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Role of economic complexity and energy sector in moving towards sustainability in the exporting economies

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ABSTRACT

The largest contributor to environmental deterioration, the carbon footprint, arises from excessive fossil fuel consumption. Meanwhile, international experts note that despite the positive dynamics in the issue of making commitments to carbon-zero targets, most companies around the globe do not have a clear plan or strategy to achieve environment-based targets. This study addresses sustainable development goals (SDGs) concerning clean energy usage, sustainability, and the environment. Hence, this study investigates the impacts of the economic complexity index (ECI), energy productivity (EPD), renewable energy electricity generation (REEG), and environment-based patents on ecological footprints (ECFP) to attain a carbon-zero environment and SDGs for forty-five exporting countries from 1990 to 2020. An extensive exploration into the connection amongst the explored variables shows that the rises in ECI, EPD, and REEG help subside ECFP in the short-term and long-term estimations. Besides, the results show a bidirectional and unidirectional causality from ECFP to REEG and EPD, respectively. The key practical policies of this work are building modernized tax systems with progressive tax policies, better tax collection, private SDGs financing with incentives regulations, promising project planning on green technologies, and accessibility of grants from global organizations and private sectors to invest in SDGs and a carbon-zero environment target.

1. Introduction

The world's imbalanced environmental situations, such as global heating, have turned researchers' and policymakers' attention more toward balancing a low-carbon and sustainable environment. Climate change and environmental deterioration are the main obstacles to sustainable economic development [1]. The widely accepted central idea of environmental protection measures at the national and global levels is sustainable development (SD). Understanding the SD concept's goals and objectives is essential for a deeper understanding. SD is assuring economic growth without forsaking the idea of sensibly utilizing environmental values and natural resources while also taking into account the rights and advantages of both the present and future generations [2]. The easiest way to connect sustainable development with future generations is through the environmental factor. Because human actions harm the environment's capacity to regenerate, they endanger the well-being of upcoming generations and their right to life. Also, the goal of sustainable development from the viewpoint of the environment is to make it possible for ecosystems to change with the environment [3]. Therefore, an ecologically sustainable system should maintain a stable resource base, refrain from exploiting environmental investment functions or renewable resource systems, and only use resources that non-renewable resource investments have sufficiently replenished. The conservation of biodiversity, atmospheric equilibrium, and other ecosystem components that cannot be categorized as commercial resources is also a part of this system [4,5].

The ecological footprint (ECFP) approach covers climate change in depth, containing more of the factors that harmfully affect the

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environment. It demonstrates how carbon dioxide emissions (CDE) stack up against other human planetary demands, such as food, clothing, wood, and land for roads and homes [6]. ECFP also broadly defines the environment that encompasses the natural, physical, economic, social, and cultural environments. Besides, it includes the concepts of carrying capacity, flexibility, and sustainability, as it proposes to impose limitations on human actions by accepting the dynamic structure and nature of the ecosystem [7]. Moreover, several scholars have found that ecological footprint plays a significant role in deteriorating the environment and causing climate change [8,9]. The factors included in the ECFP are categorized into six components: fishing grounds, cropland, grazing land, forest products, carbon footprint, and built-up land. Among these components, the carbon footprint is the fastest-growing factor, more than the sum of the effects of all other components. As shown in Fig. 1, carbon footprint records more than 60% of the global ECFP.[1]

Several countries (from developing and developed economies) began to utilize their skills and knowledge in the manufacturing of exporting products, called economic complexity (EC), and embraced a complex transformation in different sectors [10]. EC is an evaluation of expertise and innovative skills in a specific nation as delivered in the products it creates. EC of a country is computed according to the pervasiveness and variety of goods a country transports to other countries or explore how many other countries are capable enough to provide products (and the complexity of each country) [11]. Moreover, the economic complexity index (ECI) is a more precise forecaster of economic and sustainable advancement than conventional governance assessments, i.e., "GDP per capita" [12]. Countries enhance their index by growing the complexity and quantity of their exporting products. The swift and upsurge change of modern technologies plays a significant role in developing the economy and increasing the consumption of energy and different human activities that cause environmental deterioration [13].

Further, researchers are giving more attention to indicators for explaining energy, such as productivity, intensity, and efficiency, to deal with three fundamental and interconnected problems (i.e., economic development, environmental sustainability, and energy security) encountering policy-makers [14]. Although energy intensity (EINT) is mainly used more often than the other two, there are critical grounds to consider that energy productivity (EPD) brings a suitable way forward [15]. Hence, this paper considers analyzing EPD by investigating its impact and relation to ECFP. EPD is measured in dollars of GDP per unit of energy, which is more reluctantly perceived given the prevalent set of criteria for financial benefits [16]. However, it is also a crucial factor impacting ecological quality by boosting energy productivity and minimizing prices. As a result, it has been emphasized for attaining sustainable development and enhancing ecological integrity in numerous ways [17]. First, improving energy production lowers the quantity of energy utilized in the production process and decreases energy expenses, leading to more remarkable economic outcomes. Second, it reduces fossil fuel energy imports, resulting in a decrease in ecological footprint [15].

Consequently, it can be claimed that countries' major and primary dependence is on the significant consumption of non-renewable energy for generating electricity [18]. Fig. 2 depicts that fuel is the most widely consumed source for generating electricity. Fuel is the combination of natural gas, coal, and oil. Furthermore, the percentage of renewable energy sources (RESs) consumption for power generation seems promising as it shows an increment over the year [18]. RES is an integration of solar PV, wind, geothermal, hydro, and tide, and electrical energy is produced from these sources [18]. It is an accepted fact that the resources of the planet humans live on have a limit, but humans do not hesitate to spend the planet's resources as if they are endless. As a natural consequence, the world faces the effects of global warming [19].

To address the escalating environmental and economic issues, the United Nations announced the "Sustainable Development Goals (SDGs)" in 2015 [20]. As discussed in Ref. [21], governments, social organizations, and particular institutions must work together to achieve the SDGs, making it possible through scientific and technological advancements. In addition, Emin and Waseem [21] comprehensively investigated the incentives, obstacles, and possible long-term capacities that occur while attaining SDGs. Nevertheless, there has not been sufficient research exploring how energy productivity and electricity production from renewable sources might help countries reach the carbon-zero environment and SD goals. Thus, as a major goal, the current study attempts to address some of the SDGs concerned about clean energy usage, sustainability, and the environment by taking into account energy productivity, renewable electricity generation, and technologies that are friendly to the environment in connection with the economic complexity index and ecological footprints. This work takes a panel of 45 nations from 1990 to 2020 to carry out the empirical analysis on the above-mentioned significant variables. Moreover, the main motivations for conducting this study are * inadequate resources that examine how energy productivity connects with environmental quality and how it aids in curbing environmental degradation, * the difficulties associated with the insignificant role that renewable energy sources play in generating electricity, * the lack of sufficient studies that take into

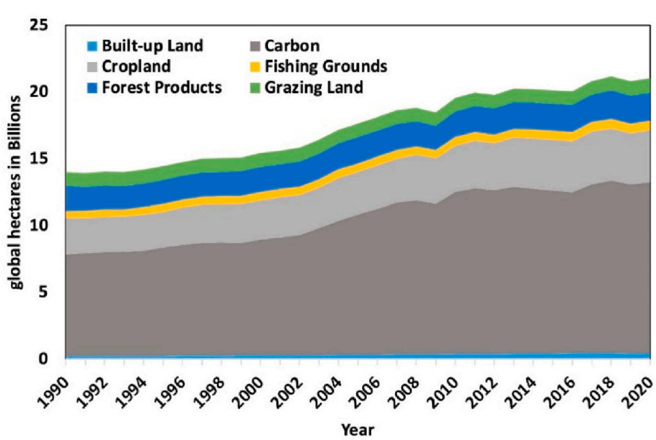

Fig. 1. World ecological footprint by land type. Source: Authors' tabulation from the global footprint network.

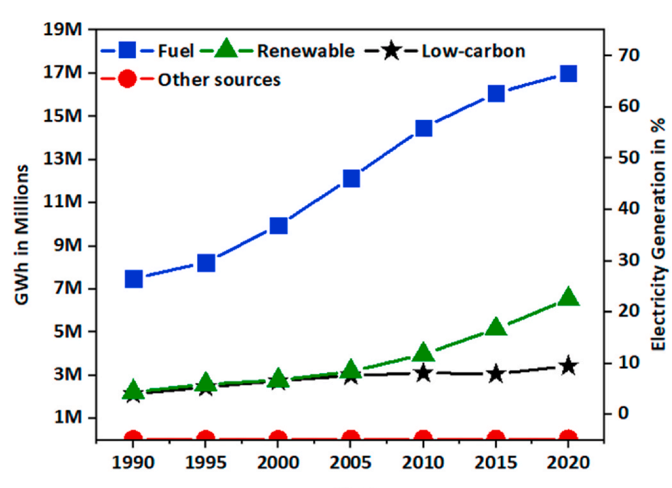

Fig. 2. World electricity generation by source in Gigawatt hours (GWh). The low-carbon sources include biofuels, waste, and nuclear [18]. Source: Authors' tabulation.

[1] https://www.footprintnetwork.org/our-work/countries/.

consideration SDGs that are specifically concerned about clean energy, and * the requirement to advance environment-friendly renewable energy technologies to alleviate environmental deterioration and achieve the carbon-zero and SD goals.

Besides, the findings of this study are anticipated to give nations further assistance in achieving the SDGs, including SDG-7, SDG-9, SDG-11, SDG-12, SDG-13, and SDG-15 (see Annex B, Fig. 5). SDG 7 aims to give everyone access to affordable, sustainable, efficient, and modern energy [22]. SDG-9 [23], which calls for sustainable manufacturing based on technological innovation, is essential to advancing cutting-edge, effective, and environmentally friendly technology because most of the ecological footprints are produced by burning fossil fuels for economic development. Sophisticated technology created by innovation can lower carbon footprint due to energy efficiency and the energy transition, which is a crucial component of boosting productivity and economic success [24]. SDG-11 aims to increase urban environments' diversity, safety, resiliency, and sustainability [25]. With a target of easing the natural resource burden and lowering waste discharges into the environment, whether it be sea, ocean, wind, or land, SDG-12 stresses diligent production and consumption methods [26]. Promoting sustainable lifestyles and corporate practices is a crucial element of this goal. SDG-13 emphasizes that greenhouse gases must be eliminated by 2050 to keep global temperatures below 1.5 °C [27]. SDG-15 focuses on protecting, restoring, and promoting sustainable use of terrestrial ecosystems, managing forestry responsibly, preventing erosion, and halting habitat loss [28].

This empirical research contributes to the energy-environment literature for several reasons. First, it covers a thirty-one-years panel data of forty-five countries lower to higher exporting nations. These exporting countries demand a huge amount of energy for manufacturing, increasing the consumption of the ecological footprint. Second, there is limited literature concerning the integrated contribution of economic complexity, energy productivity, renewable energy electricity generation, and environment-related patents on ecological footprints in achieving SDGs and a carbon-zero environment. Third, considering sustainable development objectives, this work will have significant policy inferences for decision-makers. In essence, the primary objective of the present research is to explore the connection between the economic complexity index, energy productivity, renewable energy generation, and ecological footprint; as a result, it will assist in establishing a carbon-zero environment and sustainable development by way of economic development strategies and a policy paradigm. Fourth, it adopts sophisticated and state-of-the-art panel data mechanisms for performing the intended estimations called the "cross-sectionally augmented autoregressive distributed lag (CS-ARDL)" model. Finally, it provides detailed empirical analysis and policy implications concerning the function of the explored variables that can be used as a guideline by advanced and emergent nations.

The remaining part of this study includes a literature review in Section 2. Section 3 presents the theoretical background, data, and model specifications. Section 4 discusses the flow of preliminary analysis and long-run estimations techniques. Subsequently, Section 5 contains the findings and discussions, while Section 6 concludes the study and offers policy suggestions.

2. Literature review

2.1. Sustainable development and environment

Countries were obstinate in their tendency to maintain their economic development in ways that endangered the ecological environment because they were unaware of the risk they were placing future generations [29]. Manufacturing goods and services has started to be regarded as a proxy for economic growth as industrialization has progressed. Nevertheless, as the world's population and demands grow, globalization has begun to rely more on the planet's natural resources. This circumstance highlights the importance of economic growth for natural resources and their relationship to the environment [30]. Discussions about the sustainability of development thus got underway. Since the United Nations Environment Conference in Stockholm in 1972 and until now, countries have attempted various strategies to lessen environmental pollution and preserve economic growth in an organized way by minimizing the destruction of socio-economic resources [31,32].

Sustainable Development is "development that meets the needs of the present without compromising the ability of future generations to meet their needs" [33]. The three components of sustainable development—economic, social, and environmental—should be considered within this definition's context. According to the Sustainable Development method, a nation's social and economic strategies must be integrated with its environmental plans and policies. Several studies have explored numerous macroeconomic variables in line with distinct SDGs [27,34–38]. Peng et al. [27] revealed the non-linear relationship between economic complexity, technology, size of the population, and economic growth on CO_2 in the BRICS nations, and the analysis was useful in formulating environmental policy, especially regarding SDGs-13 and 9. After researching how fossil fuels affect the environment, Shah et al. [39] recommended switching the foreign direct investment initiatives over to modern energy sources to reduce environmental damage potentially. Therefore, to achieve the SDG-7 goals established by Agenda 2030, Shah et al. underlined the imperativeness of lessening the reliance on fossil fuels and investing in renewable energy technologies. Beton Kalmaz and Awosusi [40] evaluated the connection between ecological footprint and its potential drivers, including economic expansion, renewable energy consumption, oil consumption, and capital expenditure, over the years 1965–2017 in Malaysia. Their findings decisively demonstrated that to promote clean energy, i.e., SDG-7, and climate change, i.e., SDG-13, the Malaysian government and business sector must diversify their investment portfolio.

2.2. Economic complexity index and environment

Sun et al. [41] examined the relationship between economic complexity and CO_2 emissions and suggested that increases in economic complexity improve environmental quality. Swart and Brinkmann [42] looked at how economically complicated counties, provinces, and major cities in Brazil impacted the environmental quality and unveiled that decreasing environmental deterioration is correlated with increased economic complexity. Increased economic complexity leads to more opportunities, a denser manufacturing environment, and higher pollutants. However, when economic complexity is high enough, structural reforms result in knowledge-intensive sectors, which call for a more highly trained workforce and a larger range of jobs. In examining the relationship between economic complexity and CDE in five nations, Balsalobre-Lorente et al. [43] found that economic complexity is linked to lessening environmental deterioration. They also discovered a causal connection amongst economic complexity and CDE that runs in both directions. Likewise, Caglar et al. [44] revealed similar findings for BRICS nations.

Doğan et al. [45] investigated the effects of economic complexity and other variables on energy consumption and carbon emissions for panels of the G7 and E7 countries from 1991 to 2017. The augmentation of economic complexity coincides with the advancement of industrial operations and the formation of major productions that induce more emissions during the initial stages of development. Nevertheless, as economic complexity evolves further, environmental quality suffers significantly. For a panel of 48 complex economies from 1995 to 2014, Neagu [46] investigated the relationship between the ecological footprint and economic complexity. Based on the "fully modified ordinary square (FMOLS) and dynamic ordinary least square (DOLS)" models, Neagu [46] found a confirmed long-run positive correlation among the ECFP of production and the ECI, inferring that ECI raises the level of

ECFP. On the other hand, according to econometric estimates using the CCR, DOLS, and FMOLS methods, Laverde-Rojas et al. [47] concluded that economic complexity has no beneficial impact on Colombia's climate welfare.

2.3. Energy productivity and environment

Cheng et al. [48] analyzed the contribution of energy productivity and technological innovation in making the environment sustainable in China by taking quantile data from 1991Q1 to 2017Q4. Their empirical findings revealed that an effective energy productivity implementation and innovation could improve the environment to be eco-friendly and mitigate harmful air emissions. Li et al. [49] discussed how increased energy productivity reduces CO_2 emissions and GHG, which is associated with increased use of renewable sources of energy. It was confirmed by LaBelle and Szép [50] that the developing economies in Europe are falling short of the 2020 energy efficiency goals, implying that their energy productivity is low. Majeed et al. [51] examined the factors of renewable energy in BRICS countries from 1990 to 2018 and discovered that an increase in energy productivity improves renewable energy consumption, which leads to a more sustainable environment. Amin et al. [52] utilized updated data from 1995 to 2019 to examine the effect of energy productivity on "trade-adjusted consumption-based carbon emissions" for eleven nations and discovered that energy productivity reduces carbon emissions.

Lin and Sai [53] used country-level data on twenty-one nations from 2009 to 2017 to investigate the effect of mining agglomeration on EPD in Africa. The authors discovered that industrial agglomeration has a favorable effect on increasing EPD and economic expansion makes it possible to increase EPD, whereas energy intensity impedes this development. Zhao et al. [54] examined the effects of structural change on EPD inequality in OECD nations between 1990 and 2019. This study discovered that structural transformation tends to diminish disparity in EPD using second-generation approaches and dynamic elasticity analysis. Furthermore, technological innovation has been shown to reduce EPD inequality. On the other hand, economic conflicts have been shown to impact inequality in EPD within OECD nations negatively.

2.4. Renewable energy electricity generation and the environment

By applying augmented mean group and dynamic ordinary least square [55], studied the function of renewable energy electricity and economic complexity in improving ecological quality for sixteen countries with a high economic complexity index from 1990 to 2019. According to their findings, the increment of economic complexity and the use of renewable energy decline emissions and help fulfill the carbon-zero environmental strategy. Based on data from 2000 to 2017, Sun et al. [41] scrutinized the connection between energy intensity and carbon intensity in China. The findings showed that various regions have short-term and long-term relationships. In another study, Balsalobre-Lorente et al. [56] examined how CDE changed in the EU-5 nations between 1985 and 2016 based on the output of renewable electricity sources. According to the results, employing renewable energy sources for local production has a favorable impact on CO_2 emissions and should be given more consideration in improving the quality of the environment.

Xiaosan et al. [57] investigated the link between total renewable electricity output and CDE in China using "autoregressive distributed lag" and discovered that renewable electricity generation reduced emissions in China from 1990 to 2018. Li et al. [58] investigated the influence of the ECI and renewable energy electricity on "consumption-based carbon emissions" in the leading exporting nations from 1990 to 2019 and discovered that increasing renewable energy electricity helps reduce carbon emissions. Ghasemi-mobtaker et al. [59] discussed that the proportion of RE sources like solar energy in input energy should be raised to lessen the adverse environmental effects of hydroponic forage production.

As per the above-reviewed literature, there is a gap in investigating the association between ECI, EPD, REEG, and ECFP in a sample of complex economies. This paper attempts to fill this gap in the literature by emphasizing nations with different ranks of economic complexity index. Most importantly, existing literature lack taking into consideration SDGs that are specifically concerned about clean energy.

3. Theoretical framework, data, and model specification

3.1. Theoretical framework

This section explains the analytical process in which the economic complexity index, energy productivity, the production of renewable energy electricity, and ecological patents affect the carbon-zero aim.

The ECI, which indicates the degree of expertise and proficiency necessary in manufacturing products for trade abroad, determines the economic progress of a country [9]. Transitioning to higher productivity from a low-productivity agriculture-based economy by the industries results in a shift from moderate to advanced economic complexity, which results in more complex goods [55]. Complexity in the economy describes production arrangement, which corresponds to energy use and environmental influences. Besides, a country's production structure may stimulate ecological footprints, and product complexity may cause environmental pollution [60,61]. Theoretically, economic complexity is linked to structural shifts that raise energy demand, which increases ECFP and environmental deterioration [62]. Nevertheless, in some cases, ECI helps create an eco-friendly environment due to its association with the change in the economy's structure, mirroring the degree of abilities, knowledge, and high-tech innovations entrenched in production [63]. Hence, based on the theory, ECI is predicted to have either a negative or positive impact on the ecological footprint.

Energy productivity is perceived to be a more credible criterion for evaluating a nation's level of energy efficiency [64]. EPD also shows how the nation compares to others on the basis of economic and environmental concerns. Thus, energy productivity determines the quantity of energy used to produce one unit of production [65]. In addition, energy productivity lowers the ecological footprint by decreasing the amount of energy used for manufacturing per unit of production and bringing down energy expenses [66].

Similarly, clean energy electricity reduces pollution by utilizing renewable energy sources to broaden power generation, cut prices, and produce a more sustainable electricity supply [58]. Furthermore, renewable energy sources are thought to be carbon-free and a significant response to addressing environmental problems [67]. Furthermore, utilizing electricity generated from renewable sources can increase production efficiency, stimulate economic development, and reduce negative environmental pollution [68]. Thus, renewable energy electricity generation is supposed to contribute to the carbon-zero goal.

Technological advancement might be viewed as the trigger needed to alter the economic and industrial infrastructure and guarantee that renewable energy is used more effectively in emerging nations. Additionally, eco-innovations in the energy sector are acknowledged as a facilitator for the changeover from using dirty to cleaner sources of energy, which enables a significant reduction in emissions connected to energy usage [69]. Also, optimizing resources and implementing environmentally friendly cost-cutting strategies are examples of environmental patents [70]. In accordance with this concept, eco-innovation through the clean energy transformation pathway can aid in minimizing the increment of developing economies' detrimental environmental consequences, like ecological footprints. Based on these factors, in this paper, it is anticipated that environmental innovation will negatively impact the ecological footprint in the selected nations.

The current research has mostly examined the effects of income growth on the environment using different models since environmental quality varies throughout different phases of economic advancement.

These studies have primarily focused on evaluating the connection between the environment and economic growth in light of the "environmental Kuznets curve" paradigm created by Ref. [71]. This theory holds that industrialization occurs during the early stages of economic expansion, increasing the need for energy, particularly fossil fuels in the case of emerging countries, which has an adverse impact on the environment. Nevertheless, once the economy achieves a certain turning point of economic progress, the technique effect kicks in and eliminates the trade-off between economic growth and environmental deterioration via the viewpoint of technical advancement [55].

3.2. Data

This paper utilizes yearly panel data from 1990 to 2020 for forty-five countries. Annex A presents the list of countries chosen for this study, which are selected based on data availability. Accordingly, the dependent variable is ecological footprint (ECFP) (i.e., a proxy for environmental degradation), and the explanatory variables are economic complexity index (ECI), energy productivity (EPD), renewable energy electricity generation (REEG), total patent (summation of resident and non-resident patents) (PTNT), and real gross domestic product (RGDP). Table 1 presents the variables, measuring units, and corresponding data sources. Fig. 3 depicts a conceptual framework showing the expected signs to be seen while analyzing the associations between the dependent and independent variables.

3.3. Model specification

This study primarily considers variables whose values are ascertained outside the model and driven factors for the carbon-zero goal: ECI, EPD, REEG, and PTNT. REEG is the power produced through various sources of renewable energy, including geothermal, hydro, solar photovoltaic, tide, wave, ocean, and wind. The motivation for considering REEG is that electrical power is consumed for housing and marketing throughout the world. As a result, recent studies show that several countries have considered renewable energy the primary power generation source [72]. Similarly, several economic research works urge the prominence of income of a particular country. So, this paper considers real GDP as a control variable to analyze the association of ECFP with economic advancement. The current study designs the following empirical model according to Refs. [55,73]:

$$lnECFP = f(ECI, lnEPD, lnREEG, lnPTNT, lnRGDP) \tag{1}$$

Eq. (1) can be converted into an empirical regression model as follows:

$$lnECFP_{it} = \gamma_0 + \gamma_1 ECI_{it} + \gamma_2\, lnEPD_{it} + \gamma_3 lnREEG_{it} + \gamma_4 lnPTNT_{it} + \gamma_5 lnRGDP_{it} + \varepsilon_{it} \tag{2}$$

where ***lnECFP***, ***lnEPD***, and ***lnREEG*** represent the logarithm of the ecological footprint, renewable energy electricity generation, and energy productivity, respectively. ***lnPTNT*** denotes the total patent of residential and non-residential patents. ***lnRGDP*** indicates the real gross domestic product. In Eq. (2) γ_0 - γ_5 denote the parameters of the independent variables. Furthermore, 'i' depicts the CS units, i.e., countries studied in this work, and 't' depicts the time interval of the panel data. All variables except ECI were put in natural logarithmic forms by denoting the variables with the prefix 'ln' to restrain the influences of outlier data points in the panel data.

Table 1
Variables, measuring units, and data sources.

Notation	Variable	Unit	Source
ECFP	Ecological footprint	Global hectares	[101]
ECI	Economic complexity index	Index	[102]
EPD	Energy Productivity	Percentage	[103]
REEG	Renewable electricity, % total electricity generation	Percentage	[103]
PTNT	Total resident and non-resident patents	count	[104]
RGDP	Real GDP	Current US$	[103]

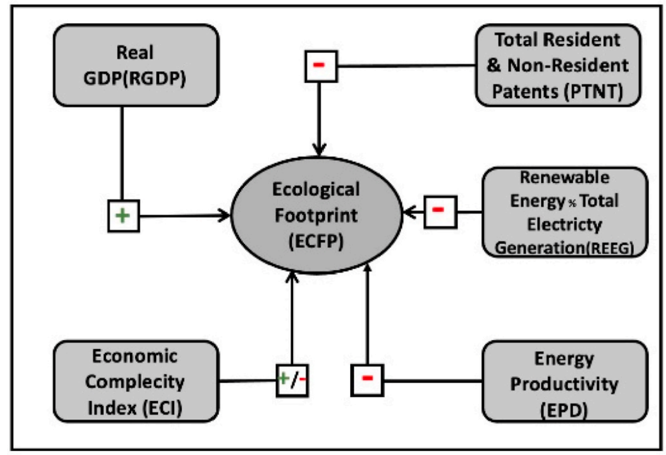

Fig. 3. Sign prediction of each independent variable against the dependent variable. Source: Authors' own tabulation.

4. Methodology

4.1. Cross-section dependence (CS-D) and slope homogeneity (SH) tests

CS-D test is computed before experimenting with the co-integration and stationarity of the panel data to avoid erroneous, inconsistent, and inaccurate results in co-integration and stationarity tests [74,75]. This study employs Pesaran's [74] CS-D test, which can be applied when "T > N" or "N > T", and it is formulated as:

$$CSD = \sqrt{\frac{2T}{N(N-1)}}\left(\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\widehat{\rho}_{ij}\right) \Longrightarrow N(0,1) \tag{3}$$

where $T = 1, 2, \ldots, N$ and $\widehat{\rho}_{ij}$ depicts pair-wise correlation coefficients. The existence of CS-D is determined based on the following hypotheses. H0: There is no CS-D, and H1: There is a CS-D. When the p-value of the test is < 0.05, the H0 hypothesis is rejected at the 5% significance level, and it is decided that CS-D is among the units that make up the panel data.

This work empirically analyzes the SH test once the CS-D test is performed. The SH test is designed by Hashem Pesaran and Yamagata [76] to examine the homogeneity of the co-integration coefficients or if the coefficients of the explanatory variables vary from one unit (country) to another. Unlike the conventional homogeneity assessing methods, SH is preferable for panel data as it considers CS-D [77]. SH test is mathematically expressed as [76]:

$$\widetilde{\Delta}_{SH} = (N)^{\frac{1}{2}}(2K)^{\frac{1}{2}}\left(\frac{1}{N}\widetilde{S} - k\right) \tag{4}$$

$$\widetilde{\Delta}_{ASH} = (N)^{\frac{1}{2}}\left(\frac{2k(T-k-1)}{T+1}\right)^{-\frac{1}{2}}\left(\frac{1}{N}\widetilde{S} - k\right) \tag{5}$$

$\widetilde{\Delta}_{SH}$ denotes the delta tilde and $\widetilde{\Delta}_{ASH}$ denotes the adjusted delta tilde.

4.2. Second-generation panel stationarity test

The fundamental issue experienced in panel stationarity evaluation is determining if the horizontal sections that make up the panel data are not dependent on each other. This work employs second-generation stationarity test techniques "Cross-Sectionally Augmented Dickey-Fuller (CADF)" and "Cross-Sectionally Augmented IPS (CIPS)" developed by Pesaran [78]. CADF is the modified version of Im et al. [79] and takes the CS-D and structural breaks in the series into account while analyzing data. In addition, CADF carries out a stationarity test on each cross-section unit (for each country) in the series that make up the panel separately or for the panel as a whole. The CADF test, which assumes that each country is influenced individually by time-effect and takes into account dimensional autocorrelation, can be applied in both "T > N″ and "N > T″ cases.

In addition, by taking the average stationarity test statistics of each cross-section (country), the t-statistics for a panel as a whole can be obtained using CIPS. The main feature of CIPS is the assumption that there is a correlation between the series belonging to the units. Moreover, Pesaran [78] created the models to avoid possible CS-D and inter-serial correlation errors while testing the presence of stationary processes in dynamic panel data. CIPS analyzes the existence of a unit root process by taking the first-order differences of the individual series and expanding the lag numbers with the CADF. The CIPS statistic can be expressed as follows [78]:

$$CIPS = \frac{1}{N}\sum_{i=1}^{N} CADF_i \quad (6)$$

The combined asymptotic limit of the CIPS statistic is not standardized, and critical values are calculated for the various *N* values.

4.3. Cross-sectional Co-integration test

This paper applies the panel co-integration test, proposed by Westerlund [75], to experiment with the relationship between ECFP and the independent variables considered in this work. The Westerlund method assesses the presence of co-integration by ascertaining if there subsists error correction for the panel as a whole or individual panel members. The co-integration test incorporates a substantial degree of heterogeneity in the long-run co-integrating relationship and the short-run dynamics and dependence across and within the CS units. The co-integration test is mathematically written as [75]:

$$\alpha_i(L)\Delta y_{it} = \delta_{1i} + \delta_{2i}t + \alpha_i\left(y_{it-1} - \beta_i' x_{it-1} + \lambda_i(L)' v_{it} + e_{it}\right. \quad (7)$$

where L denotes lag operator, δ_{1i} and δ_{2i} denote deterministic components, β_i' explains a long-run co-integration of x_{it} and y_{it}, and α_i signifies the error correction factor. Henceforth, to find the co-integration state of variables, Westerlund [75] proposed four test statistics based on Eq. (7). These statistics are categorized into panel statistics (PS) and group mean statistics (GMS). PS tests are computed by combined information about the error correction and the cross-sectional aspect of a specific panel, whereas GMS tests do not consider that information. In the case of PS, the rejection of the null hypothesis is interpreted as a confirmation of no co-integration for the whole panel. On the other hand, in GMS, the rejection of the null hypothesis is interpreted as, at the minimum, one of the CS units being co-integrated.

4.4. Cross-sectional augment autoregressive distributed lag (CS-ARDL)

This section discusses the empirical model implemented to determine the short- and long-term effects of ECI, EPD, REEG, environment-oriented patents, and income growth on the ECFP.

With SH and CS-D in the data used for analysis, selecting the most suitable estimation techniques for regressions that rationalize the mentioned issues in the short- and long-run estimation procedures is very important. Conventional estimation mechanisms explored in various studies have mainly dealt with the concern of CS-D but overlooked heterogeneity problems. As a result, this work considers applying the state-of-the-art CS-ARDL model proposed by Chudik et al. [80] to handle the mentioned issues. The model's dynamic structure is designed according to the ARDL dynamic panel specification [81]. The merits of CS-ARDL compared to other methods are i) it performs the short and long-run estimation efficiently; ii) it is robust in that it deals with the problem of endogeneity; iii) it works well for a panel data with the mixture of level and first difference order of integration; iv) it also adjusts errors and biased parameters while carrying out the estimation process. Following Chudik et al. [80], the CS-ARDL form of Eq. (1) is formulated as:

$$lnECFP_{i,t} = \mathscr{C}_i + \sum_{j=1}^{p} \partial_{j} lnECFP_{i,t-j} + \sum_{j=0}^{p} \psi_{j} \mathscr{X}_{i,t-j} + \sum_{j=0}^{3} \varpi_{j} \mathscr{Z}_{t-j} + \varepsilon_{i,t} \quad (8)$$

where $\mathscr{Z}_t = (lnECFP_t, \mathscr{X}_t)$, $\mathscr{X}_{it}$ contains a set of independent variables, i.e., $(ECI_{it}, lnEPD_{it}, lnREEG_{it}, lnPTNT_{it}, lnRGDP_{it})$, and p is the number of lags, which in this work, the lags taken is up to 3. In general, Eq. (8) includes "variables set with the cross-sectional averages of the regression, the dependent variable, and a series of their lag values" [82].

$$\begin{aligned} lnECFP_{it} = {} & \mathscr{C}_i + \sum_{j=1}^{p_y} \partial_{j} lnECFP_{i,t-j} + \sum_{j=0}^{p_x} \psi_{1j} ECI_{i,t-j} + \sum_{j=0}^{p_x} \psi_{2j} lnEPD_{i,t-j} \\ & + \sum_{j=0}^{p_x} \psi_{3j} lnREEG_{i,t-j} + \sum_{j=0}^{p_x} \psi_{4j} lnPTNT_{i,t-j} + \sum_{j=0}^{p_x} \psi_{5j} lnRGDP_{i,t-j} \\ & + \sum_{j=1}^{p} \varpi_{1j} \overline{lnECFP}_{i,t-j} + \sum_{j=0}^{p} \varpi_{2j} \overline{ECI}_{i,t-j} + \sum_{j=0}^{p} \varpi_{3j} \overline{lnEPD}_{i,t-j} \\ & + \sum_{j=0}^{p} \varpi_{4j} \overline{lnREEG}_{i,t-j} + \sum_{j=0}^{p} \varpi_{5j} \overline{lnPTNT}_{i,t-j} \\ & + \sum_{j=0}^{p} \varpi_{6j} \overline{lnRGDP}_{i,t-j} + \varepsilon_{i,t} \end{aligned} \quad (9)$$

where $\mathscr{C}_i$ indicates the impact parameters of undiscovered economies. ∂_{j} used to show how the lagged condition variable affects the data. $\psi_{1j} - \psi_{5j}$ are the parameters of the lag-input CS. $\overline{lnECFP}$, $\overline{ECI}$, $\overline{lnEPD}$, $\overline{lnREEG}$, $\overline{lnPTNT}$, and $\overline{lnRGDP}$ denote the CS modes of $ECFP, ECI, EPD, REEG, PTNT$, and $RGDP$, respectively. $\varpi_{1j} - \varpi_{6j}$ are the mean CS values of the lagged CS. Finally, p indicates the CS average lags and it is crucial to remember that p need not be same with p_y or p_x and can be determined by $p = [\sqrt[3]{T}]$ [83]. Additionally, to verify the CS-ARDL findings' robustness, this work adopts two state-of-the-art methods that consider heterogeneity and CS-D; these are the "augmented mean group (AMG)" and "common correlated effect mean group (CCEMG)" proposed by Eberhardt [84] and Pesaran [85], respectively. CCEMG minimizes a repercussion impact due to the CS-D on account of the average of the explored variables and ignores time-dummies. In contrast, the AMG method adapts time-dummies and unobserved aspects of particular data. Finally, the present study adopts the "Dumitrescu and Hurlin Granger Causality (D-HGC)" test offered by Dumitrescu and Hurlin [86] to explore the causal association between variables.

5. Results and discussion

Table 2 illustrates the CS-D test result that reveals the presence of dependency across the CS units by significantly failing to reject the alternative hypothesis of CS-D existence. Furthermore, all the variables show significant effects at a 0.01 (1%) level. Therefore, it can be inferred that CS-D exists amid all the explored variables. According to Hashem Pesaran and Yamagata [76], H0 means the slope coefficients have homogeneous features, while H1 means the presence of heterogeneity of slope coefficients. Table 2 shows that the designed model encounters a

Table 2
Cross-sectional dependence and slope homogeneity test results.

Cross-sectional dependence		
Variable	CD-test	p-value
lnECFP	16.83*	0.000
ECI	8.10*	0.000
lnEPD	75.88*	0.000
lnREEG	29.34*	0.000
lnPTNT	20.30*	0.000
lnRGDP	154.60*	0.000
Slope homogeneity		
	Value	p-value
Δ	16.611*	0.000
Δadjusted	19.071*	0.000
*: 1% significant		

Table 4
CS-ARDL, AMG, and CCEMG estimations results.

Dependent variable: lnECFP						
CS-ARDL Short-run				CS-ARDL Long-run		
	Coef.	Std. Err.	Prob.	Coef.	Std. Err.	Prob.
ECI	−0.0745**	0.0396	0.060	−0.0839**	0.0427	0.049
lnEPD	−0.3892*	0.0563	0.000	−0.4407*	0.0678	0.000
lnREEG	−0.0208**	0.0093	0.025	−0.0197***	0.0105	0.061
lnPTNT	−0.0029	0.0064	0.647	−0.0045***	0.0078	0.095
lnRGDP	0.7510*	0.0824	0.000	0.8267*	0.0965	0.000
	AMG			CCEMG		
	Coef.	Std. Err.	Prob.	Coef.	Std. Err.	Prob.
ECI	−0.0352*	0.0060	0.000	−0.0974*	0.0216	0.000
lnEPD	−0.2427*	0.0062	0.000	−0.4378*	0.0423	0.000
lnREEG	−0.0015	0.0030	0.611	−0.0074***	0.0066	0.096
lnPTNT	−0.0058*	0.0012	0.000	−0.0011	0.0018	0.519
lnRGDP	0.4777*	0.0061	0.000	0.8185*	0.0543	0.000

"Note: * and ** signify significance at 1% and 5% level, respectively."

heterogeneity issue. Besides, both delta and its adjusted p-values are statistically significant at the 1% level for the model designed in this work.

Table 3 displays the CADF and CIPS results. In the case of CADF, all the variables except REEG are stationary at the first difference of the constant & trend, and ECI and EPD show stationarity at the first difference for the constant. In the case of CIPS, for the constant & trend, ECI and RGDP unveil stationarity at the first difference that suggests rejecting the null hypothesis of non-stationary. As shown in Table 3, the explored variables show diverse order of integration that allows the implementation of panel co-integration analysis proposed by Westerlund [75] and the CS-ARDL model.

In addition, Table 3 shows that one group and two of the panel test statistics failed to reject the alternative hypothesis of co-integration presence at a 0.01 significance level, while one of the group statistics, i.e., G_a, failed to reject the null hypothesis of no-co-integration at a 0.10 significance level. Therefore, according to the finding, it can be concluded that long-term co-integration exists between variables considered in this work.

The short- and long-run estimation analyses are performed after confirming co-integration among the variables. Table 4 presents the short-run and long-run CS-ARDL results. In both estimation ways, all the explored variables other than RGDP show negative impacts against

Table 3
Second-generation panel stationarity tests report.

	Constant & trend		Constant	
	I (0)	I (1)	I (0)	I (1)
Variable	CADF			
lnECFP	−1.848	−3.477*	−2.22*	–
ECI	−1.560	−2.872*	−1.829	−2.807*
lnEPD	−2.355	−3.939*	−1.912	−3.761*
lnREEG	−2.894*	–	−1.952***	–
lnPTNT	−2.370	−3.845*	−2.113*	–
lnRGDP	−2.089	−2.761*	−2.218*	–
	CIPS			
lnECFP	−2.772*	–	−2.744*	–
ECI	−1.72	−4.856*	−1.782	−4.761*
lnEPD	−2.783*	–	−2.222**	–
lnREEG	−3.377*	–	−2.257*	–
lnPTNT	−2.574**	–	−2.269	−4.859*
lnRGDP	−1.889	−3.763*	−2.048***	–
Westerlund co-integration				
T-Statistic	Value	Z-value	P-value	
Gt	−3.627*	3.582	0.000	
Ga	−21.093***	1.076	0.093	
Pt	−18.629*	3.642	0.000	
Pa	−19.764*	2.437	0.007	

"Note: *, **, and * indicate 1%, 5%, and 10% significance levels, respectively. I (0): Order of integration at level; I(1): Order of integration at first difference."

ECFP. Explicitly, the CS-ARDL analysis reported that ECI has a negative impact on ECFP, implying a one-unit rise in the ECI declines ECFP by 0.0839 and 0.0745 units in the long- and short-term estimations with 0.05 and 0.10 statistically significant, respectively. Moreover, ECI measures the knowledge and expertise required to invent and manufacture exported products. As Pata [10] discussed, countries with high ECI have shown growth in efficiency simultaneously with their economy. Also, reaching the highest ECI might support the carbon-zero environment strategy in the long-term by reducing the carbon footprint and other elements registered above the threshold of safe ECFP. Besides, the findings suggested that ECI correlates significantly with ecological sustainability and should be prioritized in strategies for economic expansion and energy limitations. From this finding, it can be observed that increasing ECI helps to attain the eleventh and twelfth goals of sustainable development by keeping their manufacturing and consumption methods environment-friendly. Also, it is wise for the governments of the sampled countries to be more careful and responsible in consuming energy to protect the environment of the sampled countries. Previous literature [41,43,55,87] reported consistent findings with the present work.

Likewise, both short- and long-run estimation results suggested that energy productivity plays a significant role in promoting sustainable ecology as well as advancing environment quality in the explored countries. Hence, it is presumed to be one of the persuasive solutions to a carbon-zero environment, similar to the usage of RESs and the increasing number of environment-oriented technologies. Table 4 shows a 1% rise in lnEPD is recorded to lessen lnECFP by 0.4407 and 0.3892% in the long- and short-run estimations, respectively, ceteris paribus. Besides, both estimations confirmed that lnEPD negatively influences lnECFP with a 0.01 significant level. Cheng et al. [48] reported similar findings that energy productivity significantly minimizes environmental deterioration. Therefore, increased productivity and renewable energy sources will assist in reducing pollution emissions and attaining SDG-7. The countries studied in this work should follow SDG-7 and make sure that their populations have access to modern, clean, economic, reliable, durable, and feasible energy. SDG-7 states that the use of energy accounts for more than 60% of global GHG emissions [22]. In order to prevent the worst effects of climate change, the IPCC estimates that by 2050, renewable energy sources must account for around 85% of the world's energy usage, up from the current level of around 17% [88].

Similarly, REEG reported a negative and significant value at the 0.10 level. As per the findings, a 1% rise in lnREEG causes a reduction of lnECFP by 0.0197%. lnREEG has also reported a negative and significant result with a p-value <0.05 and a coefficient of −0.0208 in the short-run. However, the short-run influence of REEG is moderately bigger than the long-run effect. Contrariwise, Zeraibi et al. [82] reported a bigger long-run coefficient than the short-run for renewable energy electricity. Further, finding renewable energy electricity generation as a productive determinant to curb excessive ECFP strongly suggests using renewable sources over non-renewable energy sources, which is a critical way for the explored countries to achieve carbon-zero with a healthy environment. The empirical findings reported in Refs. [89,90] match the results of this work. In addition, throughout history, using environmentally damaging energy sources like fossil fuels has significantly impacted the environment [91,92]. This emphasizes facilitating the switch to renewable energy sources, which is essential to achieving SDG-7 and SDG-13. From this angle, this study suggests adopting clean energy laws and increasing the use of renewable energy sources.

Furthermore, lnRGDP is positively significant at the 1% level, in which a 1% rise in the lnRGDP gives rise to lnECFP by 0.751% and 0.8267% in the short-run and long-run estimation, respectively, ceteris paribus. Besides, the long-run influence of economic development is comparatively bigger than the short-run. Numerous studies regarded GDP as the strength of an economy comprising various "macroeconomics" elements, such as government expenditures, inventions, productions, and consumptions [55]. As a result, a rise in income may increase the number of productions, which leads to excessive energy usage. Thus, excessive energy consumption undoubtedly upsurges air pollution [10]. The findings of this work concerning GDP have uniformity with several existing empirical research works, for example [93–95]. On the other hand, Saboori et al. [96] discovered mixed results in the case of China and Japan regarding the connection between economic growth and the environment.

Regarding environment-related patents, the analysis results show a negative effect with a 0.10 statistically significant level. Explicitly, a 1% rise in patents and innovations produced to better the environment diminishes the lnECFP by 0.0045% in the long-run estimation. However, lnPTNT reported a negative but insignificant figure in the short-run estimation. The present work's findings match the findings reported in Refs. [97,98]. Besides, the long-run elasticity of lnPTNT is comparatively bigger than the short-run estimation, i.e., 0.0029. Also, the present work findings are consistent with those that Zeraibi et al. [82] reported. Overall, the analysis results regarding patents show that advancing and facilitating environment-oriented patents could be efficacious in diminishing excessive ECFP. Besides, the results infer that devoting to the advancement of technologies produced to achieve the carbon-zero target can benefit the countries explored in this study to minimize their ECFP. Also, the empirical findings suggest that environment-oriented patents could warrant the explored countries to subdue their hurdles regarding productive environment-oriented technologies. On the other hand, as it is also discussed in Refs. [58,99], by using cutting-edge technology instead of energy-intensive traditional manufacturing, ecological technology benefits both the environment and the economy and helps attain SDG-9. Subsequently, Table 4 displays the robustness test results from AMG and CCEMG that show consistent and highly matched findings with the CS-ARDL model.

Finally, the results from the D-HGC test revealed that variations in economic complexity index, renewable energy electricity generation, and patents have causal associations with the ecological footprint in forty-five countries explored in this work (see Table 5). Further, the results reported that ECFP has a bi-directional causality with these determinants, such as ECI, lnREEG, and lnPTNT. Therefore, policies that aim at these determinants would significantly affect lnECFP, and so is the reverse. For instance, any increment or decrement in ECI, lnREEG, or lnPTNT will expedite lnECFP; similarly, any fluctuations in lnECFP will impact these elements. The results also show that energy productivity and the economic development indicator lnRGDP do not granger cause lnECFP. The graphical representation of the causality test report is depicted in Fig. 4.

Table 5
D-HGC test report.

Null Hypothesis:	W-Stat.	Zbar-Stat.	Prob.	Remark
ECI → lnECFP	6.964*	13.139	0.000	ECFP ←→ ECI
lnECFP → ECI	5.556*	9.257	0.000	
lnEPD → lnECFP	2.422	0.613	0.540	ECFP → EPD
lnECFP → lnEPD	4.101*	5.244	0.000	
lnREEG → lnECFP	2.775***	1.587	0.100	ECFP ←→ REEG
lnECFP → lnREEG	3.527*	3.659	0.000	
lnPTNT → lnECFP	4.302*	5.796	0.000	ECFP ←→ PTNT
lnECFP → lnPTNT	3.212*	2.789	0.005	
lnRGDP → lnECFP	2.648	1.236	0.216	ECFP → RGDP
lnECFP → lnRGDP	3.006**	2.224	0.026	

"*: 1% significant, **: 5% significant, and ***:10% significant".

6. Conclusion and policy implications

Environmental and development issues have dominated the global agenda in recent years to the point where they cannot be addressed separately. Hence, this paper empirically analyzed the influence of economic complexity, energy productivity, renewable energy electricity generation, environment-oriented patents, and economic growth on the ecological footprint to attain a carbon-zero target as well as the sustainable development goals (SDGs) for a panel of forty-five countries with a mixture of high, medium, and low economic complex from 1990 to 2020. First, the CS-ARDL model was applied to perform the panel data's short- and long-run estimations. Afterward, the robustness of the long-run estimations was verified by using AMG and CCEMG approaches. Lastly, the granger causality amongst the variables was carried out using the "Dumitrescu-Hurlin Granger Causality" approach. The empirical outcomes revealed that the economic complexity index, energy productivity, renewable energy electricity generation, and patents have negative parameters and play significant roles in curbing the ecological footprint and effectively helping attain the SDGs and a carbon-zero environment. The study found that the gross domestic product is the main cause of environmental contamination. This reveals that environmental sustainability is adversely affected by the economic development systems in the sampled countries. As a result, the countries should include environmental sustainability goals in their economic growth plans. Additionally, financial support needs to be given to environmentally responsible business individuals.

According to these findings, this study recommends policies concerning carbon-zero and SDGs. The policies are briefly discussed as follows:

- The best way to achieve low carbon is to consume sources of renewable energy that lessen reliance on fuels while it is essential to enhance the production of energy. Hence, the primary ways to be

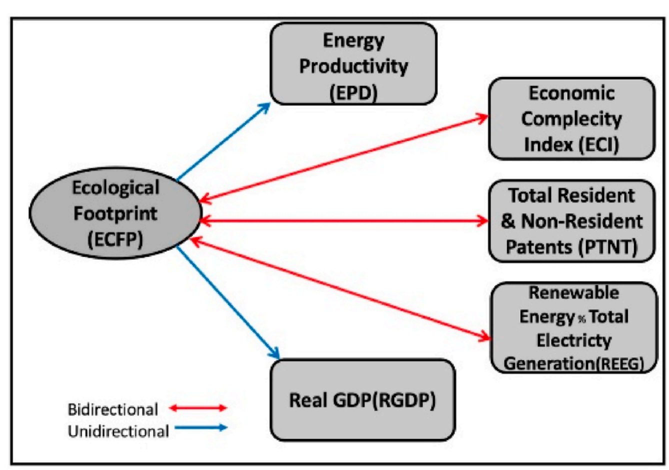

Fig. 4. Graphical representation of the Granger causality test result. Authors' own tabulation.

actively involved in developing green technologies are the advancement of RESs and energy efficiency. Thus, countries need to have large-scale government plans and programs to stimulate the development of environmental technologies and innovations based on renewable energy. Policymakers in the explored countries should pledge policies to facilitate expertise and talented individuals to produce technologies that help make the earth carbon-free.

- The sampled countries should increase their ability to use renewable energy by implementing strict measures and rules to aid the corresponding country's conversion to clean energy. Striving to achieve a sustainable environment through "ozone-friendly or energy-saving" technologies might be pricey. Work on SDGs' seventh and fifteenth goals to provide everyone access to affordable, sustainable, efficient, and modern energy and a better life on land. Invest in technologies that have the potential to mitigate carbon footprint in order to attain SDG-15. Working towards achieving SDG-7 and SDG-15 also directly fulfills the objectives of SDG-13.
- Concerned policymakers should work closely with the government to ease tax-related issues to attract more investors to the renewable energy markets. Governments should also provide financial support for the subsidies used for green projects. As a result, less carbon will be discharged into the air due to the country's support for sustainable development and a carbon-zero environment.
- Green funding is the best strategy to increase ecological sustainability practices and helps to attain the seventh, ninth, twelfth, and thirteenth objectives of sustainable development. In addition, it should not be forgotten that the most effective solution to preventing environmental problems will be realized through a well-functioning price mechanism. Therefore, the most genuine way to control environmental pollution is to include it in the price system. If countries establish such a system, the world will realize a fair cost distribution in incentives for less polluting technologies and environmental pollution costs.
- A carbon tax can reduce the potential effects of climate change [100]. Therefore, creating an intelligent carbon tax necessitates making crucial choices about which emitters to tax or not, how to assign the revenue in a way that benefits the economy and the environment, and how to set the carbon tax rates at the proper level to ensure carbon neutrality and minimal impact on energy consumers and the economy.

Despite its significance for several concerned individuals, the present work also has limitations. This research work explored only 45 nations for which data on energy productivity and renewable energy electricity generation are available. When the data issue is resolved, subsequent research will be conducted thoroughly. Future studies may also take into account external variables and statistical judgments. Besides, in future work, the authors plan to thoroughly and comprehensively investigate the consequences of the COVID-19 outbreaks on the environment and sustainable development, specifically in developing countries.

Credit author statement

Umar Numan: Conceptualization, Methodology, Data Curation, Analysis, Writing- Original draft preparation, Writing - Final version, Final version - approval, **Benjiang Ma:** Supervision, Reviewing, Final version - approval, **Muhammad Aslam**: Writing- Reviewing and Editing, Software - Visualization Reviewing, Final version - approval, **Hayat Dino Bedru**: Writing- Writing, Reviewing and Editing, Software - Visualization, Final version - approval, **Can Jiang**: Writing- Reviewing and Editing, Data Curation, Final version - approval, **Muhammad Sadiq**: Writing- Reviewing and Editing, Empirical Analysis, Final version - approval.

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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.

Data availability

Data will be made available on request.

Annex A

List of countries explored in this study

Algeria, Argentina, Australia, Austria, Bangladesh, Belgium, Brazil, Bulgaria, Canada, China, Colombia, Denmark, Ecuador, Egypt, Finland, France, Germany, Hungary, India, Indonesia, Iran, Ireland, Israel, Italy, Japan, Malaysia, Mexico, Morocco, Netherlands, New Zealand, Pakistan, Philippines, Poland, Romania, Singapore, South Africa, South Korea, Sri Lanka, Sweden, Switzerland, Thailand, Turkey, UK, USA, and Vietnam.

Annex B

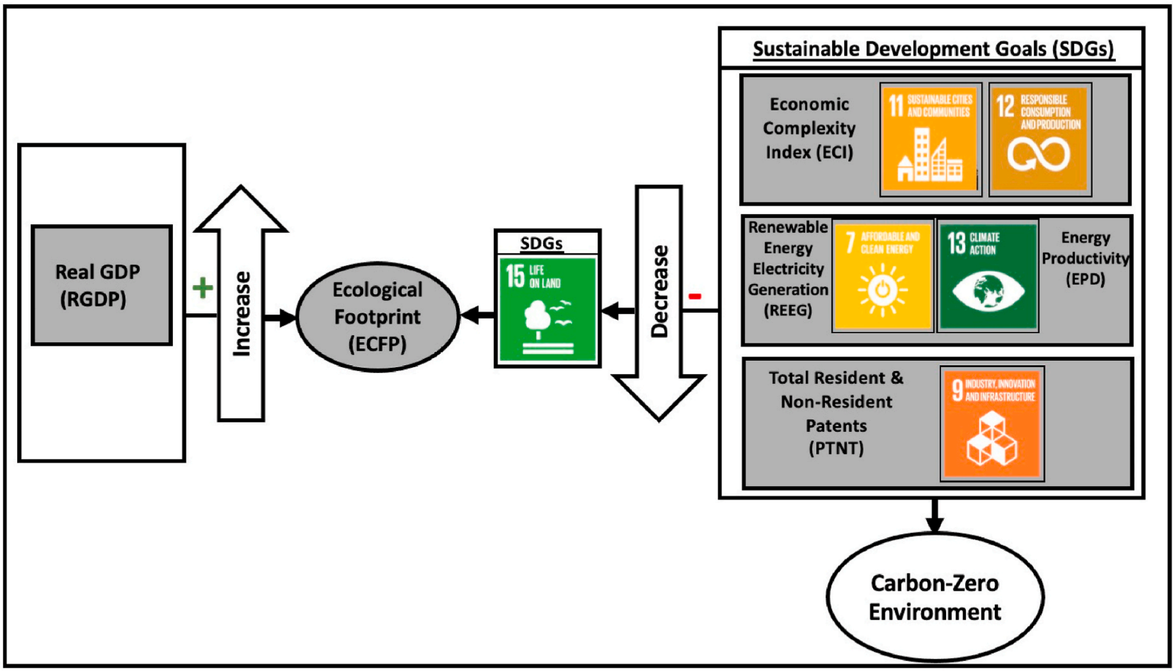

Fig. 5. SDGs considered in this study (SDGs, 2022) corresponding to the variables. Authors' own tabulation.

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