Heliyon 9 (2023) e21577

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Do environmental taxes, environmental innovation, and energy resources matter for environmental sustainability: Evidence of five sustainable economies

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ARTICLE INFO

Keywords:
Sustainable development
Environmental taxes
Environmental innovation
Energy resources

ABSTRACT

This study explores the relationship between environmental taxation, environmental technologies, energy resources, and consumption-based carbon emissions in five leading green economies from 2000 to 2019. The study applied the Cross-Sectional Auto-Regressive Distributed Lag (CS-ARDL) model to derive benchmark results, with Augmented Mean Group (AMG) and Common Correlated Effect Mean Group (CCEMG) techniques being utilized for conducting robustness analyses. The empirical findings suggest that environmental taxation, environmental innovations, and the consumption of renewable energy are associated with a reduction in consumption-based carbon emissions, thereby contributing to enhanced environmental sustainability. Conversely, the utilization of non-renewable energy is linked to an increase in consumption-based carbon emissions. These results align with the objectives outlined in the Sustainable Development Goals' 2030 agenda, particularly SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation, and Infrastructure), and SDG 13 (Climate Action), offering valuable policy implications.

1. Introduction

Every nation shoulders the responsibility of ensuring sustainability, which entails safeguarding the environment, promoting economic stability, ensuring social equity, and addressing global challenges while fostering innovation, ethical responsibility, and long-term well-being of our planet. Governments must foster a sustainable environmental mindset, encouraging their citizens to embrace greener lifestyles to promote environmental sustainability. In this context, numerous studies have investigated approaches to reconcile economic needs with the imperative of advancing environmental sustainability over the past 50 years [1].

To address this challenge, the United Nations (U·N.), in 2015, approved 17 comprehensive Sustainable Development Goals (SDGs)

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https://doi.org/10.1016/j.heliyon.2023.e21577
Received 12 December 2022; Received in revised form 24 October 2023; Accepted 24 October 2023

and adopted the 2030 agenda that guides the world economies in securing economic expansion and poverty eradication [2], green investment and technological innovation [3], energy transition and diversification [4], and environmental improvement [5]. Consequently, the SDGs propose a plan for addressing the issue of climate change by 2030. Specifically, SDG 13 and SDG 7 are strongly linked to global environmental challenges and the pursuit of sustainable, affordable energy, as they necessitate practical measures to curtail future environmental degradation and foster environmentally sustainable growth [6,7].

The 2022 United Nations Climate Agreement, COP27, convened in Sharm el-Sheikh, Egypt with the primary objective of advancing the global response to climate change and bolstering the implementation of the Paris Agreement. The Paris Agreement sets its sights on restraining the global temperature increase to below 2 °C, ideally striving for 1.5 °C. Within this framework, participating nations were tasked with deliberating and reaching consensus on strategies for reducing greenhouse gas emissions, amplifying funding for climate adaptation and mitigation, and ensuring transparency in these endeavors. The United Nations underscores a stark warning: failure to act promptly will expose the world to the devastating impacts of climate change, eclipsing even the current COVID-19 pandemic in its severity [8].

Recent research has identified probable causes of environmental deterioration and proposed various countermeasures to reduce emissions, specifically consumption-based carbon emissions ($CBCO_2$). For instance, energy consumption has been identified as the primary driver of environmental deterioration [9,10], urbanization [11], foreign direct investment [12], financial development and innovation [13,14]. Carbon dioxide emissions have increased unprecedentedly in recent years and are now considered 50 % higher than at the start of the great industrial revolution [15]. According to Amin et al. [16], China, the United States, India, and Russia had the largest CO_2 emissions in 2018. However, developed nations are more advanced than developing ones due to their sustained growth and abundant energy sources [17]. Their high emission rate is due to their greater industrial development which is mostly aided by efficiently exploring renewable energy resources under their stated plans [18].

Fig. 1 compares the consumption-based carbon emission contribution of Switzerland, Sweden, Luxembourg, Finland and Denmark. It is evident that in 2019, Luxembourg was the highest $CBCO_2$ emitter among the compared countries. However, it is also worth noticing that when compared to itself, Luxembourg has been on a decreasing trend in terms of these emissions from 2012 (47.07t) to 2019 (36.44t). Switzerland followed with 13.51t in 2019, and Finland with 11.29t. On the other hand, Denmark and Sweden have the lowest $CBCO_2$ emissions.

At the COP-26 and COP-27 conferences, the participating parties made a global commitment to achieve a 50 % reduction in carbon dioxide emissions from 2010 levels and keep the global temperature rise below 2 °C, preferably below 1.5 °C [2]. In this context, the UN-SDGs proposed a pragmatic approach to achieving access to energy by promoting sustainable, affordable green energy sources (SDG 7). The primary energy sources (fossil fuels) produce over two-thirds GHGs and 80 % CO_2 emissions [19]. Several economies, including most E.U. members, have committed to decreasing their carbon footprint by 20 % by 2020 and 40 % by 2030 [20]. Hence, the E.U. nations met their 2020 target of increasing renewable energy resources consumption to 22.1 % of total final energy utilized in 2020, up from 19.9 % in 2019. This was achieved by boosting the proportion of renewable energy in total energy output from 34.1 % in 2010 to 37.50 % in 2020 [21].

Fig. 2 illustrates the annual percentage of renewable and non-renewable energy consumption. Renewable energy consumption in the OECD economies is highly relevant, particularly in Sweden (40.07 %), Denmark (35.80 %) and Finland (34.87 %). In contrast, nonrenewable energy consumption has been linked to environmental degradation in the region, exemplified by high percentages in countries like Luxembourg (92.08 %) and Denmark (65.89 %) (see Fig. 2). As a result, this goal aligns directly with SDG 13, which underscores the imperative of prioritizing climate change mitigation to foster a healthier environment, thanks to the environmental benefits conferred by renewable sources. Furthermore, objectives such as affordable and sustainable energy (SDG 7), innovative green technologies (SDG 9), and the implementation of environmentally conscious taxation addressing sustainability challenges (SDG 13) have assumed paramount importance in the pursuit of achieving the SDGs by 2030.

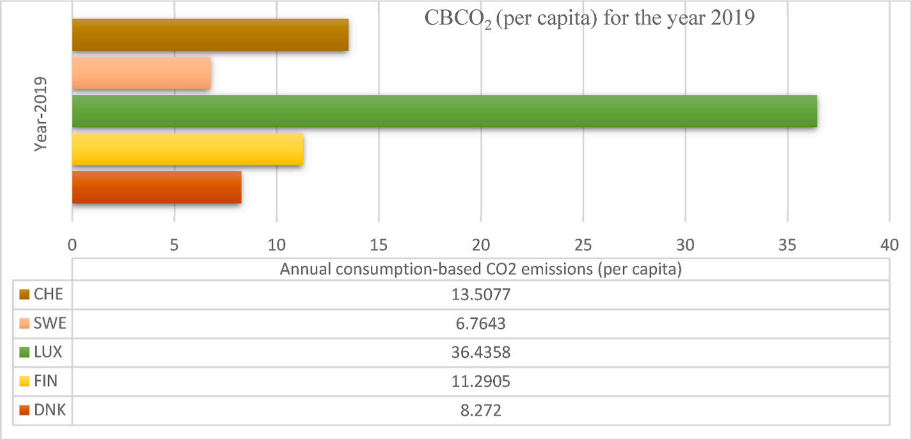

Fig. 1. Annual $CBCO_2$ (per capita) for five sustainable economies (2019).
Source: https://ourworldindata.org/

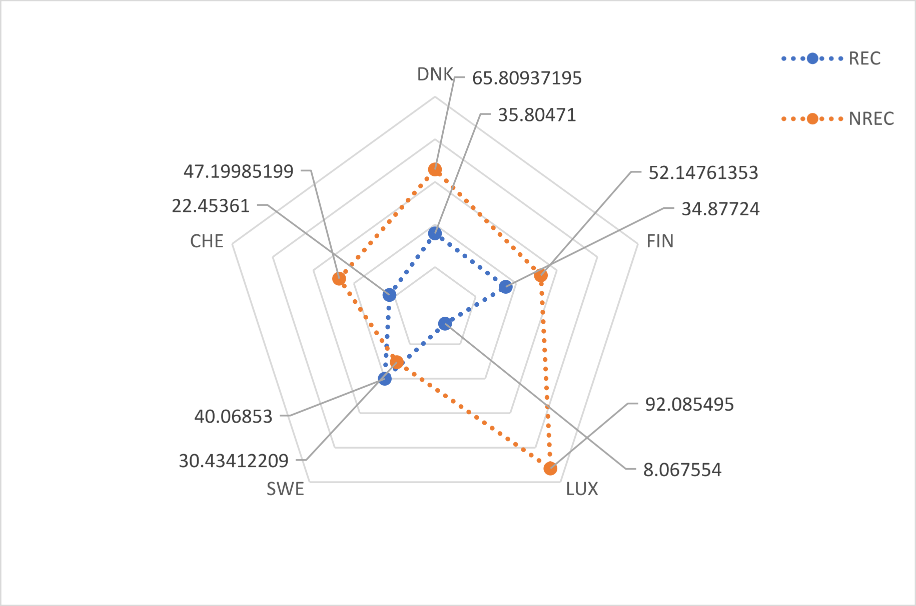

Fig. 2. The annual percentage of energy sources (renewable energy and non-renewable energy consumptions).
Source: https://ourworldindata.org/

Similarly, environmental taxes (ETAX) have demonstrated their efficacy as the most effective policy approach for fostering sustainable performance [22]. Many developing nations are now contemplating the implementation of environmental taxes to secure financing while simultaneously advancing their environmental sustainability goals. ETAX is evolving into a foundational pillar for achieving environmental sustainability and mitigating $CBCO_2$ emissions [23,24]. As previously noted [22], levying taxes on carbon emissions (carbon pricing) stands out as the most efficient approach to reducing emissions [25]. ETAX holds the potential to facilitate the attainment of a climate-neutral economy by 2050 and align with the European Green Deal's target of reducing carbon emissions by 55 % by 2030 [26].

In 2021, ETAX will account for 5.9 % of all E.U. taxes, a drop from 6.6 % over the past two decades. However, this differs significantly between nations [21]. For instance, Denmark's Green taxation as a share of GDP is the highest (3.29 %) in the OECD, followed by Finland (2.81 %) and Sweden (2.06 %) (see Fig. 3). The paper recognizes that the ETAX is the most critical environmental

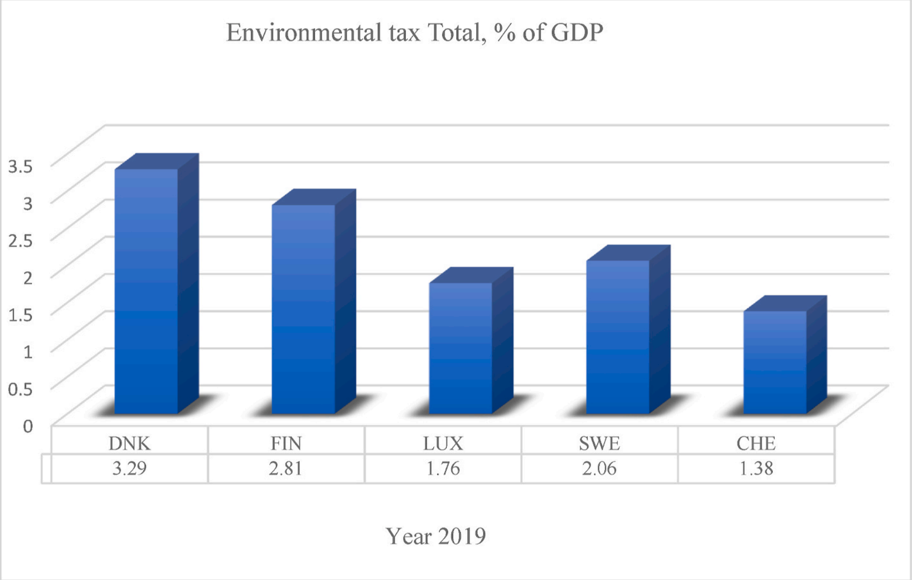

Fig. 3. Environmental taxes, total, % of GDP
Source: https://data.oecd.org/

policy instrument for identifying the mitigation influence on $CBCO_2$ and improving environmental sustainability in the region. Thus, governments can employ ETAX to meet SDGs 7 and 13 b y encouraging sustainable energy resources, discouraging non-renewable resources, and reducing carbon emissions by influencing human behaviors through taxation in energy, pollution, and transportation [27–29]. Therefore, the attainment of SDGs (specifically, 7 and 13) by 2030 is contingent on countries aligning their COP 26 targets with the adoption of ETAXs for curbing $CBCO_2$ emissions from carbon-intensive activities [22,29].

In conjunction with environmental taxes, promoting environmental-related technologies is at the heart of environmental policy. In recent decades, environmental technology (ETEC) has been acknowledged as a solution to tackle climate challenges and promote SDG 9 in OECD economies [13,30]. The significance of ETEC is imperative in combating $CBCO_2$ [31]. It not only assures innovation but also encourages production processes that contribute to producing goods and services that help reduce environmental deterioration [15]. In this context, in 2019, an investment of US$ 18.1 billion in renewable energy technology marked a substantial increase of 54 % compared to the previous year, 2018 [3]. ETEC integrates eco-friendly enhancements into its existing practices to optimize growth while minimizing environmental impact [32,33]. Furthermore, within OECD economies, Denmark (33 %), Finland (20 %), and Sweden (19 %) stand out as leaders in eco-innovation. Detailed environmental technology information for each of these five sustainable economies can be found in Fig. 4 below.

The present study evaluates the impact of environmental tax (ETAX), environmental technology (ETEC), and renewable energy resources (RENC-NREC) on consumption-based carbon dioxide ($CBCO_2$) emissions in five sustainable economies. The research centers on five exemplary nations at the forefront of implementing carbon tax policies: Sweden, Denmark, Finland, Switzerland, and Luxembourg. The examination and utilization of these environmental policies and renewable energy sources will yield valuable insights for these economies, serving as a benchmark for other countries striving to attain Sustainable Development Goals. We believe that this study will contribute to the advancement of environmental sustainability (SDG 13) through taxation measures and the promotion of environmental innovation (SDG 9) for the sustainable management of resources (SDG 13).

Sweden is internationally recognized as one of the world's foremost sustainable economies, owing to its extensive use of renewable and sustainable energy sources, coupled with its low carbon dioxide (CO_2) emissions. Over 50 % of the nation's energy consumption is derived from renewable sources, and it has set ambitious targets to reduce emissions by 85–100 % by 2045.

Switzerland boasts one of the globe's most environmentally friendly waste management systems, efficiently converting 100,000 tons of waste into sustainable energy annually. The country has made substantial investments in cutting-edge renewable energy technologies, encompassing solar electricity, wind turbines, hydropower, geothermal power, and heat pumps. Switzerland's aspiration includes achieving 100 % reliance on renewable energy, restoring 50 % of oceanic ecosystems, and attaining carbon neutrality by 2050.

Finland stands out in the realm of environmental taxation (ETAX), ranking seventh among the 34 OECD economies in terms of ETAX revenue as a percentage of GDP. Notably, taxes on energy constitute 67 % of the total environmentally related tax revenue in Finland. Presently, renewable energy sources fulfill 35 % of Finland's energy requirements. However, in order to meet the target, set forth by the Finnish Climate Change Panel, which aims for a 60 % reduction in emissions by 2030 compared to 1990, a discernible shift in the emission reduction pathway is imperative for its realization.

Denmark stands out as one of the foremost exemplars of sustainability within the panel of nations. It assumes global leadership in harnessing wind energy, with approximately 50 % of its energy production derived from wind turbines. Copenhagen, the capital of Denmark, is recognized as the world's largest green city, with ambitious plans to attain carbon neutrality by the year 2025. Notably,

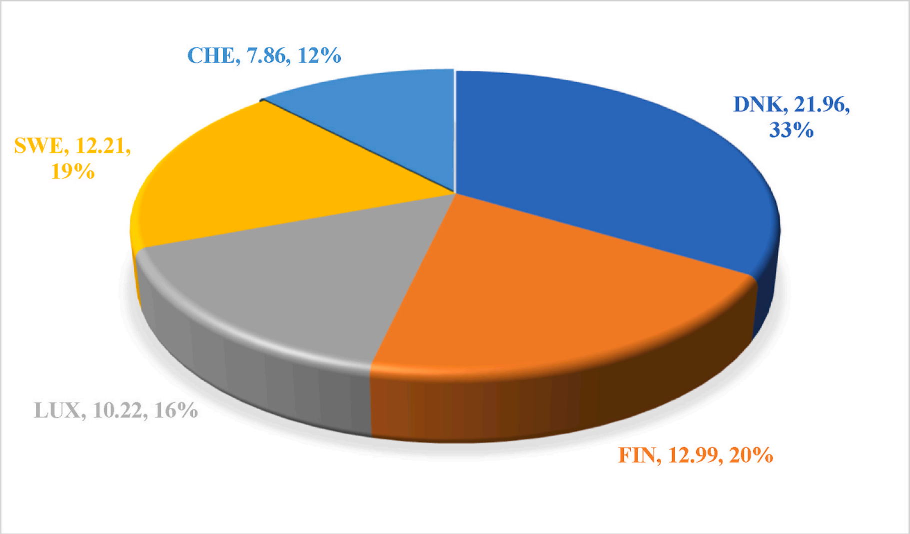

Fig. 4. Patents on environment technologies Total % (2019).
Source: https://data.oecd.org/

Denmark distinguishes itself by boasting the highest proportion of Environmental Taxes (ETAX) revenue in relation to GDP among OECD nations, with energy taxes constituting a substantial 59 % of the overall ETAX revenue.

Contrastingly, despite experiencing population growth and economic expansion, Luxembourg secures its position as the fifth-greenest country by demonstrating remarkable effectiveness in decoupling environmental concerns from economic advancement. This achievement is reflected in Luxembourg's comprehensive Environmental Performance Index (EPI) score of 79.12, a testament to its commendable stewardship of water resources, with a remarkable score of 99.76, and its seventh-place ranking in biodiversity and habitat preservation.

Economies embracing the concept of a "green economy" are those in which environmental sustainability enjoys widespread recognition by both governments and societies [22]. Consequently, focusing on these nations holds the potential to bolster crucial policy initiatives aimed at advancing sustainable development goals, particularly those related to SDGs 13, 7, and 9. Thus, to the best of the authors' knowledge, this analysis addresses a gap in the literature by shedding light on the interplay between environmental taxation (ETAX), environmental technology and innovation (ETEC), and the utilization of renewable and non-renewable energy resources (RENC-NREC) in reducing carbon dioxide emissions in these five sustainable economies.

The subsequent sections of this study are structured as follows: Section 2 provides a concise overview of the relevant literature; Section 3 outlines the research design employed in this study; Section 4 presents the research findings and examines their implications; and, finally, Section 5 briefly presents the study's conclusion.

2. Literature review

2.1. Environmental taxes and environmental sustainability

Neither economic development nor market mechanisms can adequately address the fundamental challenges posed by environmental externalities [34]. Based on recent assessments of the human impact on the environment, implementing an environmental tax (ETAX) emerges as an appealing approach for reducing emissions levels [25]. Environmental taxes (ETAX) are regarded as one of the paramount policy instruments to mitigate adverse environmental effects [22,28,29,35,36]. However, the long-term objective of environmental taxes (ETAX) lies in instigating behavioral shifts, encouraging businesses to embrace eco-environmental technologies and motivating consumers to make choices in favor of eco-friendly and sustainable products [22,23]. Researchers have scrutinized the nonlinear impact of ETAX on CO_2 through novel dynamics and innovative green technologies [37]. The empirical findings indicate that ETAX harms CO_2 emissions at high levels of globalization.

Karmaker et al. [38] affirm that environmental taxes (ETAX) will substantially enhance environmental technology and emissions control (ETEC) over the long term. Additionally, the crucial role of innovation development in facilitating industries to achieve their clean energy objectives is underscored. Most studies categorize environmental taxes or carbon taxes as pollution tax rates owing to their capacity to incentivize technological innovation. Their impact contributes significantly to enhancing environmental sustainability while concurrently reducing carbon emissions [25,36,39,40]. Similarly, in another study, a quantile approach was employed in seven green economies, revealing a favorable impact of environmental taxes (ETAX) on enhancing environmental sustainability [22]. Utilizing fixed effects for panel data encompassing 18 Latin American and Caribbean countries from 1994 to 2018 [27], employing MMQR suggests a significant and adverse effect of environmental taxes on $CBCO_2$. Similarly, the study investigated G-7 economies and found a favorable impact of ETAX on $CBCO_2$ [29,40]. European nations put environmental laws and tax policies in place, which may prevent some industries from using non-renewable resources. Our study joins the strand of [22,25,28,29,38]. The role of environmental taxes is frequently explored in several papers based on environmental technology [23].

2.2. Environmental technology and environmental sustainability

The innovation geared towards fostering environmental sustainability is commonly referred to as environmental technology, often denoted as green innovation [31]. This innovation paradigm actively promotes the utilization of RENC and contributes to enhancing environmental quality [41]. Researchers across various countries have conducted comprehensive studies examining the intricate relationship between innovation and carbon emissions [3,13,17,21,33,42]. Specifically, Ahmad et al. [43] conducted an analysis encompassing the period from 1990(Q1) to 2016(Q4), focusing on BRICS economies. Their findings indicate that ETEC measures could effectively curtail CO_2 emissions.

Similarly, Jianguo et al. [13], in their study spanning from 1998 to 2018 and encompassing a panel of 37 OECD countries, employed the system-GMM approach. Their research unveiled that the implementation of ETEC strategies not only mitigates carbon emissions but also enhances environmental sustainability within the OECD region. Furthermore, Ma et al. [44] delved into the impact of ETEC on Carbon-Based Carbon Output ($CBCO_2$) within the G-7 bloc during the period from 2004 to 2019. Employing the MMQR method, their investigation yielded compelling evidence that ETEC initiatives lead to a reduction in $CBCO_2$ levels and concurrently contribute to an improved environmental quality.

Oyebanji et al. [45] employed the ARDL approach to analyze Spain's economy and identified a positive relationship between ETEC and environmental sustainability. In a similar vein, Abid at el [46]. investigated the interplay between CO_2 emissions and innovation across eight economies from 1990 to 2019, employing the FMOLS approach, revealing an inverse relationship between innovation and CO_2 emissions. Additionally, Luo et al. [3] demonstrated that ETEC initiatives can lead to a reduction in $CBCO_2$ without compromising the final product's quality, as they enable businesses to lower their energy consumption and environmental emissions, especially in OECD economies. Consequently, both private enterprises and government institutions are increasingly allocating resources to support

ETEC initiatives, aiming to enhance sustainable development and diminish $CBCO_2$ emissions [21,33,45,47–50].

The literature investigates the impact of ETEC on $CBCO_2$ levels across different business cycles, exploring whether it leads to an increase or decrease [46,51,52]. These studies have arrived at the consensus that positive shocks to ETEC tend to result in a negative change in $CBCO_2$, while adverse shocks to ETEC correspondingly yield a positive change in $CBCO_2$. The significance of RENC-NREC hinges on the advancement of ETEC [45]. Furthermore, ETAX is expected to promote ETEC investments and increase the use of renewable energy sources, resulting in a reduction in $CBCO_2$ emissions [22,38].

2.3. Energy resources and environmental sustainability

In recent years, the literature on environmental degradation has progressively placed greater emphasis on energy resources. The role of energy resources has been subject to comprehensive examination due to their profound influence on CO_2 emissions. Existing empirical evidence pertaining to the interplay between energy consumption and CO_2 emissions predominantly relies on aggregated energy utilization, rather than isolating energy sources as discrete drivers of $CBCO_2$. Moreover, empirical research indicates that the categorization of energy sources into RENC-NREC may yield diverse effects on CO_2 emissions [5].

RENC, which refers to energy sources characterized by sustainable replenishment and the capacity for repeated utilization [1], encompasses various environmentally friendly sources such as solar energy, wind power, geothermal energy, biomass, and hydropower. In comparison to NREC sources [31], RENC sources exhibit significantly lower emissions and pollution during their collection and production processes. RENC sources have consolidated their place as the leading energy source, with renewables currently accounting for around 28 % of worldwide power, up from 19 % in 2010 [19].

From a climate change perspective, RENC is widely recognized as substantially impacting environmental quality. By reducing pollution and emissions in the atmosphere, RENC plays a crucial role in mitigating the negative effects of climate change [1,5,15,21,26,31,53–55]. Therefore, the study by Ali et al. [8] shows that energy consumption in seven emerging economies is one of the non-economic factors of CO_2 emission. According to the study, promoting RENC and enforcing strict environmental policies can help to prevent environmental degradation in the E 7 bloc. Similarly, examined the relationship between RENC and environmental sustainability, alongside other control variables, within the context of European Union countries. Their research findings proved that RENC helps mitigate environmental pollution. Contrary to RENC, fossil or NREN energy sources contribute to emissions, worsening global warming [18,56].

NREN sources refer to energy supplies that have been renewed for an extended period. Although fossil fuels are undeniably reliable economic drivers, they have significant environmental and health effects [57]. Using data from Japan's economy, Adebayo et al. [15] examined the energy-CO_2 emissions nexus, revealing that heightened energy usage corresponds to an increase in CO_2 emissions. This relationship holds implications for Non-renewable Energy Consumption (NREC) and its impact on environmental sustainability in Vietnam [18]. Numerous researchers have ascertained that non-renewable energy sources in various regions exacerbate environmental degradation [1,5,26,50,58,59].

This study contributes to the existing body of knowledge in several noteworthy ways. Firstly, it stands as the inaugural investigation wherein environmental taxes, environmental technology (ETEC), and energy resources (NREC-NREC) assume critical roles. Consequently, this research has established empirical insights into the roles of ETAX, ETEC, and energy resources in relation to consumption-based carbon emissions. Our findings suggest that the implementation of environmental tariffs not only has the potential to enhance climate health (SDG 13) but also to drive innovation development (SDG 9) and promote sustainable energy consumption (SDG 7). Furthermore, this approach aids in the formulation of policies for sample countries, aligning them with diverse Sustainable Development Goals (SDGs).

Secondly, we endeavor to fill the knowledge gap by employing the $CBCO_2$ approach to scrutinize the impact of environmental-related taxation, technological advancements, and energy resource utilization on carbon emissions at the consumption level. Furthermore, prior research has predominantly focused on the effects of environmental-related taxes and innovations as they relate to greenhouse gas (GHG) emissions, primarily CO_2. Thirdly, with a specific emphasis on the dynamics of energy resource utilization, we investigate the substantial influence of Environmental Taxes (ETAX) and Environmental Technologies (ETEC) on $CBCO_2$. Environmental taxation and the adoption of eco-friendly technologies are poised to drive the adoption of renewable energy sources, thereby facilitating a transition towards sustainable energy practices, and mitigating environmental degradation within the five sustainable economies.

Finally, our study harnesses advanced panel data methodologies, including CS-ARDL and AMG-CCEMG, to provide a comprehensive understanding of the intricate interplay between environmental-related taxation, environmental technology adoption, and energy resource utilization in the context of five sustainable nations. These findings serve as a foundation for the development of a robust policy framework aimed at fostering environmental sustainability within the sample region. Consequently, leveraging the available data, this study strives to address this research gap and assess the repercussions of environmental-related taxation, environmental technology adoption, and energy resource dynamics on $CBCO_2$ for the period spanning from 2000 to 2019 in the context of these five sustainable countries (see Table 1).

3. Research design

3.1. Data, theoretical framework, and empirical modeling

The study investigates the potential influence of ETAX, ETEC, and energy resources as key factors affecting environmental sustainability. Panel data from the period 2000 to 2019 were selected for analysis, as certain critical variables in the official database were updated only until 2019, encompassing five economies committed to sustainability. A comprehensive list of variables and their corresponding definitions can be found in Table 2.

3.2. *Regression model*

Eq. (1) represents the employed regression model for this study.

$$\boldsymbol{CBCO_2 = f[ETAX + ETEC + RENC + NREN]} \tag{1}$$

For empirical purposes, Eq. (2) serves to minimize data variability, mitigating challenges linked to multicollinearity and heteroscedasticity.

$$\boldsymbol{lnCBCO_{2i,t}} = \varnothing_i + \varnothing_t + \varnothing_1 \boldsymbol{lnETAX_{it}} + \varnothing_2 \boldsymbol{lnETEC_{it}} + \varnothing_3 \boldsymbol{lnRENC_{it}} + \varnothing_4 \boldsymbol{lnNREN_{it}} + \boldsymbol{\varepsilon_{it}}, \tag{2}$$

where $\boldsymbol{CBCO_2}$ represents consumption-based carbon emission, $\boldsymbol{i}$ represents the index for the considered sustainable economy, $\boldsymbol{t}$ denotes the time period, $\varnothing_i + \varnothing_t$ denotes the intercept of the equations , $\varnothing_1 .... \varnothing_4$ are the independent variable's impact magnitudes. and $\boldsymbol{\varepsilon}$ is the error term.

3.3. *Empirical strategy*

Our empirical approach comprises the following phases:

Firstly, we conduct tests for cross-sectional dependence (CRSD) as proposed by Pesaran [60] and assess slope homogeneity (SLPH) using the method outlined by Hashem and Pesaran [61].

In the second phase, we employ the unit root analysis method as developed by Pesaran [62] both with and without considering a structural break [63].

Moving to the third phase, we apply the panel cointegration tests proposed by Westerlund et al. [64] and Banerjee et al. [65].

Finally, for benchmark analysis, our study adopts the Common Correlated Effects Augmented Mean Group (CCEMG) and Augmented Mean Group (AMG) approaches alongside the Cointegrating Regression Durbin–Watson (CRDW) estimator to investigate short- and long-run dynamics and confirm the benchmark results. A comprehensive illustration of these stages is provided in Fig. 5.

3.4. *Cross-sectional dependency (CRSD) and slope homogeneity (SLPH) analysis*

The first step towards the model estimation is Cross-sectional dependency (CRSD) among countries/units [60]. CRSD refers to the correlation among units within the same CRSD, which can be attributed to the spillover effect of unobserved common factors or shocks. For instance, economies worldwide depend on each other due to globalization, inter-economic solid relations, and integration of finance and trade [13]. However, avoiding CRSD in panel data can generate fictitious outcomes [18]. The null hypothesis of the CRSD test states "no CRSD in panel data." Next, the empirical study proceeds to examine slope heterogeneity (SLPH). Testing for cross-country heterogeneity is crucial because, notwithstanding potential interdependencies among nations, individual countries may

Table 1
List of acronyms.

Acronym	Full Form
$CBCO_2$	Consumption-Based CO_2 emissions
ETAX	Environmental Tax
ETEC	Environmental Technology
RENC	Renewable Energy Consumption
NREC	Non-Energy Consumption
GHGs	Greenhouse Gases
U·N.	United Nations
SDGs	Sustainable Development Goals
SDG 7	Affordable and Clean Energy
SDG 9	Industry,Innovation,and Infrastructure
SDG 13	Climate Action
CRSD	Cross-Sectional Dependency
SLPH	Slope Homogeneity
CS-ARDL	Cross-SectionalAuto-Regressive Distributed Lag
AMG	Augmented Mean Group
CCEMG	Common Correlated Effect Mean Group
E.U.	European Union
CHE	Switzerland
SWE	Sweden
LUX	Luxembourg
FIN	Finland
DNK	Denmark

Table 2
Variable descriptions and data sources.

Variable's description	Abbreviation	Description	Sources
Environmental Sustainability	$CBCO_2$	Consumption-based CO_2 (per capita)	https://ourworldindata.org/
Environmental Tax	ETAX	Environmental tax Total, % of GDP	https://data.oecd.org/
Environmental technology	ETEC	Patents on environment technologies Total, %	https://data.oecd.org/
Renewable energy consumption	RENC	Renewable energy Total, % of primary energy supply	https://ourworldindata.org/
Non-Energy consumption	NREC	Fossil fuels (% equivalent primary energy)	https://ourworldindata.org/

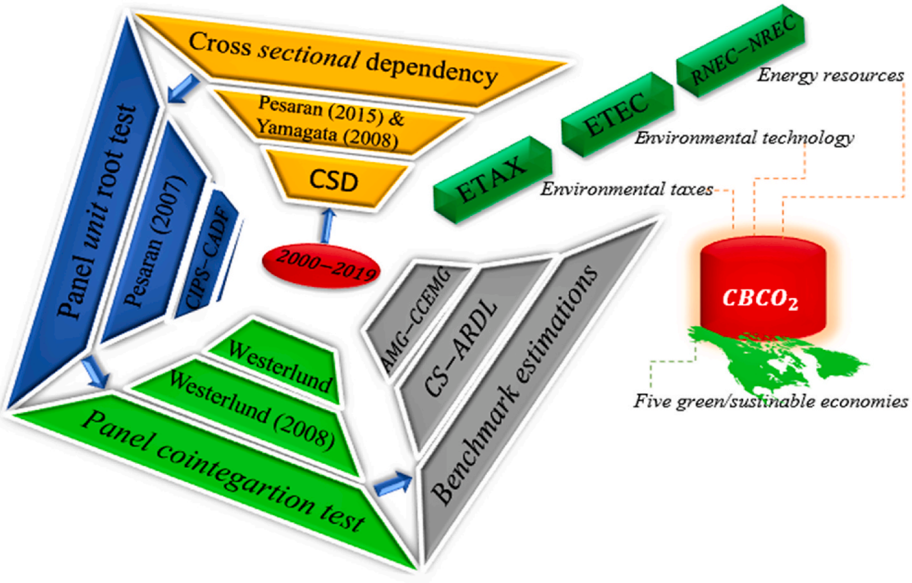

Fig. 5. Econometric analysis framework.

maintain their autonomous policy frameworks.

3.4.1. *Third-generation panel unit root analysis*

After conducting the diagnostic analysis (CRSD-SLPH) on the chosen sample size, the subsequent step involves the determination of the panel unit root test. Choosing the proper stationarity from the 1st, 2nd, and 3rd generations is critical to prevent inconsistent and deceptive findings, which can lead to poor interpretation and forecasting. According to Bai et al. [63], in order to address all the problems associated with panel data regression, the 1st and 2nd generation unit root tests are insufficient. As a result, the 3rd generation panel unit root method incorporates both national and global activities as the structural break, heterogeneous parameters, and CRSD in panel data. We adopted the approaches proposed by Bai et al. [62,63] and Pesaran [63] to identify the panel data's unit root existence, CRSD, SLPH and structural break. These assessments are essential for panel cointegration estimation.

3.5. *The panel cointegration analysis*

The study adopted two approaches for panel cointegration analysis: The Westerlund & Edgerton cointegration analysis [64] and the Banerjee & Carrion-i-Silvestre cointegration analysis [65]. The primary goal is to discover the long-run relationship between the indicators in the five sustainable countries. The Westerlund & Edgerton approach considers all panel data constraints with cointegration, such as individual cross-section structural break, CRSD, SLPH, and error term correlation. Similarly, the Banerjee & Carrion-i-Silvestre framework offers valuable insights into the realm of Commonly Rooted Structural Breaks (CRSD), distinguishing between strong and weak manifestations, while also addressing various other econometric concerns pertinent to panel data analysis. Since the panel cointegration was confirmed, our study adopted CS-ARDL for benchmark analysis and AMG-CCEMG for robustness.

3.6. *The benchmark analysis*

3.6.1. *CS-ARDL analysis*

Panel data may exhibit persistent CRSD due to unidentifiable common determinants that uniformly impact all sectors. For instance, financial and economic shocks have the potential to influence various socioeconomic elements or industries across the panel. Such a CRSD specification in the data can lead to inaccurate findings when conducting regression analysis. To address this challenge, the CS-

ARDL approach is deemed the most suitable for establishing long-term correlations. This technique permits the estimation of dynamic common correlation effects while accounting for time dynamics, CRSD, SLPH issues, and cross-country error dependence. Consequently, it enables the investigation of both short- and long-term effects [21].

The application of the CS-ARDL framework to derive common elasticity coefficients can offer valuable insights for the development of a shared policy framework aimed at promoting environmental sustainability. The preliminary form of CS-ARDL is given below.

$$\boldsymbol{CBCO_{2it}} = \sum_{\boldsymbol{i=0}}^{\boldsymbol{P_u}} \boldsymbol{\alpha_{it} CBCO_{2it-1}} + \sum_{\boldsymbol{i=0}}^{\boldsymbol{P_u}} \boldsymbol{\delta_{it} V_{it-1}} + \boldsymbol{\varepsilon_{it}} \tag{3}$$

where the dependent variable, $\boldsymbol{CBCO_2}$, represents consumption-based carbon emission and $\boldsymbol{V}$ represents all independent variables such as environmental taxes, environmental technology, and energy resources (RENC, NREC), while $\boldsymbol{\varepsilon}$ is the error term.

By employing the average cross-section of each repressive, Eq. (3) was expanded into Eq. (4) as follows.

$$\overline{\boldsymbol{W}}_{\boldsymbol{t-1}} = (\overline{\boldsymbol{CBCO}}_{\boldsymbol{2it-1}}, \overline{\boldsymbol{V}}_{\boldsymbol{it-1}}) \tag{4}$$

where, $\overline{\boldsymbol{W}}_{\boldsymbol{t-1}}$ is the average value of the dependent indicator $\overline{CBCO}_{2it-1}$ and $\overline{V}_{it-1}$ represent all explanatory variables. In order to alleviate the CRSD problem, long-run estimated values are estimated in Eq. (5) by the value of short-run assessments in the CS-ARDL estimation. The long-run coefficient and the mean group estimator are as follows in Eq. (6):

$$\partial_{\widehat{\boldsymbol{CD-ARDL},\boldsymbol{i}}} = \frac{\sum_{\boldsymbol{I=0}}^{\boldsymbol{P_v}} \widehat{\boldsymbol{\delta}}_{\boldsymbol{it}}}{\boldsymbol{1} = \sum_{\boldsymbol{I=0}}} \widehat{\boldsymbol{\alpha}}_{\boldsymbol{I,t}} \tag{5}$$

The mean group is estimated as follows in Eq. (6):

$$\widehat{\partial_{MG}} = \frac{\mathbf{1}}{\mathbf{N}} \sum_{\boldsymbol{i=1}}^{\boldsymbol{N}} \widehat{\partial}_i. \tag{6}$$

whereas the short-run dynamics indicators are as follows Eq. (7), Eq. (8), Eq. (9) and Eq. (10):

$$\Delta CBCO_{2it} = \varnothing_i [CBCO_{2it-1} - \partial_i V_{it-1}] - \sum_{i=0}^{P_u - 1} \alpha_{it} \Delta_i CBCO_{2it-1} + \sum_{i=0}^{P_v} \delta_{it} \Delta_i V_{it-1} + \sum_{i=0}^{P_w} \gamma_i \overline{W}_{t-1} + \varepsilon_{it} \tag{7}$$

where, $\Delta_i = \boldsymbol{t} - (\boldsymbol{t} - \mathbf{1})$, and

$$\widehat{\boldsymbol{\tau}}_i = -\left(\mathbf{1} - \sum_{\boldsymbol{i=0}}^{\boldsymbol{P_u}} \widehat{\boldsymbol{\alpha}}_{\boldsymbol{i,t}}\right) \tag{8}$$

$$\widehat{\boldsymbol{\vartheta}}_i = \left(\frac{\sum_{\boldsymbol{I=0}}^{\boldsymbol{P_v}} \widehat{\boldsymbol{\delta}}_{\boldsymbol{it}}}{\widehat{\boldsymbol{\tau}}_i}\right) \tag{9}$$

$$\widehat{\partial_{MG}} = \frac{\mathbf{1}}{\mathbf{N}} \sum_{\boldsymbol{i=1}}^{\boldsymbol{N}} \widehat{\partial}_i \tag{10}$$

The value of the error correlation model (ECM) is anticipated to be significant and negative (ranging −1 to 0), indicating that the model is a table and moves toward long-run equilibrium.

Table 3
Descriptive and normality analysis.

	$CBCO_2$	ETAX	ETEC	RENC	NREC
Mean	16.776	2.740	11.849	20.498	64.681
Median	13.521	2.641	10.885	21.400	61.756
Max	53.488	5.101	25.831	42.510	99.082
Min	6.764	1.380	4.750	1.041	29.918
Std	10.970	0.957	5.100	11.043	22.872
Skewness	1931	0.925	0.962	−0.222	0.169
Kurtosis	5.803	3.316	3.314	2.119	1.668
Jarque-Bera	94.923	14.359	15.815	4.058	7.866
Prob	0.000	0.000	0.000	0.131	0.019

3.6.2. AMG and CCEMG robustness analysis

The study used an augmented mean group (AMG) approach [66] and a common correlated effect mean group (CCEMG) approach [67] to investigate short- and long-run dynamics and confirm the benchmark results.

4. Results and discussion

Table 3 presents a comprehensive overview of summary statistics and the results of normality checks conducted on various variables, including CBCO2, ETAX, ETEC, and energy resources (RENC-NREC). The data encompasses measures such as mean, median, range (maximum and minimum values), standard deviation, kurtosis, skewness, and the Jarque-Bera normality test. Notably, among these variables, the mean value for the energy resources parameters in the context of sustainable economies consistently ranked highest. This analysis reveals that the energy resources indicators, denoted by RENC and NREC, exhibit greater volatility when compared to $CBCO_2$, ETEC, and ETAX, shedding light on the relative variability within these key indicators.

Environmental taxes underscore the ongoing necessity to combat environmental degradation by channeling resources into renewable energy and environmental technology, thereby enhancing environmental sustainability. Furthermore, in the normality test, the significant Jarque-Bera statistics values for most indicators confirm the presence of nonlinearity within the data for the sample countries. Additionally, the results consistently indicate that all parameters exhibit a non-normal distribution, affirming the need for empirical analysis employing CS-ARDL and AMG-CCEMG techniques.

4.1. Benchmark analysis

Tables 4 and 5 present the diagnostic test results, grounded in two empirical approaches: CRSD and SLPH. Table 4 provides insight into the empirical findings of the CRSD analysis. The alternative hypothesis (H_1) posited the presence of a CRSD issue within the data, and the research outcomes affirmed that all parameters $CBCO_2$, ETAX, ETEC, and RENC accept H_1 at a significance level of 1 %. Moreover, these nations' tax policies, economic measures, and trade strategies have exhibited heightened interdependence. These findings serve to corroborate the existence of CRSD within the dataset.

Furthermore, Table 5 presents the SLPH findings employing two tests (i.e., $\widetilde{\Delta}$ and $\widetilde{\Delta}$ adjusted) both of which confirm the rejection of the null hypothesis (H_0) associated with SLPH. Additionally, the results indicate that the slope coefficients exhibit heterogeneity based on economic circumstances, taxation policies, technological factors, consumption patterns, and energy intensity levels. This suggests that alterations in $CBCO_2$, ETAX, ETEC, or energy resource utilization within any of the five sustainable economies would exert a significant and potentially either favorable or unfavorable impact on the other five nations committed to sustainability. Consequently, both of these analyses reject the null hypotheses of SLPH and CRSD, with all findings achieving statistical significance levels at 1 %, 5 %, and 10 %, respectively.

The subsequent step involved the verification of stationarity, determination of integration order, and identification of structural break years through unit-root approaches. Table 6 was dedicated to investigating the presence of unit roots. The results reveal that all indicators, including $CBCO_2$, ETAX, ETEC, and energy resources (RENC, NREC), exhibit stationarity at the level, denoted as I (0). These findings reject the null hypothesis (H_0) at the significance levels of 1 %, 5 %, and 10 %, respectively. Nevertheless, the reliability of these outcomes in Table 6 hinges on our assessment of data stationarity in the presence of a structural break, a factor considered by Bai et al. [63]. Simultaneously, the 2nd generation unit root test findings show that all indicators such as $CBCO_2$, ETAX, ETEC, and energy resources (RENC, NREC) are stationary, which is the first difference from the previously described penal data econometrics problem.

The findings of Westerlund and Edgerton pertaining to panel integration analysis are presented in Table 7. The H_0 of the test indicates no cointegration between the core and explanatory parameters, as well as other panel data econometric constraints such as CRSD, structural break, serial correlation, and SLPH. The study results reject the null hypothesis H_0, which confirmed the long-term correlation between $CBCO_2$, ETAX, ETEC and energy resources (RENC and NREC). The null hypothesis shows no long-run cointegration among the indicators, and the alternative suggests otherwise. The results for both regimes shift and level shift reject the null hypothesis H_0 at varied order of significance, i.e., 1 %, 5 % and 10 %, respectively, which also implies that the range between parameters is stable.

Moreover, the study's findings unveil the presence of various structural breaks, indicating both level and regime shifts. Similarly, the Banerjee & Carrion-i-Silvestre cointegration analysis, as illustrated in Table 8, confirms the existence of cointegration among $CBCO_2$, ETAX, ETEC, and energy resources (RENC, NREC) across both panel and individual nations. Notably, countries such as

Table 4
Cross-sectional dependence (CRSD) analysis.

CRSD-analysis		
Indicator	Test-Stat.	(Prob.)
$CBCO_2$	4.0210***	(0.000)
ETAX	7.8701***	(0.000)
ETEC	7.6510***	(0.000)
RENC	13.070***	(0.000)
NREC	10.1300***	(0.000)

Indicates significance by 1 %***, 5 %** and 10 % *, respectively.

Table 5
The slope heterogeneity (SLPH) analysis.

SLPH test		
Stat.	Value	(Prob.)
$\hat{\Delta}$ *Delta tilde*	6.002***	(0.000)
$\widehat{\Delta}_{\text{adjusted}}$	7.174***	(0.000)

Indicates significance by 1 %***, 5 %** and 10 % *, respectively.

Table 6
The panel unit root analysis.

Indicators Level I (0)				First-Difference I(1)		
Pesaran test						
	CIPS	M-CIPS		CIPS	M-CIPS	
$CBCO_2$	−1.002***	−2.181**		–	–	
ETAX	−2.212***	−2.667**		–	–	
ETEC	−3.023***	−3.023**		–	–	
RENC	−2.081***	−2.831**		–	–	
NREC	−1.952***	−2.680**		–	–	
Bai & Carrion-i-Silvestre test						
	Z	*Pm*	P	Z	Pm	P
$CBCO_2$	0.314	0.907	22.113	−5.012***	6.021***	78.169***
ETAX	0.324	0.803	18.024	−4.014***	6.014***	65.015****
ETEC	0.447	0.841	20.668	−4.009***	5.013***	74.038***
RENC	0.439	0.364	19.009	−6.027***	7.047***	71.054***
NREC	0.517	0.413	17.014	−4.028***	5.024***	57.012***

Indicates significance by 1 %***, 5 %** and 10 % * respectively.

Table 7
The Westerlund & Edgerton cointegration analysis.

Test	No break	Mean shift	Regime shift
$Z_{\varnothing}(N)$	−3.013***	−2.917***	−4.084***
(Prob.)	(0.000)	(0.000)	(0.000)
$Z_{\pi}(N)$	−5.614***	−4.819***	−5.019***
(Prob.)	(0.000)	(0.000)	(0.000)

Indicates significance by 1 %***, 5 %** and 10 % * respectively.

Denmark, Finland, Sweden, Switzerland, and Luxembourg exhibit this cointegration phenomenon. Consequently, these cointegration analysis results pave the way for a deeper exploration of the short-term and long-term relationship impacts between ETAX, ETEC, and energy resources (RENC, NREC) on CBCO2.

After confirming the correlation between the aforementioned methods, our research employed the CS-ARDL benchmark estimation approach on panel data from five sustainable countries. This allowed us to establish both the dynamic long-run and short-run relationships between the dependent and explanatory variables. To ensure robust estimation, we also utilized AMG-CCEMG techniques.

Table 9 presents the outcomes of the CS-ARDL analysis, focusing on the long-term relationships among various indicators. The findings indicate that ETAX, ETEC, and RENC exert a positive influence on environmental sustainability across the panel. Conversely, NREC exhibits a detrimental effect, leading to a decline in environmental quality within the region. Turning our attention to the correlation between $CBCO_2$ and ETAX, the results uncover a noteworthy negative and statistically significant relationship: $CBCO_2$ is inversely and significantly linked to ETAX. Specifically, a 1 % increase in ETAX results in a substantial long-term reduction of $CBCO_2$ by a magnitude of −2.304. Similarly, in the short term, ETAX exhibits an adverse impact on $CBCO_2$, with a coefficient value of −2.068, signifying significance at the 1 % level. ETAX emerges as a pivotal factor in curbing $CBCO_2$ emissions both in the long and short run across the panel. These estimations underscore the substantial potential of implementing ETAX regulations in effectively mitigating $CBCO_2$ emissions within the sampled region.

Our empirical findings, in particular, indicate that measures associated with ETAX have a negative coefficients value in the long-run (−2.304) and in the short-run (−2.068) on $CBCO_2$, aligning with the observations made by Ullah et al. [22]. Accordingly, ETEC also negatively and substantially influences $CBCO_2$, with coefficients of −0.185 in the long run and −0.096 in the short run. The results revealed a strong inverse correlation between positive shocks to ETEC and $CBCO_2$. This suggests that propitious economic conditions, coupled with environmentally driven tax policies, play a crucial role in encouraging green innovation and reducing dependence on non-renewable energy resources. Correspondingly, industrial enterprises should transition from pollutant-emitting technologies to

Table 8
The Banerjee & Carrion-i-Silvestre cointegration analysis.

Countries	No deterministic specification	With constant	With trend
Full Sample	−3.548***	−3.235***	−4.897***
Denmark	−4.112***	−3.102***	−5.218***
Finland	−3.718***	−3.012***	−4.209***
Sweden	−4.219***	−3.049***	−4.147***
Switzerland	−4.014***	−4.117***	−3.005***
Luxembourg	−5.009***	−4.142***	−5.008***

Indicates significance by 1 %***, 5 %** and 10 % *, respectively.

Table 9
CS-ARDL analysis.

Long -run				Short-run		
Indicators	Coefficients	t-Stat.	(Prob.)	Coefficients	t-Stat.	(Prob.)
ETAX	−2.304**	−2.031	(0.042)	−2.068*	−1.940	(0.052)
ETEC	−0.185***	−5.311	(0.000)	−0.096**	−2.250	(0.021)
RENC	−0.812***	−3.570	(0.000)	−1.095***	−3.830	(0.000)
NREC	0.415**	2.470	(0.037)	0.756*	1.700	(0.048)
CSD-Stat.	–	−0.91	(0.362)			
ECT (−1)				−0.5310***	−7.864	(0.000)

Indicates significance by 1 %***, 5 %** and 10 % *, respectively.

sustainable and environmentally friendly machinery and equipment. These outcomes align harmoniously with previous research [23,68,45].

The CS-ARDL estimates consistently reveal a negative and statistically significant relationship between RENC-CBCO$_2$ in sustainable nations, both in the long-run and short-run. The negative sign indicates that a 1 % increase in RENC leads to a long-term reduction of 0.812 % and a short-term reduction of 1.095 % in CBCO$_2$. This suggests that RENC stands as an effective strategy for mitigating CBCO$_2$. The unfavorable relationship underscores RENC as a sustainable, cost-effective energy source with zero carbon emissions, thereby contributing to the mitigation of cumulative environmental risks [1,5].

Conversely, a robust and statistically significant correlation is evident between NREC and CBCO$_2$ in both the short and long term. Specifically, a 1 % escalation in NREC yields a corresponding increase of 0.415 % and 0.756 % in CBCO$_2$ emissions over the long and short durations, respectively. This noteworthy positive association underscores the challenges faced by these nations as they endeavor to promote rapid industrialization while simultaneously safeguarding their environmental quality [18,56].

Furthermore, Table 10 presents the results of the robustness analysis of AMG-CCEMG, thereby affirming the robustness of our benchmark findings. The results reveal a significant negative relationship between ETAX and CBCO$_2$, as indicated by coefficient values (AMG: 0.986 and CCEMG: 3.265). Similarly, ETEC and RENC exhibit an adverse impact on CBCO$_2$, supported by coefficient values (AMG: 0.121, −0.227 and CCEMG: 0.153, −0.075), further reinforcing the robustness of the analysis. In contrast, NREC's influence on CBCO$_2$ displays a positive trend, with coefficient values of (AMG: 0.136 and CCEMG: 0.191). Consequently, the findings of the CS-ARDL model are substantiated by the outcomes of both AMG and CCEMG analyses. For a graphical representation of these results, please refer to Fig. 6.

The summarized empirical findings in this paper suggest that the panel sample countries enhance the effectiveness of their environmental taxes (ETAX), environmental technology (ETEC), and sustainable energy sources. In pursuing a long-term environmental sustainability agenda, these nations should focus on promoting the adoption of renewable energy sources through the development of green technologies and the implementation of environmental taxation. To align with the Sustainable Development Goals (SDGs), investments in renewable energy (SDG 7) and the advancement of green innovation (SDG 9) should be actively encouraged as pivotal strategies for achieving environmental sustainability (SDG 13) in the region.

Table 10
AMG-CCEMG analysis.

	AMG			CCEMG		
Indicators	Coefficients	t-statistics	P-values	Coefficients	t-statistics	P-values
ETAX	−0.986**	−2.550	0.032	−3.2653***	−3.290	0.001
ETEC	−0.121*	−1.910	0.047	−0.153*	−1.880	0.040
RENC	−0.227**	−2.850	0.004	−0.075**	−2.314	0.003
NREC	0.136*	1.750	0.031	0.191*	1.730	0.041

Indicates significance by 1 %***, 5 %** and 10 % *, respectively.

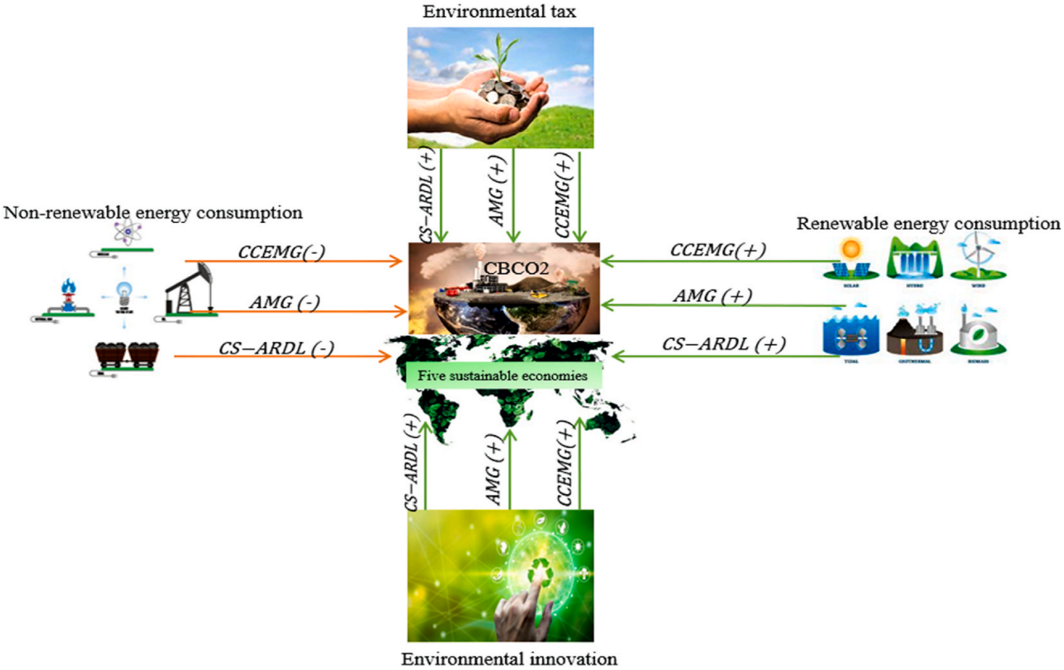

Fig. 6. Graphical interpretation of CS-ARDL, AMG-CCEMG analysis.

5. Conclusion

This study examined the relationship between environmental taxation, environmental technologies, energy resources, and consumption-based carbon emissions in five leading green economies from 2000 to 2019. The study applied the Cross-Sectional Auto-Regressive Distributed Lag (CS-ARDL) model to derive benchmark results, with Augmented Mean Group (AMG) and Common Correlated Effect Mean Group (CCEMG) techniques being utilized for conducting robustness analyses. The findings demonstrate a significant and adverse impact of environmental taxes, environmental technology, and renewable energy resources on consumption-based carbon emissions, thus enhancing environmental sustainability in the panel region. Conversely, the study indicates that non-renewable energy consumption has a detrimental effect on environmental sustainability in the region, as validated by the rigorous methodologies of CS-ARDL, AMG, and CCEMG. Based on the study's findings, we propose the following policy recommendations for policymakers and government officials.

- Environmental taxes, environmental technologies, and renewable energy can serve as effective policy tools to mitigate harmful environmental externalities. Consequently, countries should be encouraged to allocate environmentally taxable income towards projects to reduce the negative impacts of taxed sources, such as fossil fuels.
- Tax concessions should be provided to promote adopting renewable energy and environmentally friendly innovations. Industries that employ environmentally detrimental technologies should be discouraged, while the generated funds should be directed towards research and development of green technologies that contribute to reducing greenhouse gas emissions and improving overall environmental well-being.
- The income generated from environmental taxes can support sustainability efforts through various measures, including the transition to clean energy and promoting eco-innovation. Such initiatives will assist governments in achieving the objectives outlined in SDGs 7, 9, and 13.

Nevertheless, this study acknowledges certain limitations and underscores avenues for prospective research. It first suggests broadening the scope of investigation to encompass a more extensive sample, such as the European Union, G-20 economies, E−7, G-7, and OECD nations. Such a broader perspective would furnish a more comprehensive comprehension of the ramifications of environmental policies, such as environmental technologies and taxes, on domestic environmental attributes at the national level. Additionally, the research underscores the necessity of considering diverse dimensions of environmental quality beyond consumption-based CO_2 emissions. Employing various environmental indicators, including transportation-based CO_2 emissions, ecological footprint, load capacity factor, CO_2 emissions from heat and electricity production (CO_{2HE}), and liquid fuel emissions (CO_{2FL}), would enrich future investigations in this domain.

CRediT authorship contribution statement

Kishwar Ali: Conceptualization, Investigation, Methodology, Writing – original draft. **Du Jianguo:** Data curation, Supervision, Validation, Writing – review & editing, Funding acquisition. **Dervis Kirikkaleli:** Formal analysis, Project administration, Software, Supervision, Writing – original draft. **Judit Oláh:** Investigation, Methodology, Writing – original draft, Writing – review & editing, Funding acquisition. **Satar Bakhsh:** Formal analysis, Investigation, Resources, Writing – review & editing, Writing – original draft.

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.

Acknowledgements

Project no. TKP2021-NKTA-32 has been implemented with support from the National Research, Development and Innovation Fund of Hungary, financed under the TKP2021- NKTA funding scheme. Project no. 132805 has been implemented with support from the National Research, Development and Innovation Fund of Hungary, financed under the K_19 funding project.

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