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The role of green innovation and tourism towards carbon neutrality in Thailand: Evidence from bootstrap ADRL approach

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ABSTRACT

The recent years have been marked by the role of green tech innovation in decreasing carbon emissions worldwide to attain the carbon neutrality target. Despite many studies examining the nexus between the former and energy consumption, tech innovation's effects on CO2 releases have not been extensively researched, and the extant empirical findings are often contradictory. Also, a major concern regarding the available literature is the scarcity of papers that scan the impact of tourism on carbon emissions, even though the industry has a high potential to affect ambient air pollution. In this case, the evidence is mixed, and no consensus among academics on the relationships between the two. Therefore, this study seeks to investigate the relevance of green innovation and tourism in decreasing environmental damage in Thailand based on the bootstrapping ARDL causality model suggested by (McNown et al., 2018). This specification includes a new cointegration feature and conventional ARDL bounds tests, which increases the power of the t- and of the f-test and has several advantages, being more adequate for dynamic models with more than one explanatory variable. Our findings reveal that green innovation and tourism lead to lower environmental damage by reducing CO_2 emissions, similar to foreign investments and that green tech innovation improves the environmental quality via lower carbon emissions.

1. Introduction

Climate change is a global problem and an essential topic within international environmental conversations towards carbon neutrality targets. The accumulation of greenhouse gas (GHG) emissions, particularly in CO2, is central to global warming. Over the recent past, the energy industry has been one of the major drivers of toxic emissions, including CO_2 (Nawaz et al., 2021; Umar et al., 2020, 2021; Wang et al., 2021). In this regard, green-tech innovations have become instrumental in decreasing carbon emissions worldwide (Nikzad and Sedigh, 2017; Popp, 2012; Weina et al., 2016a; Zhang et al., 2016). With increasing anxiety about climate change, energy tech innovation has been the focus of many scholars (Nawaz et al., 2021; Su et al., 2020; Umar et al., 2020; Wang et al., 2021). Although many analyses unpack the story of the complex network between the former and energy use, the impact tech innovation exerts on carbon emissions has not been extensively debated. Like many other emerging states, Thailand is also exposed to massive environmental challenges, including CO_2. That is because Thailand is a major energy consumer to achieve higher living standards and economic growth. For its rapid economic development, Thailand's CO_2 emissions dependents on non-renewable energy consumption, which leads to significant amounts of toxic releases with negative effects on environmental quality (Boontome et al., 2017).

Also, Tourism is a central industry from which toxic pollutants are emitted in Thailand. The national tourism industry followed an upward trend over the past decade, and the toxic emissions of the sectors are generated by different sub-sectors, such as transportation, telecom, shopping, sightseeing, restaurants, and accommodations. According to some studies (e.g., Jamnongchob et al., 2017), the carbon emissions of tourism are only limited in Thailand and in terms of policy-oriented

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standpoint that highlights the need for more efforts to create green energy technologies and increase renewables' use to enjoy sustainable progress based on diminished carbon emissions. Researchers estimate that it will generate over 76% of total GHG emissions by 2050 if Thailand promotes a *business-as-usual* strategy (Boontome et al., 2017).

The academic arena has provided a myriad of analyses on the interplay between energy use, growth, and environmental damage and argued that to improve energy security, reduce carbon emissions, and environmental issues, traditional energy sources must be replaced with innovative, clean ones. However, methodologies for calculating CO2 emissions from the industry are largely missing, despite their importance to energy conservation and environmental damage reduction. Such an issue has highlighted some significant obstacles to achieving carbon neutrality, specifically in the region of Thailand. Scholarly evidence on the association between the two factors are mixed and even contradictory (Ganda, 2019; Hansen, 1999; Lorek and Spangenberg, 2014; Salman et al., 2019; Wang et al., 2020; Weina et al., 2016a; Zhang et al., 2016, 2020, 2021).

Based on the above discussion, several motivations to conduct this research are under observation. For instance, it is important to understand the links between energy tech innovation, CO_2 emissions, and economic development to reveal the economy's reliance on energy and reshape the energy policy, particularly in Thailand. Secondly, it seems to be a large gap in the extant literature in terms of works that review the impact of tourism on environmental degradation, despite the sector's high potential to influence ambient air pollution. Thirdly, empirical arguments are often contradictory (Akdogan et al., 2015; Amzath and Zhao, 2014; De Vita et al., 2015; Jatuporn et al., 2011; Mohammadi and Rasekhi, 2015; Rasekhi et al., 2016), and the authors have not reached a consensus on the interplay between the two variables. Therefore, the lack of extensive research focusing on understanding the relationship between tourism and environmental degradation is a literature gap that this study aims to bridge.

Besides, the motivation for conducting this research also specifies the aims to fill the literature gap by enabling a better understanding of how green tech innovation and tourism influence Thailand's carbon emissions. The methodological motivation linked with the current study is based on the bootstrapping ARDL causality model developed by (McNown et al., 2018) for both short-term and long-term nexuses between endogenous and explanatory variables. This study reveals that the partnership and investment of public and private sectors positively impact carbon emissions and lead to higher environmental damage by increasing CO_2 emissions. The advances in technology improve the quality of the environment via reductions in carbon emissions. For this reason, it is widely observed that the objective to conduct this research is significantly required because of the above-stated key issues and various motivations as stated above. To the best of our knowledge, this is the first study investigating the impact of tourism and green technology innovation on Thailand's tourism sector based on the bootstrapping ARDL causality model suggested by (McNown et al., 2018). Thus, this study contributes originality in terms of the implementation of the method in this area.

By the given findings above, this research has provided some meaningful contributions. First, this study contributes to the literature specifically from the context of a policy-oriented standpoint by taking a position on a debate regarding the nexus of green innovation and carbon emission. Specifically, this study argues that, in the case of Thailand, the advance of technology positively affects the reductions in carbon emission, which is in support of the positive nexus between the two variables, similar to (Lorek and Spangenberg, 2014; Nikzad and Sedigh, 2017; Popp, 2012; Weina et al., 2016a; Zhang et al., 2016). This would reasonably provide reasonable evidence to various policymakers, governmental officials, and other environmental activists who have some keen interest in it. Furthermore, the study also contributes to the literature by demonstrating that tourism in Thailand has a bi-directional causal relationship with CO_2 emission, which also shares the findings of some past literature in other regions, such as (Shahbaz and Rahman, 2012, 2014) and (Satti et al., 2014), among others.

The remaining parts of this article are organized in the following manner. The upcoming section presents some main ideas in the literature on the topic subject to debate. Section 3 explains the underlying methodology and the construction of the model to be used. Section 4 explains the empirical analysis and discusses the empirical findings. Lastly, the final section provides some concluding remarks and a series of policy implications.

2. Literature review

2.1. Green innovation impact on carbon emissions

Rising international concern on green development has made many nations shift from simply working to achieve growth in creating a sustainable economic model to protect environmental health (Song et al., 2019). Absent the former, no real green evolution is attainable (James et al., 2013). Scientific and tech innovations are essential to green growth (Lorek and Spangenberg, 2014), and academics have confirmed this assertion in various regions of the world (e.g. (Grover, 2013), in India (Padilla-Pérez and Gaudin, 2014); in Central America).

In the recent past, green tech innovations have become instrumental in decreasing carbon emissions worldwide (Nikzad and Sedigh, 2017; Popp, 2012; Weina et al., 2016b; Zhang et al., 2016). With increasing anxiety about climate change, energy tech innovation has been the focus of many scholars. Although many analyses unpack the story of the complex network between the former and energy use, the impact tech innovation exerts on carbon emissions has not been extensively debated. Using the spatial econometric model (Wang et al., 2020), noted that technology innovations underlying renewables decrease CO_2 emissions in China, whereas traditional energy tech reorganization fails to reduce environmental damage. Also, the authors found that the effects of tech innovations on toxic emissions are trans-regional. That means that a geographic area that enjoys renewable energy changes would enable CO_2 mitigation in the surrounding territories (Mohsin et al., 2021).

Some previous analyses argue that the effects of green tech innovation on carbon emissions vary because of different factors, *inter alia*, time, and income (Acemoglu et al., 2012; Jaffe et al., 2002). According to many papers (Braungardt et al., 2016; Hu et al., 2019; Shair et al., 2021; Umar et al., 2021), the former effectively addresses the trade-off between growth and environmental protection, as it improves energy efficiency, essential to CO_2 abatement efforts. However, not everyone agrees with this assertion. For instance (Wang and Hao, 2012), found no substantial role of energy tech patents in decreasing ambient air pollution (CO_2 emissions) in China; clean energy tech patents drive down carbon emissions only in Eastern China. In the same vein (Weina et al., 2016b), showed that green innovation does improve environmental productivity in Italy but has no important effects on carbon emissions dilution.

In recent years (Salman et al., 2019), emphasized the role of place-bound conditions and demonstrated that innovation dilutes emissions in industrialized countries and increases environmental damage in the emerging states. Through the generalized method of moments (GMM) (Ganda, 2019), discovered a negative link between the two variables (Lee and Min, 2015). also identified a negative association between development spending, CO_2 pollution, and green research. In contrast, by examining OECD members (Koçak and Ulucak, 2019), underlined that renewable energy innovation expenditure has no obvious relationship with carbon emissions. In general, there is no consensus among scholars on the energy tech innovations-environmental damage association. For example (Fethi and Rahuma, 2019), documented the evidence that green innovation has some clear obstructive implications on carbon emissions (Többelmann and Wendler, 2020). explored the environmental patent applications-CO_2 emissions link in 27 EU states during 1992–2014 and revealed that the former reduces ambient air pollution. That confirms (Agyabeng-Mensah et al., 2019) findings of the decline in carbon emission through ecological patents and trademarks.

(Hashmi and Alam, 2019) have used the modified version of the *stochastic impacts by regression on population, affluence, and technology* (STIRPAT) model while exploring the implications of environmental innovation on the reduction of toxic emissions in OECD members during 1999–2014 and revealed that an increase in green patents improves environmental damage; the same holds for environmental tax revenue per capita (Li et al., 2019). stated that green tech innovation proves beneficial only for high-income countries, and it is challenging to bring arguments that the former increases CO_2 productivity in the rest of the world. Based on the panel threshold approach developed by (Hansen, 1999), (Salman et al., 2019) studied the heterogeneous potential green tech innovation-carbon emissions nexus and extensively demonstrated that income levels cause the non-linear link between the two.

(Agyabeng-Mensah et al., 2019) examined 28 OECD member states during 1990–2014 to discover if innovation exerts any effect on CO_2-driven pollution. The authors constructed the Innovation Claudia Curve (ICC) innovation model, claiming an inverted U-shaped nexus between the two variables. First, toxic emissions grow with innovation, and after a certain threshold, they reduce environmental damage. As per the STIRPAT model results, environmental health can be enhanced via research and development (R&D) investments in nine countries in the sample and increased because of such activities in only 3 states. In a later analysis (Agyabeng-Mensah et al., 2019), worked with trademark application and climate change-related patents as a proxy for innovation to investigate the effects on ambient air pollution in OECD nations and found that both indicators are efficient in reducing CO_2-based pollution. That is confirmed by the results of (Shahbaz et al., 2021), who researched the innovation-environmental damage relationship in 47 the ten most affected MENA states over the timeframe 1990–2017 and unfolded a mutual nexus between selected variables. The Quantile Autoregressive Granger causality test's outcomes highlighted bidirectional causality connecting tech innovations and the environment's quality.

(Meirun et al., 2021) examine the effect of the dynamic of green technology innovation on carbon dioxide emission in the economy of Singapore through bootstrap ARDL methodology. For an economy like Singapore, there is a radical growth along with the population density, and for this reason, there is a significant need to examine the trend in green technology innovation and carbon emission. The study findings through BARDL from 1990 to 2018 specify a negative impact of green technology innovation on carbon dioxide emissions (Wu et al., 2020). also try to explore environmental decentralization, investment in environmental protection, and green technology innovation, specifically from China from 2008 to 2016. It is observed that environmental decentralization promotes the concept of green innovation (Wang et al., 2020). examine the role of energy technology innovation in lowering carbon dioxide emission through spatial perspective. They further claim that various studies have explored the association between energy technology innovation and energy consumption, while the relationship between green innovation and carbon emission has not received enough attention. Their study findings reveal that renewable energy technology innovation plays their major role in the abatement of CO2.

To summarize, despite many arguments in the extant literature on the existence of negative nexuses between green-tech innovations and carbon emissions (*inter alia*, Brathwaite et al., 2010; Zhu et al., 2016), the empirical findings are often contradictory.

2.2. Tourism impact on carbon emissions

The rising role of tourism in the international arena, the need to adjust very quickly to changing consumer expectations, and the complex process of climate change mitigation require a deep examination of the adequate avenues to enable e growth and reduce harmful releases (Adedoyin et al., 2020). A major concern regarding the extant literature is the scarcity of papers that look into the implications of tourism on carbon emissions even though the industry has a high potential to affect ambient air pollution (Dogan and Aslan, 2017a). Although tourism is a substantial driver of global greenhouse gas (GHG) emissions, only a handful of scholars have explored its effects on national emissions (Gössling et al., 2013). Globally, tourism ramifications on CO_2 releases are diluting must faster in developed countries compared to emerging nations. Such outcomes indicate the presence of an environmental Kuznets curve (EKC) (Paramati et al., 2017). The EKC curve that tourism's impact on carbon emissions decreases as national income increases. However, a time-series study of the link between the two variables is limited (Chen et al., 2018).

Sustainable tourism is essential for global warming mitigation, as the industry is instrumental in achieving the Kyoto Protocol goals (Dogan and Aslan, 2017a). Despite its close connection to the environment, previous works on the linear relationship between tourism and ambient air health are scarce, and more importantly, reveal mixed empirical results (Amzath and Zhao, 2014; Dogan and Seker, 2016; Jatuporn et al., 2011; Mohammadi and Rasekhi, 2015; Rasekhi et al., 2016). Although some studies have emphasized that tourism contributes to larger CO_2 emissions (Gössling et al., 2013; Haeseldonckx et al., 2007; Katircioğlu, 2014; Raza et al., 2017; Saenz-de-Miera and Rosselló, 2014; Sharif et al., 2017; Solarin, 2014), other authors highlight that it reduces the level of air pollution (e.g., Lee and Brahmasrene, 2013) for a panel of EU members (Katircioğlu, 2014); in the case of Singapore; (Dogan and Aslan, 2017a).

Based on various panel econometric models (Dogan and Aslan, 2017a, 2017b, 2017b), researched the nexus between *inter alia,* CO_2 emissions, and tourism for the leading ten most-visited states for the 1995–2011 timeframe and found that tourism is a driver of higher carbon releases. Hence, regulatory policies are required to enable sustainable tourism and clean technologies in the field. This study confirms previous findings in the literature arguing that tourism activities increase the level of carbon emissions and are a cause of environmental damage (Al-Mulali et al., 2015; Amzath and Zhao, 2014; De Vita et al., 2015; Paramati et al., 2017). (Uzuner et al., 2017) have analyzed the outcomes of international tourism in carbon emissions in seven small islands during 1995–2013. They have employed the EKC assumption to assess the long-run equilibrium via energy use and economic growth channels. The panel cointegration analysis outcomes indicate a long-run nexus and the negative impact of inbound tourism on CO_2 releases in the long term.

However, empirical findings in the literature are contradictory. For instance, based on the Emirmahmutoglu-Kose panel Granger causality test applied to data for European Union and candidate states during 1995–2001 (Dogan and Aslan, 2017b), showed unidirectional causality in the sense that tourism decreases air pollution covering from tourism to CO_2 emissions. Over recent years, Thailand has made substantial efforts to develop a strong tourism industry as part of its national growth strategy. Based on the multivariate vector autoregressive (VAR) method coupled with causality analysis, the empirical study of (Jatuporn et al., 2011) researched the tourism-carbon dioxide emissions association in Thailand for the period 1986–2010 and showed that tourism generates larger CO_2 -based pollution levels in the long-run via energy and transport consumption. Similar results have been found by (Solarin, 2014) in the context of Malaysia. The author used an extended specification of the EKC framework to scan the impacts of financial development, urbanization, and inbound tourism on carbon emissions. It is revealed that there is a negative impact of tourism on ambient air health and unidirectional causality from tourism to environmental damage.

Within a similar EKC specification for the top 20 tourist destination states (Fethi and Rahuma, 2019), applied various unit roots tests, cointegration, and panel causality tests to yearly data from 1996 to 2016. They highlighted that tourism has substantial long-term implications on the specification of EKC, while CO_2 emission greatly moves over time via tourism growth. The results also underline the latter's positive effects on carbon emissions for several countries, *inter alia*, Thailand (Balsalobre-Lorente et al., 2020). analyzed the relationships among international tourism, globalization, growth, energy use, and CO_2-based pollution in OECD members during 1994–2014 and highlighted that, among others, tourism enhances climate change. The findings also indicated an EKC curve between tourism and ambient air pollution. Differently stated, globalization seems to decrease environmental damage from international tourism. These empirical outcomes point out the need to shape regulatory measures targeted at changing the present energy mix in OECD nations by improving energy and renewables use efficiency.

Recently (Köksal et al., 2020), explored the outcomes of tourism development on toxic emissions in Northern Cyprus, an area marked by significant blooming in the leisure industry over the past decades, and confirmed, based on time-series analyses, an inverted U-shaped EKC curve, both in the presence and absence of tourism expansion. Tourism has been found to significantly increase carbon emissions in the long run, indicating that the sector's development causes environmental degradation.

3. Theoretical framework

This study considers the dynamic association between green technology innovation, tourism, urbanization, population, personal income, and carbon dioxide emissions from the context of the Turkish economy. Based on the above literature, Fig. 1 below provides the layout for a theoretical framework which is further tested through the BARDL approach.

3.1. The bootstrapping ARDL bounds testing approach

As suggested by (McNown et al., 2018), we use the model to empirically test the cointegration among the study variables. The traditional ARDL methodology provided by (Pesaran et al., 1999) and (Pesaran et al., 2001) is observed with the power properties and weak size. For these limitations, we employ the bootstrapping ARDL framework, which includes a modern cointegration test along with conventional ARDL bounds testing approach. One of the core benefits of applying bootstrap ARDL is that it increases both the *t*-test and f test's power. However (Pesaran et al., 2001), provide two major conditions to apply for cointegration. First, the coefficients in terms of error corrections should be significant. Second, the coefficients of the lagged

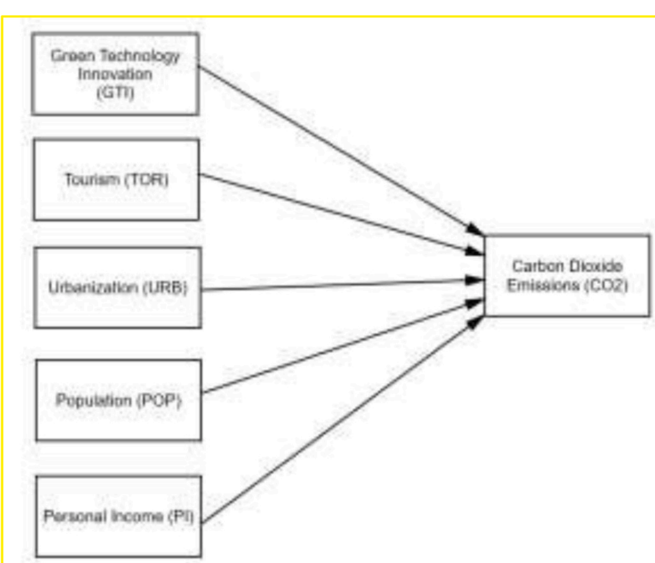

Fig. 1. Theoretical framework.

explanatory variable should also be significant. However (Pesaran et al., 2001), explain that there are no bound tests for the first case; however, for the second case, one should use critical bounds, and coefficients on error correction terms are statistically significant under the first situation. Thus, the test can be used if variables in the model are integrated of order 1 (Goh et al., 2017). opine that the conventional unit root test is awkward because their explanatory and power properties are low. However (McNown et al., 2018), bootstrapping the ARDL bounds test can resolve the issue.

Bootstrapping ARDL bound testing is unique due to two reasons. First, towards the order of variable integration properties, it is not complex. Second, it is quite suitable for the models which are dynamic time series in nature. Moreover, unlike conventional approaches, the bootstrapping ARDL bound testing addresses the problem of inconclusive cases (McNown et al., 2018). Furthermore, it also decreases the possibility of indecision cases (areas) because critical values are generated. Additionally, the bounds testing approach is observed as more adequate for dynamic models with multiple explanatory variables. As suggested by (Goh et al., 2017), the bootstrapping ARDL bounds testing procedure in its traditional implication can be specified while using three variables, as follows:

$$y_t = \sum_{i=1}^{p} \alpha_i y_{t-i} + \sum_{j=0}^{q} \beta_j x_{t-j} + \sum_{k=0}^{r} \gamma_k z_{t-k} + \sum_{l=1}^{s} \tau_l D_{t,l} + \mu_t \tag{1}$$

Where *i, j,k,* and *l* stands for lags which varies from 1 to p, 0 to q, 0 to r, and 0 to s. t denotes time; y_t denotes a dependent variable, x_t and z_t represents the predictor variables, a dummy variable $D_{t,l}$ is the break year as suggested by (Carrion-i-Silvestre et al., 2009) for the unit root test, β *and* γ shows the dummy variable coefficients. μ_t Indicates the error term covering the properties of finite variance and zero means. The model with the error correction term is specified as:

$$\triangle y_t = \varphi y_{t-1} + \gamma x_{t-1} + \psi z_{t-1} + \sum_{i=1}^{p-1} \lambda_i y_{t-1} + \sum_{j=1}^{q-1} \delta_j x_{t-j} + \sum_{i=1}^{r-1} \pi_k z_{t-k} + \sum_{i=1}^{s} \omega_i D_{t,l} + \mu_t \tag{2}$$

Here, $\lambda_i, \delta_j, \pi_k$ *and* ω_i are the connected functions in the above equation. By transforming into its error-correction form, an AR vector in the level, the derivation of the above equation from Eq. (1) is approximated. Eq. (12) is presented below with the help of an unconditional model based on the constant term (c).

$$\triangle y_t = \tilde{c} + \tilde{\phi} y_{t-1} + \tilde{\gamma} x_{t-1} + \tilde{\psi} z_{t-1} + \sum_{i=1}^{p-1} \tilde{\lambda}_i y_{t-i} + \sum_{j=1}^{q-1} \tilde{\delta}_i x_{t-j} + \sum_{i=1}^{p-1} \tilde{\pi}_i z_{t-k} + \sum_{i=1}^{p-1} \tilde{\omega}_i D_{t,l} + \tilde{\mu}_t \tag{3}$$

This equation requires the significance of the three null hypotheses to explain the cointegration between the study variables denoted as y_t , x_t and z_t. The hypotheses can be stated as:

I) All relevant error-correction terms are tested by the F1 test

*H*0: $\varphi = \gamma = \psi = 0$ whereas *H*1: At least one (φ, γ, ψ) are not zero.

II) All of the explanatory variable terms are tested by F2

*H*0: $\varphi = \gamma = 0$ against *H*1: At least one (φ, γ) are not zero.

III) Lagged dependent variable is tested by

*H*0: $\varphi = 0$ against *H*1: φ is other than zero).

Furthermore, the traditional ARDL approach allows for generating the bounds test's critical values for F1 and *T*-tests. However, it ignores the test statistic for the F2 test on the lagged explanatory variables. As compared to the conventional model, the bootstrapping approach, as provided by (McNown et al., 2018), demonstrates some critical values. Hence, to obtain empirical results, we have used the critical values demonstrated by (McNown et al., 2018).

4. Empirical analysis and result discussion

Descriptive statistics are shown in Table 1. It is found that GTI is more volatile compared to POP. PI, URB, and CO_2 are less volatile than TOR. The Jarque-Bera test outcomes indicate that all variables- CO_2, POP, URB, TOR, PI, and GTI- usually are distributed. The empirical analysis for the correlation matrix is presented in Table 2. It underlines a negative association between GTI and CO_2. A moderately negative correlation is observed between TOR and CO_2. URB, CO_2, and TOR are positively correlated, and a strong positive correlation is noted between URB and GTI. PI is positively linked with CO_2, GTI, TOR, and POP. All variables- CO_2, GTI, TOR POP- are statistically significant. On the contrary, PI showed a statistically significant result with URB.

In the very next step, the stationary properties of the study variables have been investigated. The integration order plays an important role in examining the cointegration between variables while indicating which cointegration technique is appropriate, as an unsuitable order of integration returns non-reliable results(Su et al., 2020, 2021). To avoid this issue, we have functionally used the ADF unit root test that puts up a break to a single unknown structure in the series (Carrion-i-Silvestre et al., 2009). Traditional unit root tests, such as PP (Phillips and Perron, 1988) and ADF (Dickey and Fuller, 1981) showed significant results due to their lower explanatory power (Ng-Perron, 2001). However, the ADF unit root test addresses this problem because of its greater explanatory power, giving an accurate empirical indication for structural breaks in the data series.

The unit root test results are shown in Table 3 based on the structural breaks. It is observed that in the case of structural breaks and to test the robustness of the unit root analysis, the ZA Unit root test is applied. All variables- CO_2, GTI, TOR, URB, POP, and PI- reported unit root problems at a level. Thus, after the first difference, all variables are integrated at I (1). Both ADF and ZA tests at different reveal that the null hypothesis results are highly significant. The ZA test confirms that at level, all variables contain a unit root and the existence of a structural break in the series. The breaks are present for the year 2014 Q4, 2008 Q1, 2012 Q1, 2009 Q2, 1999 Q1, 2004 Q2 for CO_2, GTI, TOR, URB, POP, and PI. That means that all variables have a distinctive order of integration; consequently, we apply a cointegration technique to inspect the existence of cointegration.

Therefore, this study has used the bootstrapping auto-regressive distributive lagged modeling (BARDL) provided by (McNown et al., 2018). This approach is utilized to check for long-term cointegration among the studied variables. This specification provides more reliable results than the traditional ARDL model presented by (Pesaran et al., 2001). It helps to identify cointegration by using a joint F-test for all the lagged level variables, traditional *t*-test, and new *t*-test on lagged level of explanatory and outcome variables, respectively. That highlights the superiority of bootstrapping ARDL over the traditional model in verifying cointegration between variables. Our findings (under Table 4) based on BARDL for both lagged levels showed highly statistically significant results. Moreover, the *t*-test and F-test on lagged regressors also support the research hypothesis, which confirms a long-run equilibrium cointegration relationship among the study variables at 1% and 5% level, respectively. The value of $\bar{R}^2$ shows that all regressors are 93.4%, explained by regressands. Moreover, the Jarque-Bera test ensures that variables are normally distributed. The findings also indicate that each variable has its independent terms, which means the serial correlation is absent (Pesaran et al., 2001).

The empirical findings for the long run are presented under Table 5. We find that GTI has a negative and highly significant effect on CO_2; *caeteris paribus*, the −0.139 value underlines the change in CO_2 for a unit change in GTI. Similarly, a unit increase in TOR reduces CO_2 by 0.211, assuming all others constantly. This empirical evidence has got literature support from (Chandran and Tang, 2013; Fei et al., 2014; Lantz and Feng, 2006). The relationship between CO_2 and URB is positive and statistically significant. Assuming all other variables constant, it is observed that a 1% increase in URB abundance causes an increase in CO_2 by 0.304%. Similarly, statistically significant results are reported for POP and PI. This dovetails research by (Arin and Braunfels, 2018; Brunnschweiler, 2008; Koitsiwe and Adachi, 2015; Moshiri and Hayati, 2017). During recent years, there has been significant green growth in the Turkish economy, which has provided some fruitful outcomes like a lower level of carbon emission from transportation while working for the green and hybrid technology.

The findings under stability analysis demonstrate that the error term is following a normal distribution. Moreover, autoregressive conditional heteroscedasticity and serial correlation are not identified in the model. The absence of white heteroscedasticity is also noted, which means that the model is well designed. In the long run, 91.5% of CO_2 is explained by GTI, TOR, URB, POP, and PI and the remaining 8.5% is due to the error term. Additionally, the Durbin Watson test shows that there is an absence of autocorrelation. Simultaneously, reliable results are shown under long-run estimation through CUSUM and $CUSUM_{sq}$ tests, respectively (Monk and Brown, 1975). argued that the stability of the parameter could be observed by CUSUM and $CUSUM_{sq}$ analysis.

Besides, finding for the short-term test are provided in Table 6. We reported that GTI declined CO_2 significantly. Similarly, the relationship between TOR and CO_2 is negative, as a 1% increase in TOR generates a 0.217% decline in CO_2, all else constant. URB and $CO_2$are positively linked at a 1% significance level. PI and POP are also positively related to CO_2. The estimates of ECM (−0.234) is the speed of adjustment, and it should be negative and significant. The result of ECM shows the deviation needed in the short-run from the long-run path by 23.4% each quarter.

Further, the short-run model also fulfills the assumptions of the diagnostic test. The result reveals that no autocorrelation conditional heteroskedasticity is present and that variation is homoscedastic. Hence, the model is well designed. The outcomes of CUSUM and $CUSUM_{sq}$ ensure the stability of short-run parameters at a 5% significance level. Subsequently, we applied the Granger Causality in Table 7 to test the relationships between selected variables. There is no evidence of any interplay among them. These findings are consistent with (Shahbaz and Rahman, 2012, 2014) and (Satti et al., 2014) who suggest that green technology, tourism, and urbanization have a bi-directional causal relationship with CO_2 emission. In contrast, there is a unidirectional Granger causality from the per capita income and population to CO_2 emission.

Table 1
Findings of descriptive statistics.

Variables	Mean	Min	Max	Std. Dev.	JB	P-Value
CO_2	2.419	2.393	2.444	0.016	1.727	0.361
GTI	3.069	2.895	3.138	0.067	3.012	0.201
TOR	2.178	2.130	2.376	0.048	1.854	0.334
URB	4.202	4.148	4.245	0.030	1.922	0.321
POP	1.214	1.203	1.222	0.008	2.406	0.241
PI	5.490	5.447	5.522	0.023	1.597	0.389

Source: Author Estimation

5. Conclusion, policy implications, and limitations

5.1. Conclusion

The current study's findings underline several relationships between CO_2, URB, POP, TOR, GTI, and PI. PI is moderately positively linked

Table 2
Findings of correlation analysis.

Correlation	CO_2	GTI	TOR	URB	POP	PI
CO_2	1					
GTI	−0.745***	1				
TOR	−0.578***	0.749***	1			
URB	0.601***	0.961***	0.366**	1		
POP	0.686***	0.474***	0.454***	0.738***	1	
PI	0.745***	0.628***	0.503***	0.232*	0.656***	1

Note: ***, ** and, * represents level of significance at 1%, 5% & 10%.

Table 3
Findings of Unit root test.

Variables	ADF (Level)	ADF (Δ)	ZA (Level)	Break Year	ZA (Δ)	Break Year
CO_2	−0.779	−5.986***	−0.997	2005 Q1	−8.126***	2014 Q4
GTI	−0.236	−3.623***	−0.272	2012 Q2	−6.399***	2008 Q1
TOR	0.662	−4.179***	0.109	2009 Q1	−5.496***	2012 Q1
URB	0.796	−3.114***	−0.759	2015 Q4	−7.571***	2009 Q2
POP	−1.081	−3.229***	−0.757	2003 Q1	−3.598***	1999 Q1
PI	0.279	−3.756***	0.330	2013 Q2	−5.437***	2004 Q2

Note: The values in the table specify the statistical values of the ADF and ZA tests. The asterisk ***, **, and * represent the significance level at 1%, 5%, and 10%, respectively.

with CO_2, GTI, TOR, and POP. All variables are having a significant impact on CO_2 emission in Thailand. PI is statistically significantly linked with URB. The abundance of natural resources Granger causes labor. Hence, the Economic Reform Protection Act (1992) implementation enables the growth of the economy. The advances in technology improve the quality of the environment via reductions in carbon emissions. However, to overcome the CO_2 emission issues, the market system should be encouraged to permit allocation schemes for carbon emission services.

Moreover, regional carbon emission trading platforms need to be developed for cooperation with information commissions provincial and municipal economies. Third, research should be promoted to design low carbon technologies that capture and store carbon dioxide and create a circular economy. Also, the country should encourage the waste recycling of the industry and households. Fourth, measures should be taken to attract foreign direct investment to address the carbon emissions problem. It is observed that the local government should increase the intensity of energy conservation and emission reduction work, as natural resources facilitate growth. Finally, natural resources could be utilized to boost capitalization. The financial sector needs to allocate more natural resources revenue for productive investments, enhancing domestic production. Moreover, this will also support vocational education, resulting in better technical skills of the labor force, positively impacting economic progress.

5.2. Policy implications

5.2.1. Central and tangential policy framework

- As energy consumption from non-renewable sources has its direct role in creating a higher level of carbon emission in Thailand's natural environment, the imposition of some strong policies and practices needs time that can lower such harmful effects to the climate. For this purpose, policymakers will have an incentive to bring significant changes in the prevailing energy consumption pattern for the economy of Thailand. However, it is also observed that sudden change in the pattern of energy consumption may create some adverse outcomes for the economic growth in the region, which is significantly dependent upon the traditional energy sources like fossil fuel and similar others. For this purpose, it is suggested that policymakers should adopt the phase-wise energy transformation from traditional sources to some renewable ones. This would justify the gradual and positive consequences for the economy and the natural environment as well.
- Also, policy support should target green manufacturing enterprises, as manufacturing firms are major contributors to ambient air pollution. When manufacturers in Thailand implement green innovation, society will benefit in terms of reduced environmental damage, more green products would be available, and the improvement in resource efficiency and economic growth would enhance the quality of life. Furthermore, the gradual decline of dependence on some traditional technology sources will help secure the natural resources reasonably. Additionally, the promotion of some green technology innovation or green innovation will help Thailand in making progress towards the achievement of their environmental goals, specifically sustainable development, during 2021 and onward. Furthermore, the government of Thailand must understand that protecting the surroundings and people's access to a clean and healthy environment must become a priority of politics, law, and economics.
- Meanwhile, the policy-making arena should design green logistic solutions for sustainable tourism that ultimately increase the quality of life in the modern climate change challenges.
- Policy actors should engage in more extensive efforts to ensure the conversion of tourism into a sustainable sector, as the latter greatly influences the societal provisions and individual values. The sustainability of tourism can be enhanced by close cooperation and sharing between various players, *inter alia,* visitors, local communities, hotels, and public authorities, so policymakers should consider this as well.

Table 4
Findings of bootstrapped ARDL cointegration analysis.

Bootstrapped ARDL Cointegration Analysis						Diagnostic tests			
Estimated Models	Lag length	Break Year	F_{PSS}	T_{DV}	T_{IV}	$\overline{R}^2$	Q-stat	LM(2)	JB
Model	2, 1, 1, 3, 3, 1	2010 Q1	17.549***	−8.001***	−6.548***	0.934	4.015	1.029	0.421

Model: CO2t = f (GTIt, TORt, URBt, POPt, PIt).
Note The asterisks *** and ** show significance at 1% and 5%levels respectively.

Table 5
Findings bootstrapped ARDL cointegration analysis (long run).

Dependent Variable = $CO2_t$			
Variable	Coefficient	T-Statistics	P. Value
Constant	0.172***	3.948	0.000
GTI_t	−0.139***	−2.842	0.001
TOR_t	−0.211***	3.345	0.000
URB_t	0.304***	3.184	0.000
POP_t	0.358***	5.024	0.000
PI_t	0.159***	3.081	0.000
D_{2009}	0.287***	2.018	0.048
R^2	0.915		
$Adj - R^2$	0.908		
Durbin Watson	2.084		
Stability Test			
Test		**F-Statistics**	**P. Value**
χ^2_{NORMAL}		0.208	0.159
χ^2_{SERIAL}		0.359	0.301
χ^2_{ARCH}		0.458	0.294
χ^2_{HETERO}		0.460	0.554
χ^2_{RESET}		0.751	0.122
CUSUM		Stable	
CUSUMsq		Stable	

Note: ***, ** and * represent level of significance at 1%, 5% and 10% respectively.

Table 6
Findings bootstrapped ARDL cointegration analysis (short run).

Dependent Variable = $CO2_t$			
Variable	Coefficient	T-Statistics	P. Value
Constant	0.125	0.517	0.605
GTI_t	−0.217***	−4.016	0.000
TOR_t	−0.122***	−3.161	0.001
URB_t	0.055***	1.991	0.047
POP_t	0.185***	9.205	0.000
PI_t	0.237***	5.1489	0.000
D_{2009}	0.082	1.082	0.281
ECM_{t-1}	−0.234***	−3.454	0.000
R^2	0.875		
$Adj - R^2$	0.871		
Durbin Watson	1.905		
Stability Test			
Test		**F-Statistics**	**P. Value**
χ^2_{NORMAL}		0.418	0.246
χ^2_{SERIAL}		0.228	0.598
χ^2_{ARCH}		0.331	0.208
χ^2_{HETERO}		0.189	0.601
χ^2_{RESET}		0.226	0.726
CUSUM		Stable	
CUSUMsq		Stable	

Note: ***, ** and * represent level of significance at 1%, 5% and 10% respectively.

5.3. Limitations and future research

After providing a meaningful conclusion and policy implications, it is imperative to mention that the above policy suggestions are not the absolute one due to several limitations associated with the present study. For example, this research has observed a general context of green technology innovation with no specific division of it to understand better which type of such innovation is more progressive towards determining the positive results about the natural environment of Thailand. Furthermore, the concept of sectoral green innovation is also ignored under the present study, limiting the policy implications. Also, this research is only considering the trends in carbon neutrality in Thailand while ignoring the rest of the ASEAN member states, who are also facing similar issues in terms of higher carbon emissions in recent years. Future research on this aspect can be taken up while considering the panel estimation of all of the ASEAN member states along with the sectoral investigation of green technology innovation too.

Table 7
Results of Granger causality.

Null Hypothesis:	F-Statistic	Prob.
GTI has not Granger Caused to CO2	18.262***	0.000
CO2 has not Granger Caused to GTI	61.698***	0.000
TOR has not Granger Caused to CO2	13.109***	0.000
CO2 has not Granger Caused to TOR	37.783***	0.000
URB has not Granger Caused to CO2	9.422***	0.002
CO2 has not Granger Caused to URB	39.796***	0.000
POP has not Granger Caused to CO2	15.593***	0.000
CO2 has not Granger Caused to POP	1.134	0.288
PI has not Granger Caused to CO2	6.185***	0.014
CO2 has not Granger Caused to PI	2.463	0.118

Note: ***, ** and * represent level of significance at 1%, 5% and 10% respectively.
Source: Author Estimations

CRediT author statement

Xiao-Guang Yue: Conceptualization, Methodology, Software, Data curation, Formal analysis, Supervision. Yiyi Liao: Conceptualization, Writing- Reviewing and Editing, Visualization, Investigation. Shiyong Zheng: Methodology, Investigation, Supervision, Writing- Reviewing and Editing. Xuefeng Shao: Software, Validation, Project administration, Writing- Original draft. Jing Gao: Conceptualization, Writing- Reviewing and 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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