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Role of green technology innovation and renewable energy in carbon neutrality: A sustainable investigation from Turkey

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ABSTRACT

After the Paris Climate Conference (COP21), many countries start progressing towards carbon neutrality targets. In doing so, green technology innovations (GTIs) and clean energy are the essential factors that can help to achieve the carbon neutrality goal. Therefore, this paper examines the linkages between green technology innovation and renewable energy and carbon dioxide emissions based on the STIRPAT model in Turkey during the time of 1990–2018. The study used testing like “unit-root” to verify the variables' integrative properties containing the information for structural breaks. Also, the bootstrapping ARDL-bound testing technique is used to analyze the relationship between the variables. The causal relationship between green technology innovation, energy consumption, renewable energy, population, income per capita, and carbon dioxide emissions is tested through a Granger causality test. The empirical findings show that green technology innovation, renewable energy, energy consumption, population, income per capita, and carbon dioxide emissions are co-integrated for the long-term association. Additionally, green technology innovation and renewable energy decline carbon dioxide emissions, whereas energy consumption, population, and per capita enhance carbon emissions. This paper helps the policymakers design a comprehensive policy for strengthening environmental sustainability through green technology innovation and renewable energy, specifically in the region of Turkey.

1. Introduction

Every country in the world needs to be consistent with its endowment of energy resources and employment of socially equitable technologies with a minimum adverse impact on nature (Umar et al., 2020a; 2020b; Su et al., 2020). However, the intolerable degradation of the natural environment through the usage of fossil fusil could only be mitigated by dissociating the energy demand from economic growth and the reduction of fossil fuels (Umar et al., 2021a). During the last decade, one of the significant contributions of (Aswathanarayana and Divi, (2009); Su et al., (2012)) has provided an informed choice to various economies about the energy technologies and energy sources to attain low-carbon economic growth. Simultaneously, the world economy experienced a catastrophic economic shutdown because of the reckless lending process of the United States (US) banks (Abreu et al., 2019; Sharif et al., 2017). The aftershocks of this recession result in a significant drop in international trade and the slumping of the prices. Almost all the countries were in great need of finding the means to get rid of this recession (Aswathanarayana and Divi, 2009). Since that time to date, the adoption of green technologies has provided a win-win situation as they are not only “green,” but most of them are not depleted when used (Aswathanarayana et al., 2010) deliver a useful discussion for the countries about the actual mix of green technology, energy, policy, and the timings for the policy incentives, based upon their socioeconomic and biophysical situations.

Comparatively to traditional economic development models, green technology innovations (GTIs) plays a fundamental role in achieving sustainable development goals along with the minimum negative consequences on the natural environment (Lin et al., 2018; Luo et al., 2019; Wu et al., 2020; Wu et al., 2021; Wu et al., 2020; Wu and Sun, 2008). Among various sustainable goals, the achievement of carbon neutrality, which refers to achieving net-zero carbon dioxide emissions, is of

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significant interest among the reserachers, policymakers, and various environmental departments in developed and developing economies. However, the term carbon emissions refer to the release of CO2 in the natural environment from different energy and trade-related sources. At present, a series of discussions about GTIs are going on where the title of “environmentally sound technologies (ESTs)" is assumed as the earliest concept (Verhoosel, 1998). However, the old-style notion of green technology is completely transformed into sustainable solutions while considering the society, economy, and the environment. For promoting green development, different countries have adopted diverse strategies. For instance, to promote and support green technologies innovation, China has suggested that Green Technology Bank (GTB) properly implement the United Nations (UN) agenda of 2030 (Wang et al., 2021; Guo et al., 2020). Similarly, to support the GTIs, a green investment bank in the United Kingdom (UK) provides direct financial support to dissimilar industries (Guo et al., 2020). Such practices have clearly defined that GTIs are committed to developing a win-win situation for both the economies and the environment. Meanwhile, GTIs are found with their optimistic externality of technology and innovation, whereas adverse externality for environmental resource utilization (Guo et al., 2018).

(Braun and Wield, 1994) delivered the initial concept of green technology who believes that it should encompass the control over pollution, ecological treatment, purification, recycling, monitoring, and various evaluation techniques. Besides, ecological factors should be considered during the production process innovation, so a new GTI system based on the traditional linear model of technology innovation has been developed. Also, the need for GTIs is observed for every single country around the globe. For this reason, the transfer of green technology is very crucial for the protection of the environment. That is because developing countries are still struggling to access modern green technologies, and more than 66.7% of the countries are still struggling for the applicable green technologies to create a balance for their environment and economy (Guo et al., 2020). A program has been launched by the United Nations Framework Convention on Climate Change (UNFCC), focusing on climate change technology with the engagement of 85 countries (Guo et al., 2020).

The efficiency and the performance of the GTIs in terms of economic outcomes can reduce environmental pollution and save resources. Some authors believe the efficiency of GTIs is the relationship between input and output in the overall activities of GTIs. Three methods are observed for measuring the regional GTIs efficiency (Luo and Liang, 2016). The first approach is focused on using only one of the patent metrics for green technology, mostly on the grounds of the accomplishments of GTIs (Jia and Zhang, 2014). offer an example of such a strategy, indicating the number of patent applications from companies and evaluating when green and general green technology information stocks have impacted technological innovations. However, one of the key demerits of this approach is that GTI is a broader concept and cannot be reflected based on one indicator. The second method to evaluate the performance of GTIs is through principal component analysis across different regions, companies, and economies. This method was evaluated by (Zhang and Zhu, (2012), who built an index system for GTIs. In contrast, the third method is based on both parametric and non-parametric methods for GTI input and output efficiencies (Li et al., 2020; Luo and Liang, 2016).

With rising financial and economic needs, emerging economies face many challenges because the rise in economic activity triggers a simultaneous upward move in energy demand, mainly from traditional sources such as gas, coal, oil, etc. (Shah et al., 2020; Umar et al., 2021b). For sustainable development, renewable energy (RE) is considered a strategic commodity (Vickers, 2017). Various sources for RE like solar, wind, waste, and biomass are assumed as cost-effective and eco-friendly, as they mitigate the pollution, provide better security to the energy, reduce harmful climate change, and finally the provision low-cost electricity to remote areas (Gielen et al., 2019; Tareen et al., 2018). However, the literature findings for the role of renewable energy in the environment are mostly positive (Shah et al., 2020). In comparison, some studies indicate that RE does not have a differential impact on energy output and carbon emissions absorption (Bilgili et al., 2016). However, the lack of technological innovation and poor transmission systems are among those causes showing the adverse impact of RE on the environment's quality (Heal, 2010). This will argue that RE 's destructive environmental effects can be regulated by such technical advances (Shahzad et al., 2017).

Turkish economy is observed as the fastest-growing OECD member and the rapid increase in greenhouse gas (GHG) emissions. Since 2008, its economy has been decoupled from energy use, air emissions, water consumption, and waste generation (OECD, 2019). However, it is noted that the high resource intensity of the Turkish economy with significant reliance on fossil fuels will increase the environmental pressure in absolute terms (Köne and Büke, 2019; Mo, 2019). Meanwhile, the greenhouse gas inventory findings reveal that overall GHG emissions as CO2 equivalent (eq) for 2018 decreased by 0.5% compared to the last year, where the energy sector has the largest share of GHG emissions (71.6%). Additionally, total GHG emission per capita was found at 4 tones CO2 eq during 1990 which was 6.5 and 6.4 tonnes CO_2 eq. per capita during 2017 and 2018, respectively (see Fig. 1). Power sector and transport emissions of the fine particulate matter create some serious health hazards and more than 90% of municipal waste is landfilled.

According to the survey results in 2018, several innovative activities were also observed in the Turkish economy, where 36% of the enterprises were considered innovation active with ten or more employees. Furthermore, 58.2% of large enterprises refer to more than 250 employees who have introduced new or improved products/business processes. However, the ratio of being innovative is 33.9% for those with 10–49 employees and 43.3% for those having 50–249 size groups. Furthermore, one-fifth of the enterprises in the Turkish region were classified as productive innovative. These innovations also include those developed for environmental protection, pollution control, energy saving, water conservation, recycling, emission reduction, low carbon, and environmental protection and ecology. All of the above figures have provided enough justification for considering Turkey's economy while observing the trends in carbon emission based on interest variables like energy consumption, green technology innovation, and various other macroeconomic dynamics.

This paper is contributing to the existing literature in the following ways: (i) it is assumed as a pioneering effort to analyze the relationship between carbon dioxide emissions, green technology innovation, energy consumption, renewable energy, population, and per capita income using the annual data from Turkish economy during 1990–2018 by considering the significant role of green technology innovation. (ii) this study examines the unit root characteristics of green technology innovation, energy consumption, renewable energy, population, per capita, and carbon dioxide emissions through ADF and ZA tests. (iii) This study applies the bootstrapping ARDL bound testing method to validate cointegration association aimed variables for analyzing the cointegration. Various benefits have been observed in the existing body of literature while utilizing the BARDL method of data analysis. For instance, the BARDL test provides an additional test regarding the significance of lagged values of the study explanatory variables, which indicates a better insight into the cointegration status of the model compared to some traditional models like OLS and simple ARDL test. Also, some other advantages for using BARDL are the elimination of inconclusive interference with the bounds test. Furthermore, another benefit of using the bootstrap ARDL test is that there is significant evidence regarding the endogeneity problem with its minor effect on the size and power dynamics of the ARDL bound testing framework. Besides (iv), we have applied the Granger causality approach to examine the causal linkage among the study variables. Empirical results indicate that both advances in renewable tech and renewable energy minimize long-run and short-run carbon dioxide emissions. However, energy consumption, population, and per capita income are causing more carbon dioxide emissions

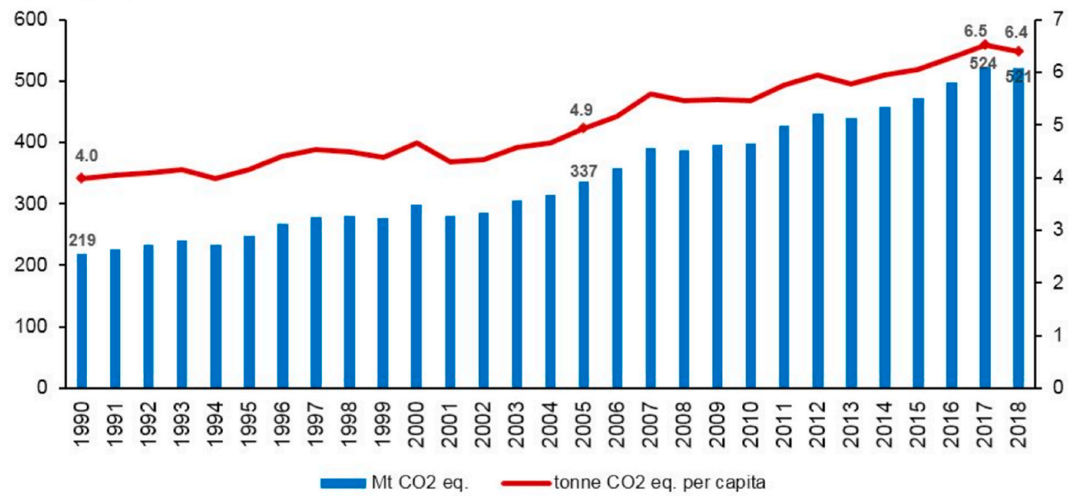

Fig. 1. Total and Per capita GHG emission during 1990–2018 (CO_2 equivalent per capita and million tonnes).
Source: Tuik.Gov.

in Turkey. The causality test suggests the presence of a significant impact between progress in green technologies and carbon dioxide emissions, renewable carbon and energy emissions, energy and carbon dioxide emissions, population and carbon dioxide emissions, and income per-capita and carbon dioxide emissions, accordingly.

The rest of the paper is divided into the following sections: Section 2 reviews the relevant literature. Section 3 describes the data, methodology, and empirical modeling. Section 4 covers the results and discussion, and Section 5 provides the conclusion and policy implications.

2. Literature review

2.1. Green technological innovation and environmental degradation

Ample research studies have explored the empirical associations between technological innovation and environmental degradation. For instance (Feng et al., 2009), investigated the relationship between urbanization, technological innovation, income level, and carbon emissions. The study's estimates found that technological advancement, rapid urbanization, and income-per-capita substantially affected environmental emissions. Their research concluded that technological innovation brings advanced technology into the nation that tends to reduce the level of carbon emissions (Ali et al., 2016). focused on identifying environmental quality and found important contributions to the reduction of co2 emissions from energy use, economic development, and technical progress (Weber and Neuhoff, 2010). showed the negative relationship between technological innovation and environmental degradation. The study concluded that technological innovation brings energy-efficient technologies that are less significant to environmental pollution. The linkage between renewable energy, technical development, and ecological pollution was examined by (Irandoust, (2016)) and inferred that renewable sources of energy and technology development significantly reduce environmental pollution that eventually enhances the quality of the environment. Simultaneously, some other researchers argued that technological innovation does not significantly contribute to the reduction in carbon emissions in developing economies. For instance (Ganda, 2019), inferred that technological progress improves energy usage, raising the atmosphere's emissions. The study further concluded that developing nations mostly rely upon conventional energy sources that significantly contribute to environmental pollution. Thus, instead of reducing carbon emissions, technological innovations tend to increase carbon emissions in developing economies.

Similarly (Bai et al., 2020), indicated that technological innovation tends to increase environmental pollution in low-income countries. Keeping in mind these contradictory results, researchers have started working on green technological innovations (Sinha et al., 2020). inspect the interplay between technological innovation and the environmental quality for the N11 economies during 1990–2017. Their study has revisited the technology policies of selected economies and environmental degradation, sustainable economic growth, and clean and affordable energy. Through bootstrap regression analysis, they have observed the effect of technological progression, renewable energy consumption, along with other macroeconomic dynamics on air pollution, based on the Environmental Kuznets Curve (Töbelmann and Wendler, 2020). Investigate the effects of environmental innovation on the carbon emissions in EU-27 member states during 1992–2014 through the generalized method of moments under dynamic panel settings. It is believed that environmental innovation did contribute to reducing carbon dioxide emissions, whereas general innovation does not cause any reduction of such emissions. Green technological innovations are used synonymously with environmental innovations, which is an efficient approach that reduces environmental pollution and positively contributes to the growth of an economy (Aggeri, 1999). Many scholars have suggested the positive impact of green technological advancement in lowering carbon emissions or enhancing environmental quality (Gao et al., 2018; Lee and Min, 2015; Schiederig et al., 2012) For instance (Zhao et al., 2015), studied the influence of R&D in green technologies on environmental wellbeing and concluded that R&D in green technological innovations is efficient for environmental quality. The positive position of green technical advancement in enhancing environmental quality was also suggested (Miao et al., 2017) (Godil et al., 2021) examine the role of technological innovation, renewable energy, and economic growth in reducing carbon emission from 1990 to 2018 in China's economy. With the help of the QARDL approach, it is observed that there is a significant influence of technological innovation, economic growth, and renewable energy on the carbon dioxide emissions for China (Wang et al., 2020). have examined the nexus between carbon emission, renewable energy, financial development, and technological innovation for the COP 21 agreements. For the purpose of data analysis (Pesaran, 2007), unit root test augmented mean group and common correlated effect mean group approach was under observation. The study's findings reveal a positive and significant association between financial development and carbon dioxide emissions along with the gross domestic product.

Additionally, there is an adverse association between technological innovation, carbon emission, and technological innovation (Cheng and Yao, 2021). consider the panel data model with the cross-sectional dependence and slope heterogeneity to observe the intensity of carbon reduction and technological innvoation in China's economy from 2000 to 2015. The findings show that a one percent increase in the technological innovation for renewable energy has reduced 0.051 percent in the carbon intensity. Also, some other studies have observed the trend in carbon dioxide emission in different economies (Mohsin et al., 2021; Nawaz et al., 2021). (Ustaoğlu and Yıldız, 2012) have focused on the Turkish economy while observing the trends in green technology innovation. They further claim that green technology has significant future potential.

For this reason, the Turkish economy has taken a leading role in manufacturing electric vehicles for the global market (Sohag et al., 2019). have examined the impact of clean energy, technology, and the miliraization on the economic grwoth regarding the green perspective for Turkey's economy. The study findings observed that clean energy is a core driving force in promoting green economic growth in Turkey's economy. However, technological innovation also fosters green economic growth in the targeted economy as well (Ulubeyli and Kazanci, 2018). have also considered the Turkish economy in determining the green building industry to examine the macro-environmental assessment based on the political, economic, social, and technological factors. Based on the study analysis, it is found that the effect of macro-environmental conditions on the industry was observed as a medium to high.

Based on the above literature, the following hypothesis is suggested:

H1: green technology innovation is playing its significant role in determining the carbon dioxide emissions in Turkey.

2.2. Energy and Environmental Degradation

2.2.1. Non-renewable energy and environmental degradation

Energy-environment nexus is a widely explored area in previous studies. Numerous researchers have worked on the effects of traditional/conventional energy sources on environmental degradation. At the same time, others worked on the contributions of renewable sources of energy to environmental degradation. Prior studies showed that conventional/non-renewable energy sources tend to increase the level of carbon emissions. For example, the effect of energy usage on Malaysia's environmental pollution was empirically tested (Saboori and Sulaiman, 2013). The research found that higher non-renewable energy usage causes environmental emissions to rise. Which ultimately leads to environmental degradation (Rehman and Rashid, 2017). did the same work for SAARC nations and found a positive relationship between the consumption of conventional energy and environmental degradation (Kousar et al., 2020). also showed the positive contributions of conventional energy sources in reducing the environmental quality in the Pakistani context.

Similarly (Sharif and Raza, 2016), indicate the positive role of conventional energy in degrading the environment's quality. The effect of residential energy use on the environmental emissions was examined by (Liu et al., (2008)) and the relevant relations between such variables were shown. This optimistic relationship between conventional energy and the ecosystem is becoming a challenge to the economy since energy is the most significant engine of nations' economic development cannot be ignored. Thus, researchers have started searching for an alternate measure of conventional energy to improve environmental quality and increase the economy's growth. Based on the above literature, the following hypothesis is suggested.

H2: non-renewable energy is playing its significant role in determining the carbon dioxide emissions in Turkey.

2.2.2. Renewable energy and environmental degradation

Renewable energy sources are among those alternative measures that improve the quality of the environment and significantly contribute to economic growth (Demirbas, 2000). Energy can be naturally produced by using renewable sources of energy to meet domestic energy requirements. These sources can produce energy without damaging environmental quality. Researchers have begun to work on the connection between alternative energy sources and the intersection of environmental quality, taking into account the value of renewable sources of energy. For instance, (Apergis and Payne, 2009), for the first time, utilized the data of six central American nations from 1974 to 2004 for examining the empirical relationship between renewable energy sources and environmental quality and showed that the consumption and production of renewable energy sources lead to reduce the level of GHG emissions (Sarkodie and Adams, 2018). investigated the influence of renewable and non-renewable sources of energy on carbon emission reduction for the case of South Africa and showed a significant association among the selected variables. The study revealed that a 1% increase in non-renewable energy sources caused to increase in the level of carbon emissions by 10,436 kt. A 1% increase in renewable energy sources led to an increase in the level of carbon emission by 2855 kt. The study concluded that non-renewable sources of energy are less significantly related to carbon emissions (Hu et al., 2014). analyzed the effect, including its production and use of renewable energy sources, mostly on the Republic of China's growth in the economy and poor air quality from 2000 to 2011. The study revealed that perhaps the production and use of renewable energy sources positively contribute to economic development but are not significantly linked to the air and water pollution of the countries selected. According to the study by (Panwar et al., (2011)), it was found that "renewable sources of energy" to be the "cleaner sources of energy" and suggested their positive position to enhance the effectiveness of the atmosphere (Wang and Wang, 2015). perceived wind energy as an essential source of renewable energy production. Therefore, the author explored the empirical contributions of wind energy to environmental pollution and found the positive contribution of energy produced from the renewable sources of wind to environmental quality. The direct impact of solar power on optimizing environmental quality was shown by (Tsoutsos et al., (2005)).

(Sharif et al., 2020a) have re-investigated the impact of both renewable and non-renewable energy consumption in the region of Turkey for ecological footprints. For this purpose, they have applied the QARDL approach from 1965 to 2017. It is observed that the role of renewable energy is good enough in decreasing the ecological footprint for the long run estimation under all of the study quantiles. Meanwhile, the study findings have confirmed the presence of the environmental Kuznets curve (EKC) (Sharif et al., 2020b). try to analyze the association between the energy utilization from some renewable sources and environmental degradation from 1990 to 2017 while applying advanced quantile modeling. The study findings confirm that there is bidirectional causality between renewable energy utilization and environmental degradation (Kalmaz and Kirikkaleli, 2019). also provide their empirical contribution for modeling CO2 emission in emerging economies with the help of energy consumption, economic growth, and other macroeconomic dynamics. Their study results confirm a long-run equilibrium association between the CO2 emission and energy consumption and other macroeconomic variables.

Based on the above discussion, it is inferred that literature work has reasonably addressed the dynamic relationship between green technological innovation and environmental degradation, non-renewable energy and environmental degradation, and renewable energy and environmental degradation as well. However, to the best of our knowledge, there is a widespread lack of consensus for examining the role of green technology innovation, renewable and non-renewable energy for environmental degradation, specifically from the context of the STIRPAT model. This would reasonably justify the contribution in the existing literature while observing the theoretical and empirical significance of this study. Also, another literature gap lies in the methodological front we have come to know that a little literature is provided by the researcher while incorporating the BARDL approach in determining the trends in environmental sustainability, specifically from the context of Turkey. Therefore, the present study has covered both theoretical and methodological literature gaps in a well manner.

(Alola and Kirikkaleli, 2019) have observed the nexus between environmental quality and renewable energy consumption for the immigration and healthcare sector in the US through wavelet and gradual-shift causality approaches. The study findings from 1999 to 2008 have revealed the fact that there is a significant feedback causality between the carbon dioxide emissions and renewable energy consumption at different scales level. However, under short-run estimation, a positive correlation exists between the study variables.

H3: renewable energy is playing its significant role in determining the carbon dioxide emissions in Turkey.

Also, our study has tested the following hypotheses as well.

H3: per capita income is playing its significant role in determining the carbon dioxide emissions in Turkey.

H3: the population is playing its significant role in determining the carbon dioxide emissions in Turkey.

3. Theoretical framework

For identifying the determinants of carbon dioxide emissions, earlier findings have provided their justification through the IPAT model (Paramati et al., 2020; Raskin, 1995; York et al., 2002). The theoretical approach of the IPAT model is based on the relationship between income, population, technology, and environmental impact where *I* denotes the pollution or environmental impact considered as a source from *P;* the population, additionally, the level of economic activities are assumed as per capita consumption represented through *A*. Finally, technological level *T* shows the amount of pollution per unit of economic activity or consumption. With further development, the IPAT model is extended by (Dietz and Rosa, 1994, 1997) into a stochastic version entitled as Stochastic Impacts by Regression on Population, Affluence, and Technology (STIRPAT) model in recent time. One of the core benefits of the STIRPAT model is to apply it for the testing of hypotheses empirically. Therefore, for the empirical investigation, we have framed the following equation:

$$CO2EM_{it} = f\left(POP_{it},\ PI_{it}, NREC_{it}, REC_{it,vi}\right) \quad (1)$$

In the above equation I, *CO2EM* is a function of population (POP), per capita income (PI), non-renewable energy consumption (NREC), and renewable energy consumption, respectively. The above-stated model was adopted from the research contributions of (Paramati et al., (2017)), where equation i indicate the impacts of both renewable and non-renewable energy consumption on the carbon dioxide emissions along with other determinants like population, per capita income, and green technology innovation as well. Fig. 2 below provides a conceptual and empirical review of the model as observed under the present study.

3.1. Data, methodology, and empirical modelling

For empirical analysis on the role of green technology innovation, renewable energy, energy consumption, population, and per capita for carbon dioxide emissions in Turkey, a set of data was collected from 1990 to 2018. Data for carbon dioxide emissions are measured in terms of per capita, and green technology innovation is measured by several registered patents related to the environment, and the data of both variables are obtained from the OECD statistics website. Furthermore, the title of renewable energy covers hydro, solar, geothermal, wind, ware sources, and tide, while non-renewable sources indicate the usage of coal, petroleum, gas, and others to generate the energy. Both renewable and non-renewable energy usage was finally calculated in terms of a ton of oil equivalent, and data for both these were extracted from a databank of the energy information administration (EIA). Finally, all the data was converted into a natural logarithmic form from per capita values to receive a more efficient estimation.

As suggested by (McNown et al., (2018)) current research utilizes "the bootstrapping ARDL cointegration approach" to investigate the co-integrating link among the desired set of variables. Additionally, the ability to cope with the power properties and the low side compared with the existing ARDL approach of (Pesaran et al., (1999)) and (Pesaran et al., (2001)) is among the significant advantages of implementing the bootstrapping ARDL approach. In general, based on the latest integration test, its bootstrapping ARDL cointegration has both the potential to increase the strength of the "T-test" as well as "F-test." In this perspective (Pesaran et al., 2001), define two criteria for recognizing that same cointegration system in which the first discuss their key results with a coefficient of error-correction term. However, the second condition specifies that explanatory variables' coefficients with the lagged values must also be significant. In particular (Pesaran et al., 2001), specify that perhaps "the critical limits," i.e., both top and bottom limits, should be used for the second instance. However, the bound test and critical limits for perhaps the first cases are not needed. This test can also be used to cope with the first condition when previously stated (coefficient for error-correction terms with their important findings), given that research variables are incorporated into the model of dimension 1. However, the traditional tests of "unit-root" can be uncomfortable due to reduced explanatory and power characteristics, as (Goh et al., 2017) expressed. The problem is fairly handled by the (McNown et al., 2018)

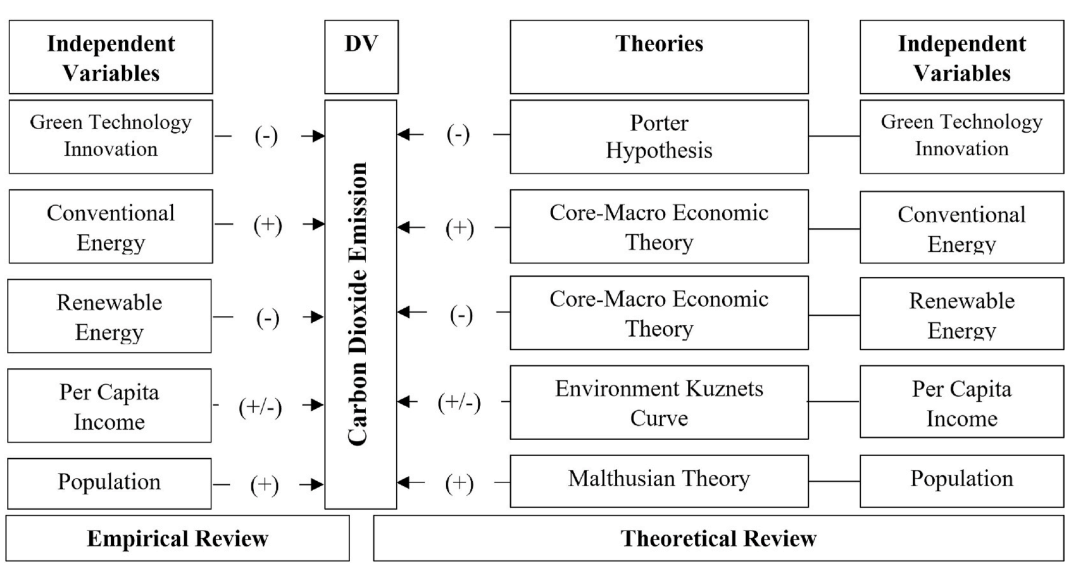

Fig. 2. Conceptual and theoretical model.

ARDL bound test when offering bootstrap.

It is possible to see its bootstrapping bound ARDL test's superiority because of its vulnerability as per the order of "the parameters' integration-properties." Temporarily, it is an applicable choice in the case of "the complex time series analysis," resolving issues such as inclusive instances associated with traditional bound ARDL evaluation (McNown et al., 2018). The production of "the measured values" by removing the probability of uncertain cases and areas (i.e., exists in conventional bound testing strategy) is another advantage of implementing the bootstrapping ARDL bound analysis. Equation ii below provides the mathematical procedure for traditional bootstrapping ARDL bound testing based on three variables.

$$y_t = \sum_{i=1}^{p} a_i y_{t-i} + \sum_{j=0}^{q} \beta_j x_{t-j} + \sum_{k=0}^{r} \gamma_k Z_{t-k} + \sum_{j=1}^{s} \tau_j D_{t,l} + \mu_t \quad (2)$$

In above Equation (1), notations like "*i*", "*j*", "*k*", and "*l*" specifies lag-terms for instance "i" = "1,2………….…p"; "j" = "0,1,2, ……… ……. q"; "k" = "0,1,2,…………….r"; "*l*" = "0,1,2,…………...s"; and "*t*" shows the period of time. In addition, y_t refers to as response variable along with x_t and z_t As explanatory variables of the study. Also, $D_{t,l}$ Shows the dummy variable indicating yearly brake based on unit root test by (Carrion-i-Silvestre et al., 2009), and the parameters of the lagged-explanatory-variables are represented through β as well as y, and for the coefficient of the dummy variable in the model. Besides, μ_t Indicates the zero mean error-term with the finite variance. Equation iii represents the error correction form of the above model, which is represented as follows:

$$\Delta y_t = \varphi y_{t-1} + \gamma x_1 + \psi_{zt-1} + \sum_{i=1}^{p-1} \lambda_i y_{t-i} + \sum_{j=1}^{q-1} \delta_j x_{t-j} + \sum_{i=1}^{r-1} \pi_{kz-k} + \sum_{i=1}^{s} \omega_i D_{t,l} + \mu_t \quad (3)$$

In the above equation (2), $\varnothing = \sum_{i=1}^{p} ai$, $\gamma = \sum_{i=1}^{q} \beta i$, and $\psi = \sum_{i=0}^{r} \gamma i$. At this point, the symbols like $\lambda_i, \delta_j, \pi_k$, and ω_i are primarily accounting for the associated functions with equation ii. Equation iii can be estimated while using a constant term which is represented through $\tilde{c}$ in the given model below:

$$\Delta y_t = \tilde{c} + \varphi y_{t-1} + \tilde{\gamma} x_{t-1} + \tilde{\psi}_{zt-1} + \sum_{i=1}^{p-1} \tilde{\lambda}_i y_{t-j} + \sum_{j=1}^{q-1} \tilde{\delta}_i x_{t-i} + \sum_{k=1}^{r-1} \tilde{\pi}_{izt-k} + \sum_{i=1}^{s} \tilde{\omega} iDt, 1 + \tilde{\mu}_t \quad (4)$$

To validate cointegration between the variables of the analysis."y_t, x_t as well as z_t", Equation iv contains 3 null hypotheses to be dismissed, which can be discussed in the following respects:

I. The F1 test, as associated with all applicable words for error correction.

$$H0: \varnothing = \psi = 0 \text{ against } H1 : \varnothing \neq y \neq \psi \neq 0 \text{ which means that any of } \varnothing, y, \text{ and } \psi \text{ are not equal to zero}$$

II. The quality of F2 according to the parameters of the response variable;

$$H0: \varnothing = \psi = 0 \text{ against } H1 : \varnothing \neq y \neq \psi \neq 0 \text{ meaning either } y \text{ and } \psi \text{ are not equal to zero}$$

III. A T-test focusing on lagging predictor variables estimates

$$H0: \varnothing = 0 \text{ against } H1 : \varnothing \neq 0 \text{ meaning that } \psi \text{ are is not equal to zero}$$

One of the essential notions is that from the traditional ARDL model, a crucial bound test value in both F1 and T-tests is created. Nevertheless, based on the lagging explanatory variables, it denies the test score for the F2 test. By applying the BARDL method, as proposed by (McNown et al., (2018)), it is possible to have critical values for all three measures. Eventually, we have used the critical values when tabulated by them to provide some robust analytical findings.

Also, the stationary test is a prerequisite for every contintgartion test. However, earlier studies have applied the ADF unit root test to examine the time-series properties of the data, which is not good for the data where there are structural breaks with their significant influence on the study findings. For this reason (Zivot and Andrews, 2002), have provided their meaningful contribution in the present literature while allowing the existence of possible structural breaks in the time series data without defining the breakpoint time. Due to this procedure, it was possible to determine the structural breakpoint endogenously while leaving the issue of selecting a breakpoint. This would justify the argument that endogenous selection of breakpoints has their key impact on the output of unit root. Therefore, the present study has also applied the ZA unit root test and the ADF to compare them better.

4. Empirical findings and discussion

The findings are reported in Table 1 shows the descriptive statistics. In terms of mean scores, we have found that PI shows the highest value, followed by ENG, GTI, and carbon emission. This would justify the argument that the average PI is more in the targeted economy while green technology innovation trends are more than carbon dioxide emissions. Additionally, we observe that GTI is more volatile compared to REN. However, REN shows more deviation compared to ENG, PI, CO2, and POP, respectively. In the present empirical literature, Jarque-Bera is the key measure of goodness of fit to claim whether the data in any study matches the normal distribution or not as observed with the help of skewness and kurtosis.

Meanwhile, the findings under Jarque-Bera are observed as non-negative where the value of far from zero specifies that data have not a normal distribution for the variables of interest. The Jarque-Bera test findings show that CO2, GTI, REN, ENG, POP, and PI have a normal distribution. The empirical findings of pair-wise correlations (Table 2) reflect a positive correlation between Carbon dioxide emissions and energy consumption, carbon dioxide emissions and population and

Table 1
Estimations of descriptive statistic.

Variables	Mean	Minimum	Maximum	Std. Dev.	Jarque-Bera	Prob
CO2	2.167	2.144	2.190	0.014	1.698	0.361
GTI	2.750	2.594	2.812	0.060	3.193	0.201
REN	1.951	1.908	2.129	0.043	1.793	0.334
ENG	3.765	3.717	3.804	0.027	1.893	0.321
POP	1.088	1.078	1.095	0.007	2.388	0.241
PI	4.919	4.881	4.948	0.021	1.609	0.389

Note: CO2: Carbon dioxide emissions, GTI: green technology innovation, REN: renewable energy, ENG: energy, POP: population, PI: personal income.
Source: Author Estimation.

Table-2
Estimations of correlation analysis.

Correlation	CO2	GTI	REN	ENC	POP	PI
CO2	1					
GTI	−0.782***	1				
REN	−0.672***	0.281	1			
ENG	0.704***	0.157	0.116	1		
POP	0.487***	0.294*	0.381**	0.672***	1	
PI	0.312**	0.384**	0.402**	0.399**	0.211	1

Variables	VIF	1/VIF
POP	1.434	0.698
ENG	1.333	0.75
REN	1.237	0.809
PI	1.222	0.818
GTI	1.205	0.83
Mean VIF	1.286	

Note: CO2: Carbon dioxide emissions, GTI: green technology innovation, REN: renewable energy, ENG: energy, POP: population, PI: personal income. Whereas: *** = p< 1%, **p< 5%, and, *p< 10%.

carbon dioxide emissions, and per capita income correlation is also significantly positive. However, Carbon dioxide emissions are observed as negatively correlated with green technology innovation and renewable energy consumption. Furthermore, energy consumption and population are also positively correlated with each other. Besides, an insignificant correlation is found between " population and per capita income" in the Turkish region during the study period. Table 2 also reports variance inflation factor (VIF) and tolerance level in terms of 1/VIF. It is observed that the individual and Mean VIF for the variables of interest is below 5, which indicates no problem for the multicollinearity among them. Similarly, tolerance values for the study variables are also above 0.10, which infer that study variables are correlated in a reasonable range.

The very next move is to investigate the stationarity of carbon dioxide emissions, green technology innovation, and renewable sources of energy, energy usage, population, and per capita income. The investigation of the order of integration of the study variable helps us decide which cointegration approach is more suitable for analyzing the cointegration relationship between Carbon dioxide emissions and its determinants. The improper order of integration of the research variables is observed to provide unclear results that could lead to incorrect statistical inference and generalization. Nevertheless, we have used the ADF test of unit root that is well recognized for handling a single unspecified structural break in the data sequence to solve these issues (Carrion-i-Silvestre et al., 2009). The above-stated test is applied to observe whether the variables are stationary at level, first difference, or if they contain mixed order of integration.

Table-3
Estimations of Unit-root testing.

Variables	ADF (Level)	ADF (Δ)	ZA (Level)	Break Year	ZA (Δ)	Break Year
CO2	0.583	−6.847***	−1.271	2010 Q1	−6.586***	2001 Q4
GTI	−0.186	−4.057***	−0.376	2009 Q2	−7.003***	2015 Q1
REN	−1.592	−3.069***	0.471	2015 Q1	−8.228***	2009 Q1
ENG	−0.358	−4.372***	−0.229	2001 Q4	−6.094***	2016 Q2
POP	−0.995	−5.281***	−1.024	2008 Q1	−4.809***	2007 Q1
PI	−0.472	−4.669***	−0.338	2015 Q2	−6.774***	2017 Q2

Note: CO2: Carbon dioxide emissions, GTI: green technology innovation, REN: renewable energy, ENG: energy, POP: population, PI: personal income. Note: The estimated values as reported in above the table define the ADF and ZA test statistic. Whereas: *** = p< 1%, **p< 5%, and, *p< 10%.

Furthermore, the ADF unit root test is suitable for the data with a small sample size. Similarly, as indicated by (Dickey and Fuller, (1981)) and (Phillips and Perron, (1988)), the standard unit root tests, like ADF and PP, may under-reject or over-reject the null hypothesis problem low explanatory power. Whereas the ADF unit root test considers these issues through its higher explanatory power, hence provide some consistent empirical facts for the presence of time series structural breaks.

The results of the ADF test for unit root with structural breaks are shown in Table 3. Carbon emissions, innovation in renewable energy, renewable energy, energy use, population, and per capita income are found to contain the unit root issue at the level. As mentioned earlier, standardized tests for unit root can lead to somewhat deceptive results in the event of structural breaks, mainly in time-series data. This problem is resolved by the ZA test, which considers one structural break as proposed by (Zivot and Andrews, (2002)), ZA hereafter). The findings for ZA tests are also provided in Table 3. Furthermore, through ADF (**Δ**) and ZA (Δ), we observe that all variables are stationary at the first difference with the structural breaks.

Table 4 predicts the findings for Bootstrapped ARDL cointegration analysis. Our findings from the F-test and T-test by bootstrapping indicated that ARDL rejected the null hypothesis of no-integration between research variables. We reject the null hypothesis as carbon dioxide emissions as a main dependent variable. That will use the combined F-test and T-test mostly on lagged dependent and lagged independent variables, respectively, to demonstrate the cointegration vector's existence throughout the Turkish carbon emission system. Also, it can be concluded that atmospheric concentrations of carbon dioxide, innovation in green technologies, renewable energy, energy consumption, and population, and the per capita income have a long-term relationship from 1990 to 2018 in Turkey. The value of R^2 is 0.901 depicts that all the explanatory variables explain the carbon dioxide emissions simultaneously. Finally, the JB test findings confirm the presence of a normal distribution of the residuals for the study model.

Table 5 shows the findings for long-run analysis, and we observe that green technology innovation has a significant and negative impact on carbon dioxide emissions. Keeping all other constant, a 1% decrease in the value of carbon dioxide emission is accompanied by a −0.202% decline in green technology innovation, showing their negative relationship. These findings are consistent with (Paramati et al., 2020), who report that green technology reduces carbon emission in OECD economies (Jordaan et al., 2017). argue that the influence of green technology innovation in reducing carbon emissions needs a systematic review to characterize the existing system, as their study indicated in Canada. The relationship between renewable energy and carbon dioxide emission is significant and negative, implying that renewable energy is a blessing to reduce the carbon emissions in the Turkish region. Keeping all other constant, a 1% decrease in renewable energy value decreases the carbon dioxide emission by −0.329%. That confirms the positive output for the reduction of carbon emission through renewable energy during the study period. This empirical finding is similar to (Adams and Acheampong, 2019), who observed that renewable energy causes a decline in carbon emissions.

Likewise, energy usage is strongly and positively correlated with carbon dioxide emission just at a 1% level. That indicates that energy consumption is not beneficial in terms of more carbon emissions in Turkey. When all else stays the same, a 0.472 percent rise in carbon emissions is fueled by a 1 percent rise in energy usage. This empirical outcome is consistent with (Khan et al., 2020), who report that energy consumption negatively affects carbon emission. The association between population and carbon emissions is statistically meaningful, suggesting that populations often play a key role in accelerating carbon emissions, such as energy usage. By maintaining other items stable, a 1 percent rise in labor boosts carbon emissions by 0.342 percent. The stated relationship between population and energy consumption is supported by the research findings of (Yeh and Liao, (2017)), who claim

Table 4
Estimation of Co-integration based on ARDL bootstrapping.

Bootstrapped ARDL Cointegration Analysis						Diagnostic tests			
Estimated Models	Lag length	Break Year	F_{PSS}	T_{DV}	T_{IV}	$\bar{R}^2$	Q-stat	LM(2)	JB
Model	1, 1, 2, 2, 0, 1	2007 Q1	18.375***	−7.853***	−4.335**	0.901	4.227	1.082	0.684

Model: $CO2_t = f(GTI_t, REN_t, ENC_t, POP_t, PI_t)$.
Note: *** = p< 1%, **p< 5%, and, *p< 10%. The optimum lag duration was determined by the Akaike Information Criterion (AIC). The F-statistic FPSS is based on the asymptotic critical boundaries created by the bootstrap process. Again for the dependent variable, TDV was its t-statistic and for the independent variables, TIV was its t-statistic, LM was its test for Langrage Multiplier measure, accompanied by the term JB for the estimation of Jarque-Bera test. Note: CO2: Carbon dioxide emissions, GTI: green technology innovation, REN: renewable energy, ENG: energy, POP: population, PI: personal income.

Table 5
Estimations of bootstrapped ARDL Co-integration (long run) analysis.

Dependent Variable = $CO2_t$			
Variable	Coefficient	T-Statistics	P. Value
Constant	0.108***	3.678	0.000
GTI_t	−0.202***	−2.972	0.002
REN_t	−0.329***	−4.076	0.000
ENC_t	0.472***	5.986	0.000
POP_t	0.342***	4.024	0.000
PI_t	0.167**	2.021	0.048
D_{2009}	0.296**	2.418	0.026
R^2	0.943		
$Adj-R^2$	0.939		
Durbin Watson	2.177		
Stability analysis			
Test		F-Statistics	P. Value
χ^2_{NORMAL}		0.217	0.184
χ^2_{SERIAL}		0.359	0.301
χ^2_{ARCH}		0.381	0.226
χ^2_{HETERO}		0.460	0.554
χ^2_{RESET}		0.784	0.147
CUSUM		Stable	
$CUSUM_{sq}$		Stable	

Note: CO2: Carbon dioxide emissions, GTI: green technology innovation, REN: renewable energy, ENG: energy, POP: population, PI: personal income. Note: *** = p< 1%, **p< 5%, and, *p< 10%.

that the growth rate of the population significantly affecting the carbon emission in Taiwan. The effect of per capita on carbon emission is also found to be positively significant at 5 percent. This would indicate that higher per capita means higher carbon emission in the Turkish economy. The historical findings reveal that a significant upward shift in per capita income in Turkey is observed over the last couple of decades, which causes more carbon emissions. The adjusted explained variation in carbon dioxide emission through all explanatory variables is 0.939% in the long run. Simultaneously, autocorrelation is detected through Durbin Watson statistics and observed as no autocorrelation in the study sample. The model under long-run analysis has passed all the stability tests and indicates no issue associated with the normality, serial correlation, heteroskedasticity, autoregressive conditional heteroskedasticity, and specification. In his research findings (Monk and Brown, 1975), suggest that stability parameters can be analyzed with the CUSUM and CUSUMsq, which indicates the stability for the long-run parameters.

Table 6 shows the empirical findings of the short-run analysis. We observe that green technology innovation declines carbon dioxide emissions significantly. That will justify that greater progress in green technology would also reduce carbon dioxide emissions in the shorter term. Renewable energy is negative and significantly linked with carbon dioxide emissions at are 1% level of significance. That shows that renewable energy contributes to changing the traditional energy pattern, discouraging more carbon emissions in the Turkish economy. However, energy consumption, population, and per capita income are positively linked with the carbon dioxide emissions are 1%, which implies that all these are among the important factors of higher carbon emission, leading to more pollution to the natural environment. The dummy variable showed an optimistic but negligible effect on carbon emissions. The estimate of ECMt-1 is negative (−0.326) and significant at 1%. The short-run model has also demonstrated the diagnostic tests where the study findings show an absence of non-normality, no serial correlation, no autoregressive conditional heteroskedasticity, and finally, the variance is homoscedastic. The short-run measurement

Table 6
Estimations of bootstrapped ARDL Co-integration (short run) analysis.

Dependent Variable = $CO2_t$			
Variable	Coefficient	T-Statistics	P. Value
Constant	0.047	0.516	0.617
GTI_t	−0.185***	−3.842	0.000
REN_t	−0.201***	−3.532	0.001
ENC_t	0.357***	2.991	0.001
POP_t	0.104***	5.443	0.000
PI_t	0.211***	4.842	0.000
D_{2009}	0.052	1.618	0.118
ECM_{t-1}	−0.326***	−3.893	0.000
R^2	0.903		
$Adj-R^2$	0.895		
Durbin Watson	2.094		
Stability analysis			
Test		**F-Statistics**	**P. Value**
χ^2_{NORMAL}		0.337	0.392
χ^2_{SERIAL}		0.226	0.604
χ^2_{ARCH}		0.331	0.208
χ^2_{HETERO}		0.164	0.688
χ^2_{RESET}		0.202	0.796
CUSUM		Stable	
CUSUMsq		Stable	

Note: CO2: Carbon dioxide emissions, GTI: green technology innovation, REN: renewable energy, ENG: energy, POP: population, PI: personal income. Note: *** = p< 1%, **p< 5%, and, *p< 10%.

Table 7
Estimations of Granger causality.

H_0:	F-Statistic	Prob.
GTI does not induce CO2 from Granger Cause	27.473***	0.000
CO2 does not induce GTI from Granger Cause	18.362***	0.000
REN does not induce CO2 from Granger Cause	22.593***	0.000
CO2 does not induce REN from Granger Cause	38.573***	0.000
ENC does not induce CO2 from Granger Cause	48.483***	0.000
CO2 does not induce ENC from Granger Cause	39.796***	0.000
POP does not induce CO2 from Granger Cause	20.583***	0.000
CO2 does not induce POP from Granger Cause	6.038**	0.018
PI does not induce CO2 from Granger Cause	10.542***	0.000
CO2 does not induce PI from Granger Cause	4.968*	0.058

Note: CO2: Carbon dioxide emissions, GTI: green technology innovation, REN: renewable energy, ENG: energy, POP: population, PI: personal income. Note: *** = p< 1%, **p< 5%, and, *p< 10%. Source: Author Estimations.

model is fairly built as CUSUM and CUSUMsq confirm the presence of stability in the short-run parameters.

Finally, a causal relationship between the study variable is examined through the VECM Granger causality approach, and findings are presented in Table 7. In the literature of time series analysis, the significance of Granger causality can not be ignored because it helps determine whether one time series is useful in forecasting another. It is observed that the value of F-statistics for the first null hypotheses in Table 7 is significant at 1%. That shows that GTI granger causes CO2 and rejecting the first null hypotheses. Similarly, CO2 granger causes GTI at 1% with the F-statistics of 18.362. That means that both CO2 and GTI granger cause to each other.

Furthermore, REN positively Granger causes CO2, whereas CO2 positively causes REN at a 1% level of significance. For the ENC-CO2 relationship, significant evidence is observed for ENC causes CO2 and CO2 causes ENC with the F-statistics of 48.48 and 39.79, respectively. Additionally, population causes CO2, and CO2 causes POP, hence supporting the study's alternative hypotheses. Finally, we observe that PI granger causes CO2 and CO2 granger causes PI at 1% and 10% level of significance.

5. Conclusion and policy implications

Turkey starts progressing towards carbon neutrality target after the Paris Climate Conference (Conference of the Paris COP: 21). This study tries to investigate a step towards carbon neutrality by examining the relationship between carbon dioxide emissions, green technology innovation, energy consumption, renewable energy, population, and per capita income from 1990 to 2018 in the Turkish economy. The empirical findings confirm cointegration amid green technology innovation, renewable energy, energy consumption, population, per capita income, and carbon dioxide emissions. The impact of green technology innovation and renewable energy on carbon dioxide emission is negatively significant in the long run, whereas the impact of energy consumption, population, and per capita income is positively significant for carbon dioxide emissions. Similarly, in the short run, both green technology innovation and renewable energy show their negative and significant impact on carbon emissions, while the rest of the determinants positively impact carbon dioxide emissions. The empirical results of the causality test show a two-way causality among innovation in green technologies and carbon emissions, renewable energy and carbon emissions, energy use and emissions of carbon dioxide, population and emissions of carbon dioxide, and per capita income and emissions of carbon dioxide.

Both green technology innovation and renewables have a detrimental influence on carbon emissions in the sense of policy consequences. That would suggest that there should be more policy development for higher green technology innovation and some renewable sources of energy while achieving sustainable development for the natural environment. Our findings show that both green technology innovation, carbon dioxide emissions, and renewable energy and carbon dioxide emissions are interdependent. In such conditions, improving the economic trend towards more green technology innovations and renewable energy sources will directly affect the carbon emissions in the natural environment. The Turkish government should develop policies for green technology innovation, renewable energy, and the CO2 triangle. Our empirical results further show that energy consumption, population, and per capita are positively impacting CO2. In this regard, the local government needs to implement incentive programs to increase renewable energy consumption to bring some good results. Whereas some supportable policies are also required to control the increasing threat of population, which in return causing higher carbon emissions. Moreover, such empirical findings have also cleared the fact that there are more challenges for the government and policymakers to pursue some adequate macro-economics reforms in dealing with the direct relationship between energy, population, personal income, and carbon emission. Based on this challenging fact, our study stresses the need to develop and implement some serious policies through which the direct and positive influence of factors like population, energy, and personal income on carbon emissions can be controlled more strategically.

Finally, this research is observed with several limitations. Firstly, the current study observes the trends in carbon neutrality while observing the role of green technology innovation and renewable energy for the Turkish economy. This would show that the rest of the OECD members are not under consideration in the present study. Secondly, the role of economic growth in determining environmental degradation is widely observed in the present literature based on a theoretical assumption like Environmental Kuznets Curve (EKC). However, the current study is entirely missing for analyzing this trend in carbon emission based on the theoretical foundation of EKC. Future studies are highly suggested to consider these limitations for better generation and policy implications as well.

Credit author statement

Shan Shan: Conceptualization, Methodology, Software, Data curation, Formal analysis, Supervision. Sema Yılmaz Genç: Conceptualization, Software, Formal analysis, Writing – review & editing, Hafiz Waqas Kamran: Conceptualization, Methodology, Software, Data curation, Formal analysis, Supervision. Gheorghita Dinca: Conceptualization, Validation, Project administration, Writing – review & editing

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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