Received: 17 June 2022 | Revised: 13 January 2023 | Accepted: 28 January 2023

DOI: 10.1002/sd.2514

RESEARCH ARTICLE

Sustainable Development WILEY

Sustainable development policies of renewable energy and technological innovation toward climate and sustainable development goals

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Funding information
Scientific Research at King Khalid University, Saudi Arabia for funding this work through Large Research Groups Program under, Grant/Award Number: L.R.G.P2/174/43

Abstract

This study seeks to investigate the possibility of achieving Chinese climate and sustainable development goals (SDGs) with technological innovations and renewable energy policies. Currently, China is ranked first in global emissions. Hence, we utilized Chinese data of 1996Q1 2018Q4 to investigate the policy implication of technological innovation and renewal energy towards its climate goals. Economic development, technology, energy and environmental policies are incorporated in our study for clear insight on the impact of technology and renewable energy on China's climate goals. We adopt different scientific approaches (structural break, bound method of co-integration, autoregressive dynamic lag-ARDL dynamics and granger causality test) for both quantitative and theoretical analyses. Our discussions and policy inference are based on the findings from ARDL and granger causality analyses. Findings from ARDL tests debunk the inverted U-shape EKC hypothesis for China. Technological innovations and renewable energies are found impacting favorably on Chinese environment by reducing carbon emissions. Output derived from Causality supports the results from ARDL with nexus established amongst the selected instruments. From the findings, we conclude by advocating for policy to be framed on renewable energy sector through investment and technological boosting towards a SDG for China.

KEYWORDS

China's sustainability study, economic growth, EKC, energy policy, technological policy, urbanization

1 | INTRODUCTION

The global impact of climate change is on the increasing trend with massive wildfires, droughts, hurricanes and floods, and it is reflected in the estimations that this effect will increase exponentially if no action is taken. According to these forecasts, global temperatures are expected to reach 3.2°C by 2100, with 2019 being the second warmest year on record.[1] This has enabled Climate Action to become one of the UN Sustainable Development Goals (SDGs), and the responsibility of all countries to take action against the climate crisis has become clear. The agenda of 193 countries that gathered under the umbrella of the United Nations for a global sustainable development in 2015 is summarized as follows; end poverty, protect the planet and live in prosperity for all. The UN SDGs as grouped into

17 targets align into China's priority, that is, sustainable development. The target is climate problems and poverty reduction which are rooted in China's crowded population, production capacity and high rated energy consumption.[2] On the other hand, the measures to be taken by countries that cause high carbon emissions, especially in this responsibility sharing, play a critical role in action against climate change. In this context, China and the United States are the two top most countries in global carbon emissions and China is rated high in energy consumption because of its increasing industrial and manufacturing activities which are more in fossil fuel. Amidst the campaign on how to mitigate carbon emissions, it will be interesting if China will shift from carbon economy by increasing its green production through deregulation of the renewable energy sector to accommodate all players (both public and private) in the sector.

As it is declared by President Xi Jinping of China in September 2020, China's climate goal is "to have CO_2 emissions peak before 2030 and achieve carbon neutrality before 2060".[3] The realization of this goal depends on the efforts of the China's authorities as well as the correct determination of the factors affecting carbon emissions. Majority of human activities that induce greenhouse gas emissions are centered on economic activities (industrial and manufacturing engagements) with excessive utilization of fossil fuels targeted on economic growth (Udemba, 2020). These economic activities are mostly concentrated at the cities which are associated with increase in number of people and businesses (i.e., population). Common feature of Chinese economic growth is the domineering force of fossil fuels such as coal, oil, and gas. Following the call for climate action ("achieving climate goals through carbon neutrality and other ways of controlling climate change") by nations including China, strategic policies are expected to be adopted for easy achievement of these goals (climate and SDGs). Technological innovation and renewable energy policies are two policies that have been studied by different scholars in separate ways towards the abatement of carbon emission but not too many studies have combined both policies in investigating the possibility of achieving climate goals especially for the case of China. Innovation involves the ability to conceive, develop and adopt new system totally different from the existing system. The interplay between technological innovation and renewable energy is vital in achieving a greater breakthrough in renewable energy installation and expansion due to cost minimization which is achieved from technological innovation cum research and development (R&D). The existing technological system is framed according to the use of fossil fuels which promote carbon emissions because of the excessive utilization of fossil fuels. Apart from few advanced nations that are shifting from carbon economy to green economy, many other countries especially the emerging countries like China are still operating carbon intensive economy. Shifting perspective from the old idea through technological innovation has not been taken into consideration by many scholars. Many scholars (Azam et al., 2021; Dong et al., 2020) have studied the mitigating power of renewable energy consumption on carbon emissions, while others (Alam et al., 2020; Liu et al., 2021) have considered technology in fostering good environmental development.

Against this background, the present study seeks to identify the best policy to ameliorate the increasing Chinese carbon emission and enhance its climate and SDGs through carbon neutrality. For effective investigation into the best practice and policy for achieving the sustainable goals, we combined and utilized technological innovation and renewable energy policies in testing the mitigating power of the chosen policies (technology and renewable energy) in abating carbon emissions. To achieve the objective of this study, we compliment the technological innovation and renewable energy with other control variables (such as urbanization and economic growth) to test the China's environmental and climate goals. China is among the largest emerging countries with domineering features of increase economic growth and rural urban migration (urbanization). We apply environmental Kuznets curve (EKC) to expose the development (economic and environmental) pattern in existence for China. Different methods (structural break tests, bound tests of cointegration, and ARDL methods) are utilized in this study. In extension, granger causality is equally applied for a robust check to the findings from other methods. Apart from our study, other studies have worked on Chinese environmental performance amidst high emissions, but none of them has studied the nexus among technological innovation and renewable energy in a quantitative expression to test the ability of China to mitigate emissions. Also, most studies on Chinese climate goals are based on panel studies (such as BRICS and seven emerging economies, etc.), hence, the need for in-depth study of China in a country specific approach. Thus, the present study is a time series study that focuses on in-depth study of China with significant findings and analyses. By adopting both technological innovation and renewable energy policies, this study is intended to close the gap of nexus between innovation (technological) and renewable energy development for the case of China in the current literature. The objectives of this study are as follows: (a) to test the impact of technological innovation towards mitigating Chinese carbon emissions, (b) to test the impact of renewable energy sector development towards mitigating Chinese emissions, (c) to test the impact of urbanization and economic growth on Chinese environmental performance, (d) to test EKC hypothesis for the case of China, (e) to test the effect of nexus between technological innovation and renewable energy sector on carbon emission through granger causality. Findings from our study have implications and will be relevance to other countries with likely economic and environmental features like China, hence, aid in valid conclusion with factual policy framing and recommendation.

Other parts of this study are Sections 1–5 for theoretical background, literature review, methodology and data, empirical discussion, and conclusion with policy recommendation.

2 | LITERATURE REVIEW

Renewable energy consumption, technological innovations (or R&D expenditures as an indicator of it), urbanization and economic growth are frequently analyzed in the literature as the leading determinants of carbon dioxide emissions. In this sense, there are empirical studies for both China and countries outside of China. Despite the differences in the methods used and the countries studied, the finding that renewable energy and technological innovations play a role in reducing CO_2 emissions, with the exception of a few studies, stands out. There is no consensus on the impact of urbanization and economic growth on CO_2.

Considering the literature evaluating the relationship between renewable energy consumption and CO_2 emissions, Dong et al. (2020) covering 120 countries between 1995 and 2015, Akram et al. (2020) covering 66 developing countries between 1990 and 2014 and Anser et al. (2020)'s studies covering developing economies of Latin America and the Caribbean is that CO_2 emissions decrease as renewable energy consumption increases. This negative correlation between the two variables was found by Azam et al. (2021), Haldar and Sethi (2021), Altinoz and Dogan (2021), Hasanov et al. (2021) and Radmehr et al. (2021) was also repeated in his studies. In addition, Udemba and Tosun (2022) concluded that the use of renewable energy negatively affects CO_2 emissions in their study with Brazilian time series of approximately 50 years. Saidi and Omri (2020) studied 15 major renewable energy-consuming countries over the 1990–2014 periods, unlike previous studies, could not find a long-term relationship between renewable energy consumption and CO_2 emissions. However, according to this study, there is a bidirectional causality between the two variables in the short run. Since there is a positive and high coefficient relationship between the urbanization variable and the CO_2 emission variable, the cause of pollution in the mentioned countries is urbanization, not the use of non-renewable energies. Therefore, with some exceptions, the hypothesis that there is a negative relationship between renewable energy consumption and CO_2 emissions can be accepted. This situation is reported by Chen, Wang, and Zhong (2019), Chen, Zhao, et al. (2019), Wang et al. (2018), Yu et al. (2020), Zhang, Yang, et al. (2021), Zhang and Zhang (2021), and Huang, Xue, and Khan (2021) were also reflected in their studies, and in these studies 1993–2011, 1980–2014, 1995–2012, 2005–2016, 2004–2019, 1960–2019, respectively. It has been determined that there is a negative relationship between renewable energy consumption and CO_2 emissions in China in the 1995–2019 periods.

Many scholars (Akram et al., 2020; Altinoz & Dogan, 2021; Anser et al., 2020; Azam et al., 2021; Dong et al., 2020; Haldar & Sethi, 2021; Hasanov et al., 2021; Radmehr et al., 2021; Saidi & Omri, 2020) have studied the mitigating power of renewable energy consumption on carbon emissions, while others (Alam et al., 2020; Bai et al., 2020; Erdoğan et al., 2020; Huang, Wu, & Zhu, 2021; Khan, Ali, Kirikkaleli, et al., 2020; Kihombo et al., 2021; Lin & Zhu, 2019; Liu et al., 2021; Mo, 2021; Paramati et al., 2020; Petrović & Lobanov, 2020; Sheng et al., 2019; Yu & Du, 2019; Zhang et al., 2020) have considered technology in fostering good environmental development.

R&D studies are an area that needs to be supported in order to develop the necessary technical knowledge and technologies to reach renewable energy. Developed knowledge and techniques help to provide better service and prevent environmental damage by increasing energy efficiency. Similarly, there are many studies that conclude that there is a negative relationship between R&D expenditures and CO_2 emissions, which are an indicator of technological innovation. Alam et al. (2020) for the period 1996–2013, Petrović and Lobanov (2020) for the period 1981–2014 OECD countries, Erdoğan et al. (2020) G20 countries for the period 1991–2017, Paramati et al. (2020) examined 25 European Union (EU) member countries for 1998–2014 and found an inverse relationship between the two variables. This result was repeated by Huang, Wu, and Zhu (2021), Kihombo et al. (2021), Mo (2021), and Philip et al. (2022), for different countries and country groups. It was also confirmed by Lin and Zhu (2019), Yu and Du (2019), Sheng et al. (2019), Zhang et al. (2020), Bai et al. (2020), Khan, Ali, Kirikkaleli, et al., 2020, Liu et al. (2021), who analyzed China, where technological innovation will lead to a decline in CO_2 emissions, although the country and research method change. However, the development of technologies that will produce renewable energy is extremely expensive. For this reason, if developing countries spend their limited resources only on R&D of renewable energy, this may mean excluding other production factors. In this case, it can hinder the development of economies. For this reason, it is important to maintain a balance of expenditures.

Although it is observed that the increase in urbanization and economic growth mostly has an increasing effect on CO_2 emissions, it has been reflected in some studies that CO_2 emissions also change according to income or different stages of urbanization. Scholars (Khan, Ali, Umar, et al., 2020; Majeed & Tauqir, 2020; Umar et al., 2020; Zhang et al., 2023) have attempted to study the implication of economic growth and other related factors towards the determination of China's climate action. According the findings from the work of Umar et al., 2020, using ARDL ad dynamic ordinary least square they found economic growth and natural resource having positive relationship with carbon emissions, while the study from Majeed & Tauqir, 2020, applying dynamic generalization method of moment for a panel study found economic growth exerting a non-uniform impact on environmental performance of the selected countries From the work of Zhang et al. (2023), using ARDL and Fourier Toda Yamamoto, they found economic growth and energy use impacting negatively on China's environmental development. From the work of Khan, Zhang, Kumar, et al., 2020, they applied structural equation to study China's environmental development and found that the use of renewable energy sources and will improve both environmental and economic growth. According to Wang et al. (2021) and Musah et al. (2021) concluded that both economic growth and urbanization increase CO_2 emissions, while Muhammad et al. (2020) found an inverted U-shaped relationship between urbanization and CO_2 emissions only in high-income BRICS countries. One of the researchers dealing with China, Xiaoyuan et al. (2020), Zheng et al. (2021) and Zhou et al. (2021), urbanization causes an increase in carbon emissions. Huo et al. (2021), on the other hand, found that CO_2 emissions will increase with the increase in per capita income with the encouragement of urbanization in China. Incorporating income into the model with urbanization, Zhang, Wang, et al. (2021) found that urban expansion has a more significant effect on carbon emissions than economic growth in China, while Sun and Huang (2020) concluded that after a certain critical point of urbanization, the growth rate in CO_2 emissions will exceed the economic growth rate. Relatively unlike Sun and Huang, Zhao et al. (2020) found that as the level of economic development improves, CO_2 emissions will decrease. This result was also supported by Wang, Mirza, et al.'s (2020) study and it was determined that advanced levels of urbanization would reduce carbon emissions (Hao et al., 2021).

3 | DATA AND METHODS AND MODELLING

3.1 | Data and variables

Chinese quarterly data of 1996–2018 are utilized in this work to investigate the policy implication of technological innovation and renewal energy consumption. The data was converted into quarterly data for expansion and availability of more sample period. We acknowledged that the method (Autoregressive Distributed Lag-ARDL) adopted in our study accommodate limited sample period, however, in order for a more valid and undisputed results, we convert the annual data into quarterly data through match sum method with Eviews software. Among the variables adopted in this study which are considered important for the analysis are technological innovation as proxy by research and development expenditure, renewable energy as proxy by the summation of the renewable energy sources and urbanization as proxy by urban population. Other control variables also utilized in this research are economic growth and its squared proxy as income per capita and squared income per capita. The indicator for measuring sustainability through environmental performance is carbon dioxide (CO_2) emissions. Following the strategic position carbon emission occupies in the composition of greenhouse gas emission (i.e., about 70%) and its direct impact on the environment, it is adopted as the dependent variable and the indicator to measure sustainable development of China through its environment performance. The data are sourced from British Petroleum (2019). The focus of this study is on both technological innovation and energy policies toward mitigating carbon emission and achieving climate goals.

3.1.1 | Explanatory variables

Technological innovation has been considered by researchers (Chen & Lee, 2020; Lin & Zhu, 2019; Yu & Du, 2019) from different perspectives (patents and R&D) as a contributing factor in moderating climate change and achieving sustainable development. We adopt R&D as a proxy to technological innovation because of its ability to reflect the indigenous research and development activities (Coe & Helpman, 1995; Huang et al., 2019a). The expected impact of technological innovation on environment is positive with adverse connection with CO_2 emissions, that is, $(\beta_1 = (\partial CO_{2t}/\partial TECH) < 0)$. The R&D data are sourced from 2019 World Bank Development Indicator (WDI).

Energy policy is among the policies adopted in this study (with focus on renewable energy) to investigate the current climate performance of China and its ability to achieve climate cum SDG. Currently, China has the largest installed capacity of three major renewables (hydro, solar, and wind power) globally. The inexhaustible nature of renewable energy source due to the availability of water, wind and Sun has made it to be preferred to fossil fuels such as coal, oil, and gas which are finite (exhaustible) in nature in achieving SDGs. The interplay between technological innovation and renewable energy is vital in achieving a greater breakthrough in renewable energy installation and expansion due to cost minimization which is achieved from technological innovation cum research and development (R&D). Renewable energy source has been utilized by Alola and Kirikkaleli (2019), Kirikkaleli and Adebayo (2020), and Shahbaz et al. (2020) to test the possibility of achieving climate goals. Hence, the expected impact of renewable energy source on environment is positive through its adverse connection with CO_2 emissions, that is, $(\beta_1 = (\partial CO_{2t}/\partial REN) < 0)$.

Economic growth and Urbanization (urban population) are adopted in this study to uncover the implication of economic activities and rural–urban migration on the Chinese environment. Income per capita is adopted to proxy economic growth. Environmental Kuznets curve is utilized in this study by incorporating squared economic growth to depicts the impacts of successive economic growth on the environment of China through the historical pattern of relationship that exist between economic growth and the environment via greenhouse gas emissions. It is believed that most developing economies including China are still keen towards economic growth than environmental development at the early stage of growth, and economic activities are dominated by excessive utilization of fossil fuel energy sources. Economic growth with EKC has been utilized by Alola and Joshua (2020), Bekun et al. (2020), Kirikkaleli and Adebayo (2020), Udemba and Yalçıntaş (2021), Udemba (2021a, 2021b), and Udemba et al. (2020) to investigate the environmental development amidst economic growth and they mixed results. When the impact on the environment is positive or negative, the relationship between economic growth, urbanization and environment through carbon emissions are negative or positive, that is, $(\beta_1 = (\partial CO_{2t}/\partial GDP) < 0)$ or $(\beta_1 = (\partial CO_{2t}/\partial GDP) > 0)$ for economic growth and $(\beta_1 = (\partial CO_{2t}/\partial URB) < 0)$ or $(\beta_1 = (\partial CO_{2t}/\partial URB) > 0)$ for urbanization.

As stated before, the sources of the data utilized in this study are BP data review for emissions and energy-related variables, and WDI for economic growth, technological innovation and urbanization. The data utilized in this study are explained and summarized in Table 1. The graphical representation of the trend of the variables is equally shown in Figure 1 immediately after the Table 1.

3.2 | Methodology, theoretical background, and modelling

3.2.1 | Methodology

Authors applied different methods in order to achieve the intent of this study. Scientific methods such as bound test cointegration for the

TABLE 1 Intro of Data and instruments.

Variables	Short Names	Measurements	Sources
Economic growth	GDP	GDP per capita (US$)	World Bank Development Indicators (WDI)
Squared Economic growth	GDP^2	GDP per capita (US$)	WDI
Technological (R&D) Innovation	TECH	Research and Development expenditure	WDI
Renewable Energy Consumption	REN	Million tonnes oil equivalent	British Petroleum (BP) data review
Carbon dioxide emissions	CO_2	Million tonnes of CO_2	BP data review
Urbanization	URB	Urban population	WDI

Source: Authors' Compilation.

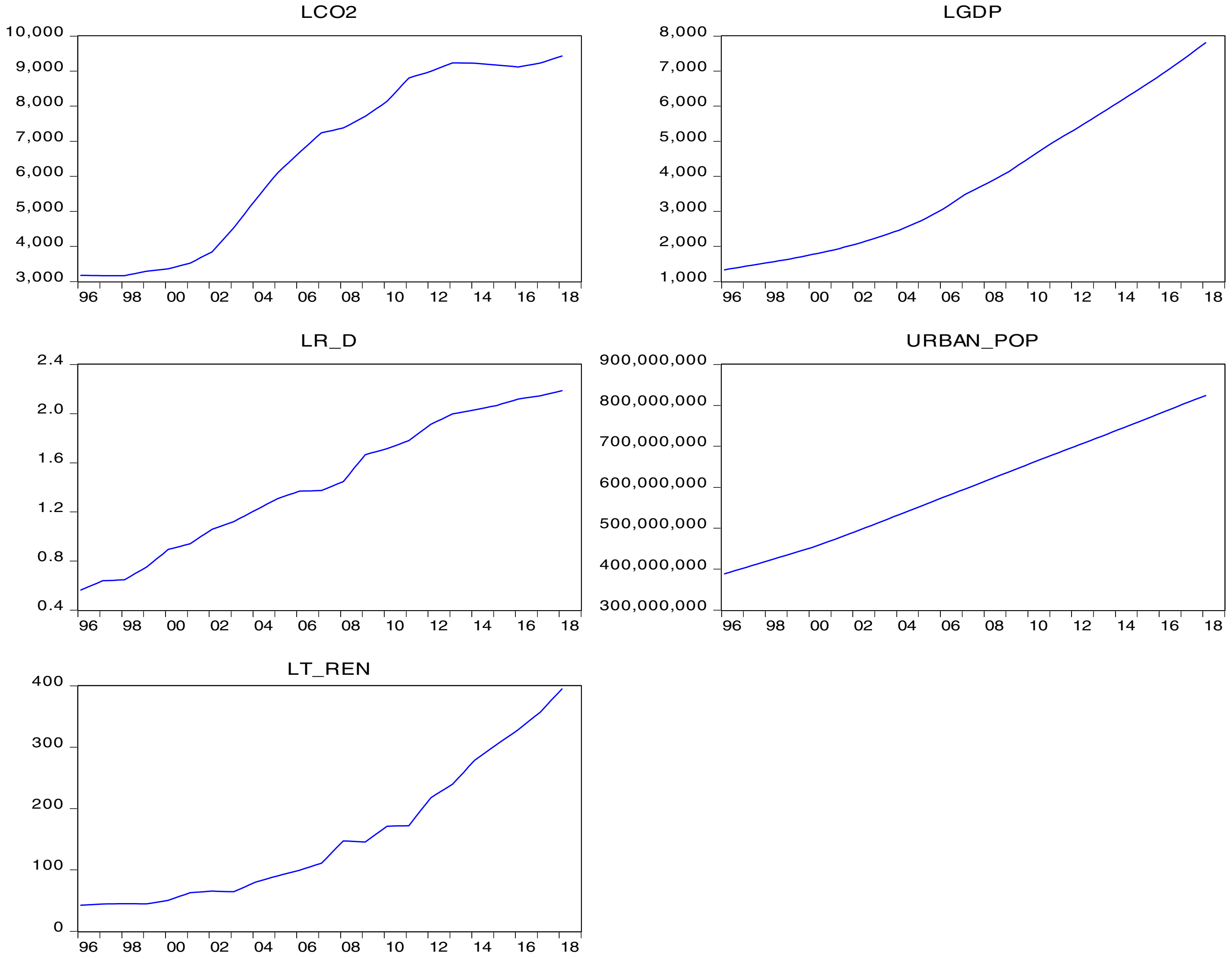

FIGURE 1 The graphs Economic development (GDP per capita), carbon emissions, renewable energy source, technological innovations, and urbanization as they appeared in Chinese data of 1996Q1 2018Q4. *Source*: Authors' computation. [Colour figure can be viewed at wileyonlinelibrary.com]

evidence of long run relationship among the variables, granger causality for inference and forecasting measures, structural break test as a supplement to unit root test and shock for validating the stability of the data and variables applied in this study, descriptive statistics and stationarity test are all adopted in this study to expose the distributive tendencies of the data and series.

3.2.2 | Theoretical background and modelling

Modelling of this study follows after the theoretical background of the study-IPAT (STIRPAT) and ARDL-bound test. STIRPAT is extended version of IPAT which accommodate the empirical and hypothetical testing of human involvement and impact on environmental development through other factors such as population, technology, and wealth/affluence. Following the ability of STIRPAT model to accommodate functional form of the variable, this study also incorporate EKC hypothesis in the model. Hence, the model according to IPAT and STIRPAT are as follows (Ehrlich & Holdren, 1970; Ehrlich & Holdren, 1971; Fan et al., 2006; York et al., 2002, 2003):

The IPAT model takes this form:

$$I = PAT \tag{1}$$

While, the STIRPAT model in a statistical form is expressed as follows:

$$I = \alpha P^b A^c T^d \text{ e} \tag{2}$$

Equation (1) transformed to logarithmic form which enables the conversion of the exponents into coefficients of the variables. Hence, model in log form is as follows:

$$lI = \alpha + blP + clA + dlT + e \tag{3}$$

The properties of Equations (3)–(5) have been explained from the Equations (1) and (2) from theoretical framework section with little clarification on the changes that occurred in the position of b, c and d. Instead of remaining as the exponents of the fundamental/explanatory variables as they appeared in Equation (1), they are converted to coefficients of the variables in a logarithmic form. Equations (1)–(3) contain three fundamental variable that are common with IPAT model. But with expansion of IPAT to STIRPAT the above equations can be expanded to contain other control variables with the polynomial form (Destek, 2018; Dietz & Rosa, 1994; Guo et al., 2019). Variables adopted in this study as displayed in Table 1 are economic growth, squared economic growth, technological innovation, renewable energy consumption, carbon dioxide emissions and urbanization. While carbon emission (I), urbanization (P), economic growth (A) and technological innovation (T) represent the three basic variables in the original IPAT model, other variables (squared economic growth, and renewable energy consumption) included in the model gives the model the extended version of IPAT (STIRPAT) which is allowed to contain other variables both in linear and quadratic form. Hence, the expanded IPAT (STIRPAT) model with inclusion of other variables is expressed as follows:

$$lCO_2 = a_o + a_1 lURB + a_2 lGDP + a_3 lGDP^2 + a_4 TECH + a_6 lR.E + e \tag{4}$$

From Equation (4), $lCO_2, lURB, lGDP, lGDP^2, TECH, lR.E,$ and e represent carbon dioxide emissions measured in million tonnes of carbon dioxide, population proxy by urban population, economic growth, and squared economic growth proxy by GDP per capita and squared GDP per capita (all measured in US$), technological innovation, renewable energy measured in million tonnes of oil equivalent and error term. All the instruments are stated in log form. As remarked before, all the economic related variables (GDP per capita, technology, and urban population) are sourced from World Bank Data (WDI) while the energy-related variables (carbon dioxide emissions, renewable energy) are sourced from BP review.

Additionally, we adopt ARDL-bound method to test for the cointegration and the possibility of long period connection among the instruments. The cointegration modelling is according to ARDL model with addition of short path and long path models. ARDL-bound test is favored among other methods of cointegration because of its suitability in estimating mixed order of integration of the series and analysis with small sample size with the exception of order $I(2)$. The bound method of cointegration test is calculated by comparing the values of both F and T stats with the critical values of upper bound, and cointegration is confirmed if the values of F and T stats are greater than the values of upper bound. The hypothetical statement of non-existence or existence of cointegration is expressed with null hypothesis and alternative hypothesis as: Null (H_0): $a_i = 0$ and the Alter (H_1): $b_i \neq 0$. While the null hypothesis is of opinion that there is no cointegration, the alternative hypothesis is rejecting the notion by saying there is cointegration. The ARDL-bound is modelled with addition of short path, long path, and error correction model (ECM) as follows:

$$\begin{aligned}\Delta lCO_{2t} = {} & a_0 + a_1 lCO_{2t-1} + a_2 lURB_{t-1} + a_3 lGDP_{t-1} + a_4 lGDP^2{}_{t-1} \\ & + a_5 TECH_{t-1} + a_6 lR.E_{t-1} + \sum_{i=0}^{s-1} \emptyset_1 \Delta lCO_{2t-i} + \sum_{i=0}^{t-1} \emptyset_2 \Delta lURB_{t-i} \\ & + \sum_{i=0}^{t-1} \emptyset_3 \Delta lGDP_{t-i} + \sum_{i=0}^{t-1} \emptyset_4 \Delta lGDP^2{}_{t-1} + \sum_{i=0}^{t-1} \emptyset_5 \Delta TECH_{t-i} \\ & + \sum_{i=0}^{t-1} \emptyset_6 \Delta lR.\mathrm{E}_{t-i} + ECM_{t-i} + \varepsilon_t\end{aligned} \tag{5}$$

The properties in Equation (5) have been defined and explained in Equations (1)–(4). Remaining properties are a_i, $\emptyset_i$ (i = 1, 2 .etc.), $\sum, \Delta$ and ECM_{t-i} and they represent long run (a_i) and short run ($\emptyset_i$) coefficients, summation of short run and differenced operator of the instruments ($\sum, \Delta$), and the error correction model (ECM_{t-i}) which shows the capacity to amend short path imbalance and establish equilibrium in the long path.

4 | RESULTS AND DISCUSSIONS

4.1 | Summary of statistics

The feature of the data applied in this paper is explained with statistics. The statistics exposes the distributional nature and the stability tendencies of the data utilized in this study. From the outcome of descriptive statistics, information on the distribution and stability tendencies of the data is confirmed with Kurtosis and skewness. Hence, all the outcomes of kurtosis are all well below 3 showing that the data is well and normally distributed. Even the outcome of skewness points towards the normally distributed data with all the outcomes been below 1 or −1 (Table 2).

TABLE 2 Descriptive statistics.

	CO_2	GDP	REN	R_D	URBAN_POP
Mean	6522.769	3837.998	133.3445	1.433870	5.98E+08
Median	7240.328	3480.153	109.8031	1.373690	5.96E+08
Maximum	9428.712	7806.953	272.0799	2.185680	8.24E+08
Minimum	3163.740	1332.417	42.53292	0.563240	3.89E+08
Std. Dev.	2418.979	2003.850	78.78259	0.517620	1.31E+08
Skewness	−0.240779	0.429508	0.460609	−0.104582	0.061328
Kurtosis	1.418230	1.838738	1.774628	1.694514	1.755962
Jarque-Bera	10.13820	7.737205	8.715251	6.482328	5.794925
Probability	0.006288	0.020888	0.012809	0.039118	0.055163
Sum	580526.5	341581.8	11867.66	127.6145	5.32E+10
Sum Sq. Dev.	5.15E+08	3.53E+08	546189.3	23.57784	1.50E+18
Observations	89	89	89	89	89

Source: Authors' computation.

TABLE 3 Unit root test.

Variables	@Level		@ 1st Diff		
	Intercept	Intercept and trend	Intercept	Intercept and trend	Order
PP					
LCO_2	−0.8284	−1.1667	−1.7598	−1.8850*	*I*(1)
LGDP	3.6897	- 3.6190*	−1.6418	0.4684	*I*(0)
LURB	0.9764	−3.5198*	−1.3007	0.2912	*I*(0)
LTECH	−1.4580	−0.4647	−2.9415*	−3.3595*	*I*(1)
LREN	5.4921	−0.7698	−1.5809	−3.8512**	*I*(1)
ADF					
LCO_2	−1.5781	−1.0295	−2.3382	−2.6705**	*I*(1)
LGDP	−1.1391	−3.9596**	−1.6383	−0.1989	*I*(0)
LURB	1.2243	−3.5551*	−1.3007	0.4834	*I*(0)
LTECH	−1.5356	−1.3046	−2.9436*	−3.3549*	*I*(1)
LREN	−1.2874	−2.0678**	1.4437	2.8252*	MIXED
KPSS					
LCO_2	0.6443**	0.1285*	0.1764	0.1409*	MIXED
LGDP	0.6701**	0.1807**	0.5591**	0.1952**	MIXED
LURB	0.6846**	0.1369*	0.2649	0.1856**	MIXED
LTECH	0.6772**	0.1333*	0.3448	0.1253*	MIXED
LREN	0.5582**	0.1804**	0.5633**	0.1911**	MIXED

Note: *, **, and *** represent significant levels at 10%, 5%, and 1%.
Source: Authors' calculation.

4.2 | Unit root test

Stationarity of the instruments applied in this study is tested with unit root test and structural break test. This test assures that the time series study is void of error and misinterpretation of the findings in the analysis. For this purpose, approaches such as augmented dickey fuller—Dickey & Fuller (1979), Phillips and Perron (1988), and kwiatkowski et al. (1992) are applied for the basic unit root test, while Zivot & Andrew (2002) method of structural break test is applied as a robust check to the basic unit root test. Structural break test is considered necessary because of inability of the conventional unit root tests in capturing the impact of structural shock (such as policy effect of macroeconomic shock, natural disasters or health challenges) of any economy on the indicators and variables use in researching the economy. Most times, the outcome of unit root tends to determine the rightful approach for other estimates and analyses (cointegration) adopted in any research. However, the cointegration test approach (the ARDL bound test) adopted in this study does not need any special criterion before utilizing it to investigate the existence of cointegration. Findings from both unit root and structural break tests show

TABLE 4 Structural Break output.

Variables	ZA	*p*-Value	Lag	Break period	CV@ 1%	CV@5%
LCO_2	−3.922***	0.0003	4	2010Q3	−4.80	−4.42
LGDP	−3.191	0.313	4	2001Q1	−4.80	−4.42
LURB	−4.351901	0.176129	4	2001Q2	−5.34	−4.93
LTECH	−4.8012***	0.000	4	2013Q4	−4.80	−4.42
LREN	−2.561019	0.102477	4	2002Q3	−4.80	−4.42
$DLCO_2$	−3.298**	0.000	4	2002Q3	−4.80	−4.42
DLGDP	−3.653***	0.004	4	2006Q3	−4.80	−4.42
DLURB	−4.613777	0.825264	4	2003Q3	−4.80	−4.42
DLTECH	3.937996**	0.054	4	2011Q3	−4.80	−4.42
DLREN	−3.501**	0.015	4	2013Q4	−4.80	−4.42

Note: *, **, and *** represent significant levels at 10%, 5%, and 1%.
Source: Authors' calculation.

different order of integration, *I*(1) and *I*(0) among the series and structural break in the China's economy. The break dates are as follows: 2002Q3 and 2010Q3 for CO_2, 2001Q1and 2006Q3 for economic growth, 2001Q2 and 2003Q3 for urbanization, 2011Q3 and 2013Q4 for technological innovation, 2002Q3 and 2013Q4 for renewable energy. The break dates range from 2001Q2 to 2013Q4 and are well accommodated in the tested period of this research (1996Q1-2018Q4). Findings from structural break tests give credence to the assertion of Li, hence, the long run path of China's economic growth are found to have been caused by shocks from population growth, capital accumulation and technological innovations with some natural events. Even the great leap forward in China is part of the shocks. Literature have it that most countries of the world including China have experienced macroeconomic and financial shocks such as 1998 and 2008/2010 global financial shocks which are capable of distorting the stability of the variables for research in those countries. Both results are presented in Tables 3 and 4.

4.3 | Cointegration and dynamic (short run and long run) relationships

After the estimation of the unit root test and the confirmation of mixed order of integration among the series, we proceed with the estimation and analysis of cointegration with dynamic short run and long run relationship among the selected variables. ARDL bound test is applied for the test of cointegration and likelihood of adjustment of disequilibrium in the long period with long path relation among the variables. Contegration is confirmed with *F*-test (10.37) greater than the critical value of upper (4.59). The ability of the model to adjust to equilibrium in the long run after disequilibrium in the short run is confirmed with negative output of error correction model (ECM) at 12.3 percent (−0.123480).

Diagnostic tests such serial and auto correlations, heteroscedasticity, residual cumulative sum and cumulative sum square (CUSUM and $CUSUM^2$) are all estimated to ascertain the correctness and stability of our model, and if the model is free from any econometric problem which can lead to spurious results and wrong interpretations and explanation. The outcome of the tests show that the analysis is free from any econometric problem with values of auto, serial and heteroscedasticity as follows: LM Serial test *F*-stats = 1.017[0.32] R^2 = 1.581[0.21] for serial correlation, Heteros.test *F*-stats = 0.791[0.75] R^2 = 25.04 [0.68] for heteroscedasticity, while Durbin Watson value that clears the analysis from autocorrelation is 1.793. Also, the accurateness of the model adopted in this study is confirmed with residual cumulative sum and cumulative sum square (CUSUM and $CUSUM^2$) and the outcome shows that the model is stable, and the outcome is displayed in Figures 2 and 3 immediately after Table 5. The outcome of lag selection is 5. This result is available on request. From the preliminary test, we found the goodness of fit for the adopted model to be R^2 = 0.980 and Adjusted R^2 = 0.973. This means that 98% variation in dependent variable (carbon emission) is described by the exogenous instruments (economic growth, urbanization, technology, and renewable energy), while the residual part of dependent variable is accounted for by the residual (i.e., error correction).

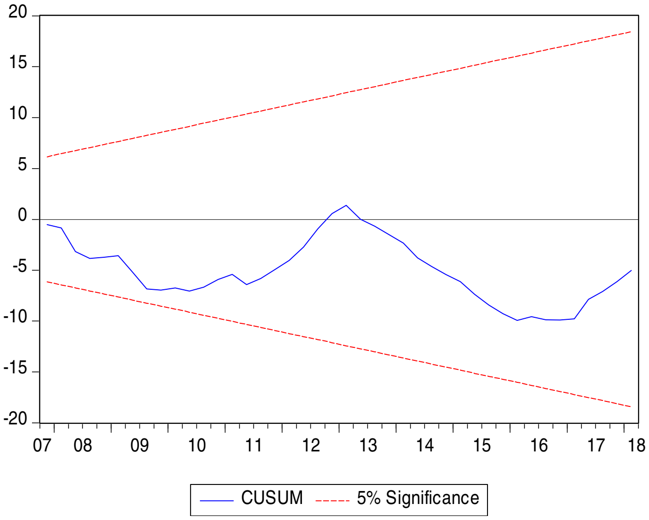

FIGURE 2 Residual of cumulative sum. *Source*: Authors' Computation. [Colour figure can be viewed at wileyonlinelibrary.com]

The results from ARDL are as follows: a negative and positive relationships are confirmed between economic growth (GDP per capita) and carbon emission (CO$_2$) at 1.20 (−1.20) and 0.00023 respectively in both periods (short run and long run). This suggests that carbon emission is reduced in the initial stage of China's economic development and later spike which contradict the existence of inverted U-shape EKC for China. Most economic activities (such as manufacturing and industrial activities, transportation etc.) are concentrated in the cities, and these activities are responsible for excessive utilization of energies which includes fossil fuels and are capable of generating greenhouse gas emissions. These economic activities are energy oriented and intensive in nature (excessive energy consumption), and the energy mix of the country (China in our study) determines the relationship between the carbon emissions and the economic growth of the country. The greater share of fossil fuels source in the energy mix will definitely result in greater carbon emission and vice versa for the case of renewable energy source. Economic growth and urbanization can either have negative or positive impact on the environment depends on the policies (such as technological innovation and energy policies) adopted by the country. Our finding aligns with the findings of Yilanci and Pata (2020) for China, Pata and Caglar (2021) for China, and refutes the finding from Xie et al. (2019) for China.

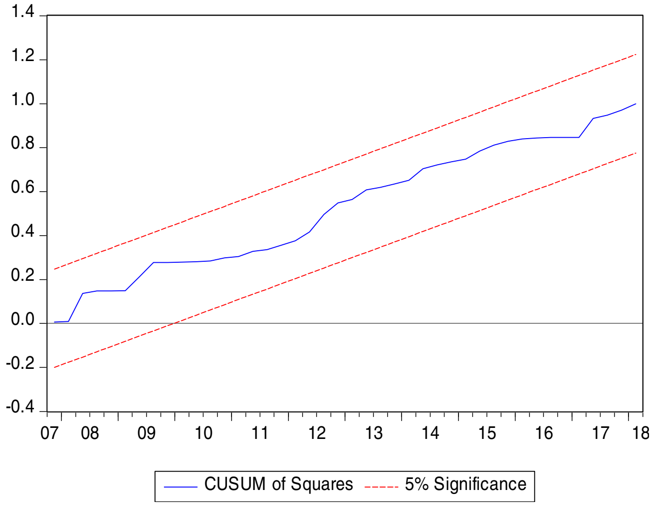

FIGURE 3 Residual of cumulative sum square. *Source*: Authors' Computation. [Colour figure can be viewed at wileyonlinelibrary.com]

We also find a positive relationship between urbanization and carbon emission for China at 1.61E−06 (0.00000161) for both periods. This means a percent increase in urban population will cause 0.0000061 percent increase in China's carbon emissions. This suggests that Chinese cities where the bulk of industrial and manufacturing activities are situated are responsible for some level of carbon emission. Factors (such as economic effects and population effects) are most times contributing factors in promoting carbon emission in a highly economic and population concentrated cities. From the value of the coefficient, it is also discovered that the level of emissions induce by urbanization is negligible but should be put into consideration in policy formulating. This result backs the results from Wu et al. (2016) for China, Liu et al. (2018) for China, Huo et al. (2020) for China.

Further in our findings is the significant negative relationship that we find between technological innovations and carbon emissions at 10.47 (−10.47254). This finding suggests that technological innovations are impacting favorable on the Chinese environmental development and has potential of aiding the country to achieve its climate and SDGs. Quantitatively, a percent increase in China's technological innovation will lead to 10.47254 decrease in China's carbon emissions. This uphold the fact that technological innovation anchored on research

TABLE 5 Cointegration/ARDL model,

Variables	Coef Short-run	SE	*T*-stats	Variables	Coef Long-run	SE	*T*-stats
DLY	−1.200	0.599	−2.003**	LY	−1.200	0.931	−1.290
DLY^2	0.0002	6.36E−05	3.671***	LY^2	0.0002	9.92E−05	2.353**
DLURB	1.61E−06	1.66E−05	0.097	LURB	1.61E−06	1.97E−05	0.082
DLTECH	−10.47	1.623	−6.452***	LTECH	−10.47	2.314	−4.526***
DLR.E	−7.973	0.940	−8.484***	LR.E	−7.973	1.416	−5.630***
CointEq(−1)	−0.124	0.014	−8.983***	C	−3.922	1.373	−2.857***
R^2	0.980						
Adj R^2	0.973						
D.Watson	1.793						
Wald test	*F*-stats = 130.5	*p*-v = 0.000					
Bound-Coint. test	*F*-stats = 10.37	*K* = 5, @1%	*I*(0) = 3.351	*I*(1) = 4.59			
LM Serial test	*F*-stats = 1.017	R^2 = 1.581	[0.32] [0.21]				
Heteros.test	*F*-stats = 0.791	R^2 = 25.04	[0.75] [0.68]				

Note: *, **, and *** represent significant levels at 10%, 5%, and 1%.
Source: Authors' calculation.

development that leads to discoveries of new ideas, technologies and other approaches will definitely contribute towards achieving good environment quality. Most of the findings (Chen, Zhao, et al., 2019; Dong et al., 2018) support the notion that technological innovation aids in mitigating carbon emission. Most times, innovation and technological progress are made easy through R&D and this promotes low carbon economy (Chen, Zhao, et al., 2019; Dong et al., 2018; Huang et al., 2017; Huang et al., 2018; Lin & Du, 2017). This finding supports the findings from Khan, Ali, Kirikkaleli, et al. (2020), Khan, Ali, Umar, et al. (2020), Khan, Zhang, Kumar, et al. (2020) for China, Ma et al. (2021) for China; Jin et al. (2017) for China.

Also, a significant negative connection is established amongst renewable energy use and China's carbon emissions at 7.972461 (−7.972461) in both periods (short run and long run). This suggests that renewable energy source consumption contributes in abating the China's carbon emissions, and this equally points towards the need for Chinese authorities to adopt expansion policy in its energy policy (i.e., expansion of renewable energy sector). The policy could be in form of deregulation of the renewable energy sector thereby accommodating multiple and diverse players ranging from public to the private sectors. China considers alternative source of energy as not only a moderating agent against CO$_2$ emission but as a source of energy security. China's ambition to increase its share of renewable in its energy mix is confirmed from China's Action Plan for the Prevention and Control of Air Pollution initiated by China's State Council in September, 2013 (Andrews-Speed and Philip, 2014). China's share of renewable sources in its energy mix had been systematically rising over a period of time. Among the Chinese policies towards renewable expansion is its investment into the sector. China's investment in renewable energy has been enormous amounting to 45% of the global renewable investments (Frankfurt School – UNEP Collaborating Centre for Climate & Sustainable Energy Finance, 2018). The speed at which China is developing its renewable energy points toward ability to decarburize its carbon emissions through energy policy (with focus on renewable energy source). Statistically, a percent increase in renewable energy consumption will lead to 7.972461 percentage decrease in Chinese emissions in both periods (short run and

TABLE 6 VEC/Block exogenuity Granger causality test.

Null Hypothesis	Chi-sq	*p*-Value	Causality	Decision	Direction
Variables					
LCO$_2$					
LGDP	15.72	0.000	YES	REJECT H_0	[LGDP↔LCO$_2$] *BI-DIRECTIONAL*
LURB	23.34	0.000	YES	ACCEPTH_0	[LURB↔LCO$_2$] *BI-DIRECTIONAL*
LTECH	6.641	0.010	YES	REJECT H_0	[LTECH↔LCO$_2$] *BI-DIRECTIONAL*
LREN	19.21	0.000	YES	REJECT H_0	[LREN→LCO$_2$] *UNI-DIRECTIONAL*
LGDP					
LCO$_2$	26.40	0.000	YES	REJECT H_0	[LCO$_2$↔LGDP] *BI-DIRECTIONAL*
LURB	23.07	0.000	YES	REJECT H_0	[LURB↔LGDP] *BI-DIRECTIONAL*
LTECH	1.282	0.257	NO	REJECT H_0	[LTECH↔LGDP] *BI-DIRECTIONAL*
LREN	3.043	0.081	YES	REJECT H_0	[LREN→LGDP] *UNI-DIRECTIONAL*
LURB					
LGDP	33.24	0.000	YES	ACCEPTH_0	[LGDP↔LURB] *BI-DIRECTIONAL*
LCO$_2$	4.827	0.028	YES	REJECT H_0	[LCO$_2$↔LURB] *BI-DIRECTIONAL*
LTECH	2.455	0.117	NO	ACCEPTH_0	[TECH≠LURB] *NEUTRAL*
LREN	11.50	0.000	YES	REJECT H_0	[LIREN→LURB] *UNI-DIRECTIONAL*
LTECH					
LGDP	6.837	0.009	YES	REJECT H_0	[LGDP↔LTECH] *BI-DIRECTIONAL*
LURB	0.878	0.348	NO	ACCEPTH_0	[LURB≠LTECH] *NEUTRAL*
LCO$_2$	7.117	0.008	YES	REJECT H_0	[LCO$_2$↔LTECH] *BI-DIRECTIONAL*
LREN	0.166	0.684	NO	ACCEPTH_0	[LIREN≠LTECH] *NEUTRAL*
LREN					
LGDP	0.127	0.721	NO	ACCEPTH_0	[LREN→LGDP] *UNI-DIRECTIONAL*
LURB	2.147	0.143	NO	ACCEPTH_0	[LREN→LURB] *UNI-DIRECTIONAL*
LTECH	1.462	0.227	NO	ACCEPTH_0	[LREN≠LTECH] *NEUTRA*
LCO$_2$	1.677	0.195	NO	ACCEPTH_0	[LREN→LCO$_2$] *UNI-DIRECTIONAL*

Note: *, **, and *** represent significant levels at 10%, 5%, and 1%.
Source: Authors' calculation.

long run). This finding supports the findings from Dai et al. (2018) for China; Long et al. (2015) for China; Ji et al. (2020) for G7 countries; Mensah et al. (2018) for 28 selected OECD countries; Bhattacharya et al. (2020) for 70 countries; Inglesi-Lotz and Dogan (2018) for Sub-Saharan African countries.

In summary, our results from both periods of ARDL established a pathway of achieving climate and SDGs for China through adoption of technological innovation and renewable energy policies which displayed the possibility of decarburization of Chinese economy. With the values of coefficients of urbanization (0.0000061), technology (−10.47254) and renewable energy (−7.972461) from the findings, a careful mix of technological innovation and renewable energy will ensure eco-friendly and green conscious urban growth. Hence, the value of urbanization is negligible compare with the values of technology and renewable energy respectively which points towards overwhelming influence of technology and renewable energy over urbanization and other carbon intensive sources.

4.4 | Diagnostic test

4.5 | Granger causality

Granger causality is among the approaches utilized in our study as a robust check to the findings from the short run and long run dynamic ARDL estimations. Findings from the granger causality exposed the inferential and forecasting power of the selected variables towards ascertaining their impacts on climate change and carbon mitigation. Considering the mixed order of integration among the series established from the unit root and structural break tests, we applied VEC/Block exogenuity Granger causality test. Results from the granger are as follows: bi-directional causal inference is found between carbon emission, and economic growth, urbanization and technological innovations; between economic growth and urbanization and technological innovations. However, one way (uni-directional) granger causality is established transmitting from renewable energy to carbon emissions (CO_2), economic growth, and urbanization. The bi-directional transmission among the variables from our findings exposed the significant position of the selected variables, and the stand out of renewable energy in transmitting to every other variables shows the mitigating effect of renewable energy. Hence, findings from granger causality test supports the results from the ARDL in both periods with the position of technological innovations and renewable energy (Table 6).

5 | CONCLUDING REMARK AND POLICY RECOMMENDATION

This is study is centered on Chinese ability to achieve its climate and SDGs through the proposed policies (technological innovations and renewable energy). We argue that the achievement of this great goals will largely depend on the mitigation of carbon emissions through the highlighted policies (technology and renewable energy). For effective investigation and exposure on this subject, we utilized different methods (descriptive information, structural break, bound test of cointegration, ARDL dynamics and granger causality) which cover both empirical and theoretical aspects of our work. Estimates, findings and explanation of all the approaches are satisfactorily detailed in the body of the study under different headings and subheadings in a coherent manner, but for the emphasis and policy inference findings from ARDL and granger analysis are reiterated here in the conclusion section. We adopted variables from both economic, energy and environmental indicators such as economic growth and its squared term proxy by GDP per capita, urbanization proxy by urban population, technological innovations proxy by research and development (R &D) expenditure, renewable energy and carbon dioxide emissions (CO_2) for in depth and clear exposition of our objectives, which are (a) to test the impact of technological innovation towards mitigating Chinese carbon emissions, (b) to test the impact of renewable energy sector development towards mitigating Chinese emissions, (c) to test the impact of urbanization and economic growth on Chinese environmental performance, (d) to test EKC hypothesis for the case of China, (e) to test the effect of nexus between technological innovation and renewable energy sector on carbon emission through granger causality, on Chinese sustainability goals. Results from ARDL estimate are as follows: Non-existence of inverted U-shape EKC for China showing the divergent point from the great leap forward in China's macroeconomic development. Urbanization is found expanding the carbon emission which has negative impact on Chinese environment, while the technological innovations and renewable energy policies are found abating carbon emissions in a great percentage which amounts to positive impact on Chinese environment. Findings from granger causality established both two-way causal transmission (found between carbon emission, and economic growth, urbanization and technological innovations; between economic growth and urbanization and technological innovations) and one way transmission (transmitting from renewable energy to carbon emissions [CO_2], economic growth, and urbanization) among the selected variables. As remarked from the discussion, findings from short run and long run dynamics of ARDL established a pathway of achieving climate and SDGs for China through adoption of technological innovation and renewable energy policies which displayed the possibility of decarburization of Chinese economy. With the values of coefficients of urbanization (0.00000161), technology (−10.47254) and renewable energy (−7.972461) from the findings, a careful mix of technological innovation and renewable energy will ensure eco-friendly and green conscious urban growth. Hence, the value of urbanization is negligible compare with the values of technology and renewable energy respectively which points towards overwhelming influence of technology and renewable energy over urbanization and other carbon intensive sources. Also, from granger causality findings, the bi-directional transmission among the variables, and the stand out of renewable energy in transmitting to every other variables revealed the significant impact of the selected variables in China's sustainability and shows the mitigating effect of renewable energy. Hence, findings from granger causality test supports the results from the ARDL with the position of technological innovations and renewable energy.

From the findings, specific policies such as: First, deregulation of renewable energy sector. This policy will reassure investors (both private and public investors) in renewable sector to engage in a healthy competitive manner. This will definitely reduce the cost of accessing renewable energy by both household and industrial sectors. Hence, this policy will aid in actualizing SDGs target of improving both the socioeconomic welfare of the people and ameliorate environmental dilapidation. Second, Public financing and creating investing opportunities in renewable energy sector. Chinese financing and investment strategy through its green bond should be strengthened and enhanced. As at 2018, China emerged the highest and major green bond market globally with about 268 billion RMB with about 8.23 trillion RMB green loans in a bid to curb climate change (Berrouet et al., 2019). Financing of climate goals through green bonds will amount to a strategic means of achieving climate and SDGs. Through this policy, China will likely draw both local, national and transnational financial investment and support into its renewable energy sector. This policy will not only influence the expansion of renewable energy sector but will boost the technological innovation through research and development expenditure. Third, Chinese authorities should incorporate cleaner production through environmental pollution tax. Initiating pollution tax through placing of a ceiling on emissions and pollution will aid in checkmating the industrial excesses in carbon emission and pollution. This will equally shift industrial policies toward green production which will reduce carbon intensive in the economy. Also, this policy will aid in actualizing SDGs target of improving environmental quality through carbon emission reduction. This study and its findings with policy inference has great implication for many emerging economies (BRICS countries) with the same economic model like China.

Conclusively, this study may have some limitations (data sample limitation and omission of important variables) that made it possible for this topic to be opened for continuous research. Other variables such as institutional quality can be considered in the continuation of research in this topic in future. Also, the sample period of this study ends at 2018, and this is part of limitations of our study which can be explored and corrected by future researchers.

ACKNOWLEDGMENTS

The authors state here and acknowledge that this present study has not been submitted in any outlet for publication.

FUNDING INFORMATION

The authors extend their appreciation to the Deanship of Scientific Research at King Khalid University, Saudi Arabia for funding this work through Large Research Groups Program under grant number L.R.G. P2/174/43.

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ENDNOTES

[1] See https://sdgs.un.org/goals/goal13

[2] See https://unstats.un.org/sdgs/dataportal/countryprofiles/CHN

[3] See https://www.nytimes.com/2020/09/22/climate/china-emissions.html

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How to cite this article: Xing, L., Udemba, E. N., Tosun, M., Abdallah, I., & Boukhris, I. (2023). Sustainable development policies of renewable energy and technological innovation toward climate and sustainable development goals. *Sustainable Development*, 1–15. https://doi.org/10.1002/sd.2514