effect decreases with economic development. When GDP per capita exceeds US\$19,984, technology advancement significantly reduces CO<sub>2</sub> emissions, implying that the EKC theory holds. However, it should be noted that, although developed countries have higher incomes and are more likely to produce low-carbon and energy-efficient technologies, they are still likely to increase CO<sub>2</sub> emissions (Cheng et al. 2018), especially after GDP per capita moves beyond US\$61,666.

There is also a significant turning point in high-income countries (non-OECD). When GDP per capita exceeds US\$26,225 (in 2010 prices), technology advancement significantly reduces CO<sub>2</sub> emissions. However, different from OECD countries, when it exceeds US\$33,917 (in 2010 prices), technology advancement significantly increases CO<sub>2</sub>

emissions instead (Santra 2017). Overall, an N-shaped relation appears between technology advancement and CO<sub>2</sub> emissions in high-income countries (non-OECD).

As for middle- and low-income countries, technology advancement always promotes CO<sub>2</sub> emissions, meaning there is an absence of the EKC hypothesis, such as for China (Chen et al. 2020) and Malaysia (Ali et al. 2017). Interestingly, however, it can be seen that the marginal effect tends to be decreasing. This indicates that, due to the economic development level, technology advancement in middle- and low-income countries mainly focuses on production promotion while neglecting environmental protection to a certain extent. Nevertheless, the effort on CO<sub>2</sub> emission mitigation can still be found as the marginal effect of technology advancement decreases with the promotion of economic development.

Figure 2 shows threshold distributions of countries with different economic development levels. Here, the OECD countries are divided into three groups. Most OECD countries, such as France, Iceland, Belgium, Germany, Finland, Japan, the UK, and the USA, are within regime 3, where there is a significantly negative effect. Turkey, Portugal, Poland, and Mexico are distributed in regime 1 and regime 2, which show a significantly positive effect. Norway and Luxembourg are distributed in regime 4. The high-income countries (non-OECD) are divided into three groups. Argentina, Russia, Uruguay, and Trinidad and Tobago are currently transforming



**Fig. 2** Threshold distributions of countries with different economic development levels

from regime 1 to regime 2, in which these countries show a positive effect relying on large-scale energy production and consumption. Cyprus presents a significantly negative effect, while Brunei and Singapore are in regime 4, showing a positive effect due to population and energy consumption increasing. It is also found that most middle- and low-income countries have sustained economic growth during 1990 to 2014 and have been transforming from regime 1 to regime 4. However, the positive effect of technology advancement on CO<sub>2</sub> emissions remains relatively significant.

### Robustness test

Considering that the TFP estimation may be biased, this study further employs the bootstrap DEA model to estimate TFP of different countries and to calculate the index, and the results are still robust. First, Table 9 shows that without considering the impact of economic development level, the impact of technology advancement on CO<sub>2</sub> emissions is still insignificant, and the basic regression results are consistent with Table 4. Furthermore, this study tests the threshold regression results of different countries, which also show better robustness (Table 10).

## Conclusions and implications

### Conclusions

This study incorporates technology advancement, economic development levels, and CO<sub>2</sub> emissions into a unified framework and analyzes the threshold effects of technology advancement on CO<sub>2</sub> emissions by empirically combining the STIRPAT model and PTR model. The findings herein verify that the impact of technology advancement on CO<sub>2</sub> emissions closely relates to changes in the level of economic development. After considering economic development's influence on technology advancement, technology advancement and CO<sub>2</sub> emissions present an inverted U-shaped relationship, but this process varies for different countries. The relationship between technology advancement and CO<sub>2</sub> emissions has an inverted U-shaped trend in OECD countries, while high-income countries (non-OECD) show an N-shaped correlation. As for middle- and low-income countries, technology advancement always promotes CO<sub>2</sub> emissions, meaning there is an absence of EKC. However, efforts at CO<sub>2</sub> emission mitigation can be found as the marginal effect decreases. Moreover, when population, energy consumption, and

**Table 9** Robustness test of the basic regression

Variable	(1) Full sample	(2) High-income (OECD)	(3) High-income (non-OECD)	(4) Middle-income	(5) Low-income
<i>lntech-bootstrap</i>	− 0.00636 (− 0.67)	− 0.00359 (− 0.58)	− 0.0150 (− 1.23)	0.00561 (0.36)	0.00339 (0.14)
<i>lnpop</i>	1.885*** (34.15)	1.281*** (19.37)	0.592*** (5.43)	1.070*** (11.61)	2.161*** (15.01)
<i>lnpgdp</i>	1.053*** (32.11)	1.025*** (28.39)	0.778*** (16.72)	1.426*** (26.78)	0.838*** (9.32)
<i>lntrade</i>	0.0230 (1.01)	− 0.0433* (− 1.76)	− 0.0173 (− 0.52)	− 0.0858** (− 2.28)	− 0.00415 (− 0.09)
<i>lnservice</i>	0.0350 (0.74)	− 0.134** (− 2.02)	− 0.319*** (− 3.34)	0.0868 (1.12)	− 0.117 (− 1.19)
<i>lnenergy</i>	0.703*** (20.98)	0.814*** (31.19)	0.833*** (13.41)	1.038*** (19.86)	0.410*** (5.16)
<i>lnurban</i>	0.227*** (3.13)	0.708*** (7.54)	0.0970 (0.47)	− 0.851*** (− 9.48)	0.213 (1.21)
<i>lnfd</i>	0.0122 (1.16)	− 0.0923*** (− 7.98)	− 0.00215 (− 0.08)	0.0208* (1.76)	0.144*** (5.54)
Individual	Yes	Yes	Yes	Yes	Yes
Time	Yes	Yes	Yes	Yes	Yes
_cons	− 34.43*** (− 33.42)	− 25.72*** (− 22.63)	− 9.343*** (− 3.79)	− 20.72*** (− 11.39)	− 36.24*** (− 12.70)
<i>N</i>	1650	625	175	350	500
<i>R</i> <sup>2</sup>	0.805	0.847	0.928	0.941	0.830

*t* statistics in parentheses

- \**p* < 0.1
- \*\**p* < 0.05
- \*\*\**p* < 0.01

**Table 10** Robustness test of the threshold regression

Variable	(1) Full sample	(2) High-income (OECD)	(3) High-income (non-OECD)	(4) Middle-income	(5) Low-income
<i>lntech-bootstrap</i> ( <i>lnpgdp</i> ≤ $\theta_1$ )	0.1191*** (5.6354)	0.0689*** (4.0873)	0.0750*** (6.1135)	0.1382*** (5.0356)	0.0951*** (4.8840)
<i>lntech-bootstrap</i> ( $\theta_1 < \textit{lnpgdp} \leq \theta_2$ )	0.0601*** (6.1890)	0.0211*** (2.9138)	0.0457*** (4.5500)	0.0491*** (7.4111)	0.3082*** (3.4119)
<i>lntech-bootstrap</i> ( $\theta_2 < \textit{lnpgdp} \leq \theta_3$ )	0.0325*** (7.9888)	− 0.0173*** (− 8.1462)	− 0.0041 (− 0.5079)	0.0043 (0.3857)	0.0575*** (5.7887)
<i>lntech-bootstrap</i> ( <i>lnpgdp</i> > $\theta_3$ )	− 0.0112*** (− 4.8183)	0.0074 (1.3621)	0.0259* (1.8354)	0.0802** (2.4225)	0.0153** (2.0083)

*t* statistics in parentheses

- \**p* < 0.1
- \*\**p* < 0.05
- \*\*\**p* < 0.01

economic scale continue to increase, CO<sub>2</sub> emissions will increase accordingly, whereas trade openness reduces CO<sub>2</sub> emissions following the pollution-halo hypothesis. Due to differences in economic development, the service industry and financial development have a non-significant effect on carbon dioxide emission reduction.

### Policy implications

Based on the above results, some policy implications for governments and residents can be drawn. First, all countries should develop their CO<sub>2</sub> emission reduction plans based on their corresponding stages of economic development. Technology advancement is indeed related to economic development stages. Even for OECD countries, in terms of the present study, CO<sub>2</sub> emissions are likely to increase if no corresponding measures are taken. Therefore, governments and enterprises not only should focus on research and development activities for economic growth but they must also improve environment-friendly activities.

Second, “common but differentiated responsibilities” should be recognized as the consensus for tackling global climate change. Therefore, developing and developed countries should cooperate closely together to reduce carbon emissions. The great efforts of developing countries around the world should be observed in regard to the marginal effect changing along with technology advancement. Consequently, high-income countries can pay more attention to environment-friendly and energy-saving technology innovation as well as deregulation of new technologies related to CO<sub>2</sub> emission reduction at the same time. Middle-income and low-income countries may strive to promote economic efficiency with advanced technology applications, which means countries should cooperate to establish much freer and fairer international trade networks, which may facilitate technology spillovers between different countries. As a consequence, the division of responsibilities for carbon reduction needs to be considered overall, both for developed and developing countries.

Third, except for technology advancement, governments should also pay more attention to population scale, energy consumption, and industrial transformation, which also have important impacts on CO<sub>2</sub> emissions. For low-income countries, such as the Philippines, policy-makers should focus on high-quality development of their economy as well as the introduction of advanced foreign direct investment and new technologies. In addition, governments should set up reasonable population policies to ensure a demographic dividend and to curb excessive population growth at the same time. For middle-income countries, like China, governments should target improving resource efficiency rather than rapid economic growth with industrial transformation and renewable energy utilization. In high-income countries (non-OECD), such as

Russia and Uruguay, which excessively depend on resource-based industries, one essential policy is industrial structure adjustment to reduce energy intensity. High-income (OECD) countries should pay attention to efficient and environment-friendly economic growth, as well as initiate more energy conservation policies in order to reduce emissions. Moreover, governments and residents should promote low-carbon consumption policies that help raise welfare expenditures.

Last but not the least, compared with high-income countries, the poor quality of financial development has instead promoted CO<sub>2</sub> emissions in middle-income countries and low-income countries, and these countries have historically emitted relatively high carbon pollutants. Therefore, these countries should improve their technological level to reduce carbon dioxide emissions, increase the availability of credit by introducing high-quality foreign direct investment and capital markets, and promote technological progress, especially in energy-saving projects and technologies. It must be emphasized that in addition to the development of the financial sector, these countries should also support and encourage energy transformation, energy structure optimization, and population growth control. In addition, it is necessary to control rapid population growth and build low-carbon development in the process of urbanization.

This paper on the whole finds a non-linear effect of technology advancement on CO<sub>2</sub> emissions, which is influenced by the level of economic development, but there are still limitations. First, due to the limitation of balanced panel data, the sample of non-OECD high-income countries is small, which may affect the results. Second, this study pays more attention to the comparison of different types of countries, leading to in-depth analysis of specific countries. Third, this article chooses the TFP index as the proxy variable for technology advancement, which has certain reference significance from the perspective of the neoclassical economic model. However, it ignores the endogenous structural characteristics of technology advancement and the influence of institutions on technology advancement. Future research can further expand the dataset to enrich the research sample. At the same time, technology can be further decomposed, and structural differences over the impact of technology advancement and productivity on CO<sub>2</sub> emissions can then be compared in greater depth.

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responsible for its visualization and supervision; Chien-Chiang Lee is responsible for the investigation, analysis, and corresponding author.

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**Consent to participate** All authors participated in this article.

**Consent to publish** All authors have given consent to the publication of this article.

**Data availability** Data are available from the authors upon request.

**Compliance with ethical standards**

**Appendix**

**Table 11** List of sample countries

High-income (OECD) (25)		High-income (non-OECD) (7)	Middle-income (14)	Low-income (20)	
Australia	Mexico	Argentina	Algeria	Bangladesh	Philippines
Austria	Netherlands	Brunei Darussalam	Brazil	Benin	Senegal
Belgium	New Zealand	Cyprus	Bulgaria	Bolivia	Sri Lanka
Chile	Norway	Russian Federation	China	Cameroon	Sudan
Denmark	Poland	Singapore	Costa Rica	Congo	Togo
Finland	Portugal	Trinidad and Tobago	Dominican Republic	Egypt	Ukraine
France	Spain	Uruguay	Ecuador	El Salvador	
Germany	Sweden		Jordan	Honduras	
Greece	Turkey		Malaysia	India	
Iceland	United Kingdom		Mauritius	Indonesia	
Ireland	United States		Panama	Kenya	
Italy			Peru	Morocco	
Japan			South Africa	Mozambique	
Luxembourg			Thailand	Pakistan	

Note: Based on the World Bank database

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