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Achieving green environment targets in the world's top 10 emitter countries: the role of green innovations and renewable electricity production

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ABSTRACT

The rapid pace of industrialisation and economic development in recent decades is not without its environmental consequences. Electricity production, though an important determinant of economic development, remained under studied in the existing literature and only a few models on the electricity production-environmental degradation nexus are available. As a first attempt, this study examines the impact of renewable and non-renewable electricity generation and eco-innovations on CO_2 emissions in the world's top emitting countries under the umbrella of the Environmental Kuznets Curve (E.K.C.) Hypothesis. Second-generation panel data techniques, i.e., C.I.P.S. and Bai and Carrion-I-Silvestre (2009) unit root tests, Westerlund and Edgerton (2008) and Banerjee and Carrion-i-Silvestre (2017) cointegration techniques and Cross-Sectionally Augmented Distributed Lag Model for short and long run coefficient estimations have been employed in the study. It is found that renewable electricity production and eco-innovations have negative effects, whereas non-renewable electricity production has positive effect on CO_2 emission. Moreover, the estimation demonstrated the E.K.C. validation in these countries. It is recommended that fossil fuel dependency in the electricity sector should be reduced by devising policies directed towards green electricity measures. More investment in green innovations to achieve green environment and sustainable growth is also recommended by the study.

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1. Introduction

Economic development has become the primary focus of many countries in the present era of fast industrialisation which is directly related with several factors that are

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alleged to be responsible for the environmental deterioration (Su et al., 2021; Umar et al., 2021). Therefore, considerable amount of attention has been paid to the increasing environmental problems in the past few decades (Nathaniel et al., 2021). CO_2 emission is widely considered as the world's most serious environmental issue that results from complicated interplay between three main parameters: economic development, energy and the environment, that posits a serious threat to human life and the sustainability of the environment (Belaid & Zrelli, 2019). In general, energy is considered as the chief environmental degrading factor. It is a fundamental component of economic production, and hence of economic growth and societal development, but it is also a significant source of greenhouse gas (G.H.G.) emissions (Nathaniel et al., 2021). Growing energy demands have resulted in widespread use of nonrenewable energy sources such as coal, gas and oil, posing significant pollution problems. Green energy sources, on the other hand, such as bio-energy, geothermal, hydropower, wind and solar energy are the ultimate solution to climate issues (Gyamfi et al., 2021). Increased renewable energy supply would enable carbon-intensive energy sources to be replaced, resulting in considerable reductions in pollutant emissions (Belaid & Zrelli, 2019).

The shift to a renewable-energy-based energy system is the corridor to realise sustainable development goals (S.D.G.) 7[1] providing clean and affordable energy. In electricity terms, renewable energy can be electric energy generated from wind, flowing water, biomass, sunlight, or other sources such as hydrogen, wave energy, etc. (Zhong et al., 2021). Electricity is used in numerous productive operations such as manufacturing and computing. That is, electricity is generated because productive (and recreational) activities necessitate it (Crestanello, 2020). The carbon intensity – the quantity of CO_2 emitted per watt of electricity – is determined by the mix, or the source utilised (Belaid & Zrelli, 2019). Electricity generation from fossil fuels is considered as the main cause of the CO_2 emission. The renewables climate mitigation hypothesis states that the extent of national measures related to renewable energy production will be negatively related with carbon emissions. Simply stated, the more a country uses renewable electricity, the lower its emissions will be (Sovacool et al., 2020). According to a recent estimate of International Energy Agency (IEA, 2021a), the electricity and heat production account for 42% (one-third) of global CO_2 emission (Figure 1). This is attributed to the widespread use of coal and carbon-intensive fossil fuel in the generation of electricity and heat (Figure 2) (IEA, 2021a). In order to achieve the S.D.G., governments of many countries have taken the initiatives to replace polluted energy resources replacement with renewable sources at electricity plants. In 2019, global renewable electricity production has an increase of 6%, where solar and wind P.V. technologies accounted for 64% of this increase. Despite the fact that renewable energy accounted for about 27% of global electricity production in 2019, the renewable energy as a whole still has to grow significantly to fulfill the S.D.G. share of nearly 50% of generation by 2030 (IEA, 2021b).

In addition to renewable energy resources, novel environmentally friendly green technology breakthroughs are also helpful to address a wide range of pollution-related challenges. Green technology or eco-innovation are defined as 'the process that promotes the development of new products and technologies with the goal of decreasing

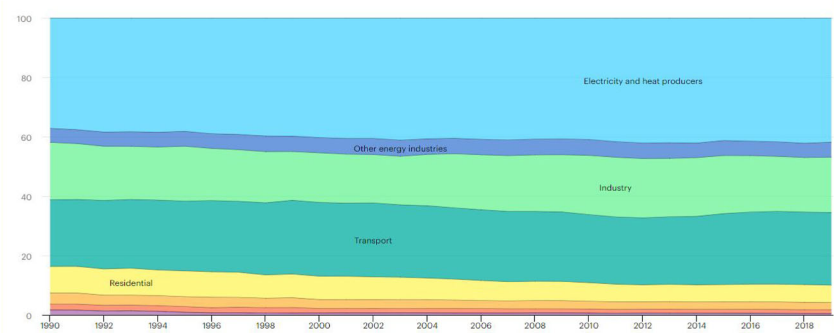

Figure 1. CO_2 emissions by sector (%), World 1990–2019.
Source: International Energy Agency (2021).

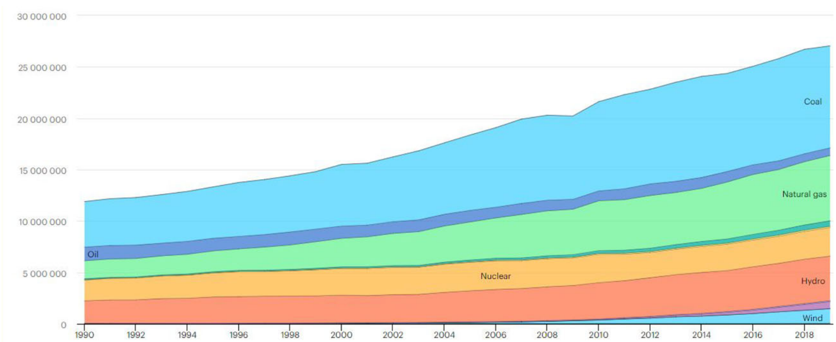

Figure 2. Electricity generation (GWH) by source, World 1990–2019.
Source: International Energy Agency (2021).

environmental hazards such as pollution and negative impact of resource exploitation (e.g., energy)' (Sun et al., 2020; Takalo & Tooranloo, 2021) and can be helpful to reintroduce life into the ecosystem (Shair et al., 2021; Wu et al., 2021). It encompasses pollution elimination, energy conservation and environmental management technologies. Eco-innovations are referred as one of the main factors to achieve S.D.G., and United Nations (U.N.) general assembly forces the countries to focus more on eco-innovations to achieve S.D.G.s (Imekova & Boltanova, 2019). Green technology has the ability to eliminate carbon emissions by incorporating environmentally friendly technologies into existing activities to achieve maximum growth at the lowest possible environmental price (Nikzad & Sedigh, 2017; Umar et al., 2020) through reducing the use of natural sources, e.g., oil and coal to meet energy requirements (Chien, Sadiq et al., 2021; Umar et al., 2020). These environmental innovations result in the reduction rather than an increase in pollution caused by the burning of organic fuel products (Chien, Ananzeh et al., 2021).

Given the relevancy of renewable energy and eco-innovations in CO_2 emission reduction, the primary objective of this study is to identify the role of these factors under Environmental Kuznets Curve (E.K.C.) framework in world's top emitter countries namely Canada, China, Germany, India, Russia, Iran, Japan, South Korea, Saudi Arabia and the U.S.A. over 1995–2019 period. The rationale for selecting top emitter

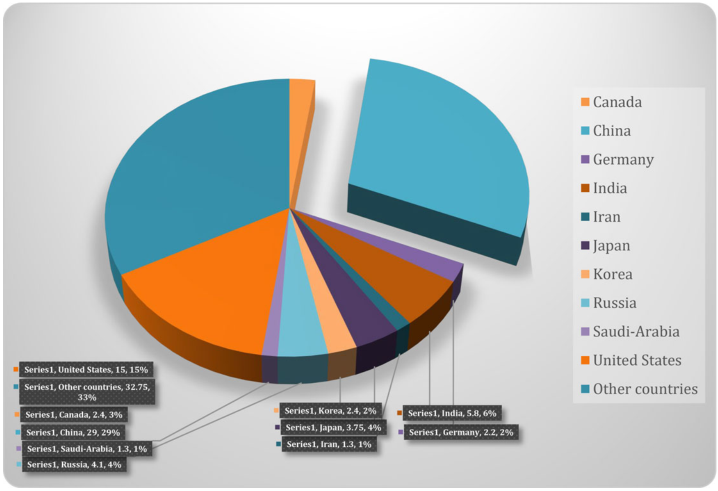

Figure 3. Electricity production by top emitter countries (percentage of world electricity production, 2020).
Source: British Petroleum (2021).

countries lies in the fact that these world's top emitter countries extensively release heat-absorbing gases into the atmosphere because of their economic expansion, and therefore, are frequently sacrificing environmental quality during their process of economic growth. These countries collectively account for two-third of global carbon emissions. In 2019, these 10 main polluting economies actively cause carbon emissions such as Canada (1.6%), China (27.8%), India (7.3%), Iran (1.8%), Russia (4.8%), Germany (2.1%), Japan (3.3%), Saudi Arabia (1.6%), South Korea (2%), U.S. (15.1%), having thee-fourth contribution in the total global pollution. It shows that these countries are the leaders of environmental damages (Usman et al., 2021). Moreover, these countries together account for 65% of global G.D.P., 51% of the world population, 80% of total global fossil fuel consumption and 67.5% of total fossil CO_2 worldwide (Bank, 2020).

Meanwhile, these countries are the largest electricity producers in the world collectively accounting for 67.75% of total world's electricity production (BP, 2021). China has the highest electricity production in the world followed by the U.S., India, Russia, and Japan (Figure 3). The world's top emitters have enormous renewable energy potential. Meanwhile, fossil fuels continue to dominate the electrical generation mix, while renewable energy is underutilised in these countries as shown in (Table 1). It can be seen that Saudi Arabia has zero utilization of the renewable resources in its electricity production mix as the proportion of non-renewable electricity production in the total electricity production is 100% in 2019. Iran, India, China and the U.S. also have more proportion of non-renewable electricity in total electricity generation. This under-utilization of capacity of electricity production from renewable sources is leading to maximum contribution of non-renewable electricity and heat production towards CO_2 emission in these countries (IRENA, 2021) and the ratio of CO_2 emission from electricity production is the highest among all the sectors in these countries (IEA, 2020).

Table 1. Contribution of renewable and non-renewable resources in total electricity production in top emitter countries (2019).

Country	Electricity-production (TWH)	Renewable electricity production capacity (%)	Share of renewables in total electricity production (%)	Share of non-renewables in total electricity production (%)	Share of electricity production in total CO_2 emission (Mt CO_2)	Renewable electricity avoided CO_2 emission (Mt) (approx)
Canada	660.4	67	62	38	86	300/400
China	7503.4	41	26	74	4569	2000/6000
India	1558.7	30	17	83	1198	400/1500
Iran	318.7	15	6	94	81	20/180
Germany	612.4	56	40	60	29	170/450
Japan	1036.3	39	18	82	525	120/700
Korea	584.7	15	5.0	95	306	10/320
Russia	1118.1	20	18	82	840	100/1000
Saudi-Arabia	357.4	1.0	0	100	81	0/250
United-States	4401.3	25	17	83	1700	300/2500

Source: International Renewable Energy Agency (IRENA, 2021), British Petroleum (BP, 2021).

It is therefore reasonable that countries with the highest levels of emissions have more spending on environmental related technologies to cut emissions than countries with lower levels of emissions. According to recent statistics of O.E.C.D., the ratio of environmental technologies has an increasing trend over the last two decades in world's top emitter countries. China has become a leader in environmental actions in the last few years. Germany tends to be one of the most striving countries in the field of environmental innovation. It has a well-deserved position as a leader in waste recycling, management and environmental technologies. Germany continues to rank high in terms of eco-innovation inputs and is above the European Union average in terms of eco-innovative outputs (OECD, 2021). Korea has made substantial progress in eco-label system to protect the environment and ensure safe consumption by consumers (Oh et al., 2020). The understanding about the need for eco-innovations for accelerated and sustainable development is rising in Russia recently. Moreover, the U.S., Canada and Japan are among the 36 states of the world that are at their stage of innovative development of country (Imekova & Boltanova, 2019). Figure 4 shows that in 2018, Germany and Saudi Arabia had the highest share of the environmental related technologies in all technologies as compared to China, Russia and India. The proportion of climate change and mitigation technologies specifically related to energy production is highest in Korea and lowest in India among the high emitting countries (OECD, 2021).

The contribution of our study in the literature is four folds: First, despite being the culprits for global environmental degradation, the world's top emitter countries did not get much attention in the existing literature, thus our study is going to be a significant contribution in the limited existing literature on these countries. Second, unlike the traditional approach of considering energy consumption, our study goes a step further by using the 'electricity production', due to two main reasons: first, it is the sector that is anticipated to expand rapidly in the future as more end-uses of energy from households to transport get electrified. Electricity is projected to account for 40% of the increase in energy consumption from current levels to projected levels in 2040 (IEA, 2017) and second, it is one of the most damaging human activity in

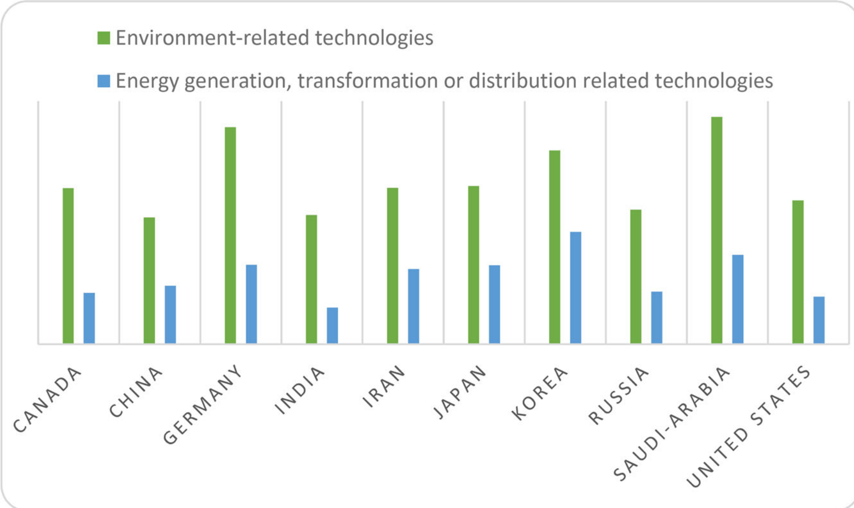

Figure 4. Environmental technologies (percentage of all technologies) in top emitter countries (2018).
Source: OECD.

the world as shown in (Figure 1). In particular, our study is estimating the role of renewable and non-renewable electricity generation and environmental innovations on CO_2 emission in world's top 10 emitter countries because as stated earlier, these countries are the world's largest electricity producing countries which are heavily reliant on fossil fuels for their electricity generation despite having potential for renewable electricity production, and are heading towards the adoption of more environmental innovations, therefore identifying whether these factors can help these countries in achieving green environment target. Third, under the umbrella of the E.K.C. theory, the literature is quiet on the position of these highest carbon emitters in global environmental deterioration in the presence of electricity production and eco-innovations. Therefore, our study opens a new area for future exploration on these high emitters. Fourth, the most central aspect of any analysis is the selection of the econometric techniques that produce meaningful analytical results and satisfy the study goals. The current study employs second-generation econometric methodologies that provide efficient estimation in the presence of the cross-sectional dependence, heterogeneity and structural breaks in panel data.

The remaining study is structured as follows: a brief review of the empirical literature is covered in section 2. Data and empirical estimation methodology are given in section 3. Empirical results and their discussion are provided in section 4. Last, section 5 concludes the study and suggests worthy policies.

2. Review of existing literature

2.1. Theoretical framework

The nexus between eco-innovations, renewable electricity, non-renewable electricity production and CO_2 emission can be described under the theoretical underpinnings of the E.K.C. hypothesis. E.K.C. asserts that an increase in income raises the pollution level at the initial stages of economic growth until a threshold level reaches, where the relation between these two components becomes negative (Al-Mulali & Ozturk, 2016). According to the E.K.C. hypothesis, economic growth affects environmental quality in three ways.[2] Initially, the economic growth has detrimental impacts on the environmental quality due to the scale effects and the composition effects that leads to more use of the fossil fuels for national outputs production. Previous research has asserted that use of fossil fuels electricity generation is harmful for the environment because fossil fuels contain hydro-carbons (Bento & Moutinho, 2016; Murshed, 2020). The fossil fuels combustion for electricity production releases toxic gases that deteriorate the atmospheric quality (Murshed, Alam et al., 2021; Murshed, Rahman et al., 2021). Conversely, the electricity production from renewable resources has the capability to improve the environmental quality by decreasing the fossil fuels extractions and limiting the overall level of emission (Zeraibi et al., 2021).

The turning point under E.K.C. will occur as the income of country rises resulting in population awareness about the environment. Therefore, the demand for a clean environment would rise. As a result, the government will be encouraged to implement various economic strategies to curb pollution. This technique effect is expected to encourage the use of new technologies to help reduce G.H.G. emissions (Al-Mulali & Ozturk, 2016). As an economy gets significant advancements in technology in the post-industrialization period, the technique effect causes the economy to take more environmental protection measures (Ali, Gong et al., 2021). Hence, economic policies and public awareness may be able to assist in the reduction of environmental damage. Furthermore, the number of technologies and projects that support energy efficiency and renewable energy (as these technologies and projects are known to be costly) also increase with the increase in income (Al-Mulali & Ozturk, 2016). Consequently, sources of renewable energy are likely to minimise the emissions. Furthermore, implementation of green growth policies is essential because they not only improve the environmental quality but also help to conserve ecological resources (Anwar, Siddique et al., 2021; Zeraibi et al., 2021). As a result, the relationship between economic growth and environmental quality is considered to have an inverted U shape, certifying economic expansion as a short run characteristic and a long run remedy to an economy's environmental problems (Murshed et al., 2021).

Empirical literature

A number of studies are documented in the existing literature about the role of economic growth, eco-innovations and renewable/non-renewable energy on environmental quality. A short and concise review of previous studies about these factors is given below.

Economic growth and CO_2 emission (E.K.C. hypothesis)

Several studies have widely explored the economic growth and CO_2 emission relationship under the framework of E.K.C. in the previous literature. However, the findings of these studies were somewhat dissimilar. For instance, Murshed et al. (2021) proved the validity of E.K.C. hypothesis for South-Asian countries; Nathaniel et al. (2021) for N-11 countries; Murshed et al. (2021) for Bangladesh; Apergis and Ozturk (2015) for Asian countries; Ali, Dogan et al. (2021) for top emitter countries; Balsalobre-Lorente et al. (2021) for E.U. countries; and Murshed et al. (2020) for OPEC countries. However, Al-Mulali et al. (2015) found the invalidity of E.K.C. hypothesis for Vietnam; Jebli and Youssef (2015) for Tunisia; Mert and Bölük (2016) for Kyoto Annex countries; Ben Jebli et al. (2015) for sub-Saharan Africa; and Ozturk and Al-Mulali (2015) for Cambodia.

Green innovations and CO_2 emissions

The importance of technology improvements and innovations for the stable expansion of the production capacity and environmental quality improvement is extensively explored in the literature (Hashmi & Alam, 2019; Khan et al., 2020; Shao et al., 2021; Tao et al., 2021). For instance, Murshed and Alam (2021) evaluated technological innovations, economic growth, household consumption expenditures oil-price shocks and income inequality as the determinants of demand for total and renewable and non-renewable energy in Bangladesh. Their findings showed that technological innovations reduced the demands for total and non-renewable energy but increased the demand for renewable energy. Household consumption expenditure and economic growth positively affected the electricity and primary energy demands whereas income inequality had the opposite effect. Positive shocks in oil price did not influence the demand for renewable energy but slightly reduced for non-renewable energy (Murshed & Alam, 2021). Ullah et al. (2021) estimated the asymmetric and symmetric effect of technology innovation on CO_2 emissions for Pakistan. According to study findings, patent had negative but trademark had positive symmetric effect on CO_2 emissions in short run, but insignificant effects in long run in Pakistan in linear A.R.D.L. model. Whereas negative and positive patent shocks had insignificant asymmetric short run effects while the insignificant effect of positive trademark shock and negative significant effect of negative shock on carbon emissions was found in the short run in a non-linear A.R.D.L. model (Ullah et al., 2021).

Khan et al. (2020) studied how eco-innovations, trade, non-renewable energy and G.D.P. affected carbon dioxide emissions by analysing the panel data of G7 economies. Their results indicated that eco innovations led to less use of non-renewable energy in G7 countries resulting in lower emissions of adverse externalities in the environment (Anwar, Malik et al., 2021). Using ecological footprint as a measure of environmental degradation, Ahmad et al. (2021) analysed the effects of eco-innovations, urbanisation, financial globalisation and economic growth on ecological footprints in G-7 countries. Their analysis proved that eco-innovation and financial globalisation decreased whereas urbanisation increased ecological footprints. Moreover, eco-innovation indirectly affected environment through the channel of urbanisation. The validation of E.K.C. hypothesis in G-7 countries was proved by their study (Ahmad et al., 2021).

Ali et al. (2021) examined the linkage between trade and CO_2 emissions, and the effects of renewable energy consumption and environmental innovation on emissions in the top 10 emitter countries and concluded that an increase in the renewable energy use, trade and innovation reduced CO_2 emission (Ali, Dogan et al., 2021). Alvarez-Herranz et al. (2017) analysed the data of 17 O.E.C.D. economies and their findings revealed the negative impact of eco-innovations on CO_2 emission that necessitated the adoption of low carbon technologies for environmentally-friendly growth. Energy efficiency technologies, according to the author, were useful in shifting the economic system to more green technologies such as renewable energies (Alvarez-Herranz et al., 2017). The findings of Ahmed et al. (2016) by using the European countries' data, confirmed that technological advancement was helpful to lessen CO_2 emissions (Ahmed et al., 2016). Environmental innovation, according to Henriques and Borowiecki (2017), was an essential strategy to enhance the long-term quality of the environment in Europe. Similar finding was observed by Töbelmann and Wendler (2020) for 27 EU countries. Sun et al. (2021) scrutinised the link between eco-innovations, globalisation, and CO_2 reduction in the USA, and found that eco-innovation was a mitigating factor whereas globalisation was a stimulating factor of CO_2 emission (Sun et al., 2021). Hence, the hypothesis is established as:

Hypothesis 1. Green Innovations affect CO_2 emission significantly.

Renewable energy consumption/renewable electricity production and CO_2 emission

Recent research has focused on how renewable and nonrenewable energy sources affect environmental quality in different countries and regions. The first time, energy consumption was disaggregated into renewable and non-renewable consumption by Richmond and Kaufmann (2006). Using data for 36 non-O.E.C.D. and O.E.C.D. economies, researchers analysed the role of each energy source on CO_2 emissions by taking the economic development into consideration to determine the turning point between income growth and carbon emissions. Their findings revealed an inverse association between carbon emission and renewable energy for O.E.C.D. economies (Richmond & Kaufmann, 2006). Apergis and Ozturk (2015) scrutinised the relationship of renewable energy, G.D.P., nuclear energy with carbon emissions for 19 developing and industrialised countries. Surprisingly, renewable energy was found to increase while nuclear energy was found to decrease the CO_2 emission in their empirical results (Anwar, Sharif et al., 2021; Apergis & Ozturk, 2015).

Murshed et al. (2021) scrutinised the effect of intra-trade integration and renewable energy transition on CO_2 emission controlling for other macroeconomic factors in selected South Asian economies. Their empirical estimations indicated that renewable energy and trade facilitations were helpful to reduce CO_2 emissions in the short and long run. The study also proved the validity of E.K.C. hypothesis in the selected countries (Murshed et al., 2021). Sovacool et al. (2020) compared the effects of renewable and nuclear energy on carbon abatement using panel data from 123 economies. According to their findings, renewable energy had positive contributions in achieving a carbon-neutral environment (Sovacool et al., 2020). Similarly Saidi and Omri (2020) analysed the 15 O.E.C.D. economies data and both nuclear and renewable energy were found to eliminate CO_2 emission and led to carbon neutrality in their results. Nathaniel and Iheonu (2019) also estimated the contribution of non-renewable and renewable energy consumption in CO_2 elimination in Africa. An insignificant effect of renewable energy in CO_2 emission but a significant effect of non-renewable energy in increasing CO_2 emission was indicated from their study (Nathaniel & Iheonu, 2019; Wang et al., 2021).

Very few studies are found in the literature that studied the impact of renewable or non-renewable electricity production on the environment. For example, using the data for five south-east Asian countries, the study of Zeraibi et al. (2021) attempted to estimate the impact of renewable electricity production capacity, financial development, and economic growth and technology innovations on ecological footprints. Their findings revealed that technological innovation and higher capacity of renewable electricity production reduced ecological footprints, whereas economic growth and higher financial development increased the ecological footprints (Zeraibi et al., 2021). Jun et al. (2021) studied the effects of renewable energy production, income and globalisation on CO_2 emission by analysing the data of B.R.I.C.S. countries. Their results found the stimulating impact of globalisation, energy consumption and income on CO_2. Analysing the data of 25 O.E.C.D. countries, Ng et al. (2019) studied the causality between carbon emissions, renewable electricity, non-renewable electricity production and economic growth. According to their results, renewable electricity had an adverse impact on emissions whereas the reverse result was indicated for non-renewable electricity production. Furthermore, a bidirectional causal relationship was revealed for carbon emissions and renewable electricity as well as non-renewable electricity production (Ng et al., 2019). Analysing the data for China, Li et al. (2021) scrutinised the link between export diversification and renewable electricity output on CO_2 emissions. Their findings indicated renewable electricity production and export diversification were predicted to decelerate CO_2, supporting carbon neutrality in the long run (Li et al., 2021; The Phan et al., 2021). A similar attempt was made by Usama et al. (2020) to see the effect of renewable electricity and renewable electricity generation in affecting CO_2 emissions under the E.K.C. framework in Ethiopia. Their study had a surprising finding that both non-renewable and renewable electricity generation declined carbon emissions in Ethiopia (Usama et al., 2020). Hence the hypothesis is established as:

Hypothesis 2: Renewable and non-renewable electricity production affect CO_2 emission significantly.

Existing literature extensively studied different relationships between eco-innovations, renewable/non-renewable energy consumption and CO_2 emission, but the impacts of renewable and non-renewable electricity production on CO_2 emission has not been investigated extensively by the previous studies. Similarly, none of the aforementioned researchers studied highly polluted economies except (Ali, Dogan et al., 2021), but they overlooked the role of renewable and non-renewable electricity production in top polluted countries. Therefore, the present study estimates the effect of electricity production on CO_2 emission in the high emitter countries (because of the significance of this sector as discussed in the introduction section), in the presence of E.K.C. by utilising the most recent data (1995–2019) and most novel econometric

Table 2. Description of the variables.

Variables	Measurement	Data Source
CO_2 emission (dependent variable)	Carbon dioxide emission (killo ton)	WDI
Eco-innovations	Environment- related technologies (% of all technologies)	OECD
Renewable Electricity	Renewable electricity net generation (billion kilowatt-hours)	EIA
Non-Renewable Electricity	Fossil fuel electricity net generation (billion kilowatt-hours)	EIA
Economic Growth	GDP per capita and GDP per capita square	WDI

Notes: Where, WDI = World Development Indicators, EIA = U.S Energy Information Administration OECD = Organization for Economic Co-operation and Development.

estimations that take cross-sectional dependence and slope heterogeneity issues into consideration, thereby contributing to the limited existing research on highly emitter countries.

3. Data and econometric methodology

In our study, data for the world's top 10 emitter countries (Canada, China, Iran, India, Japan, Russia, Germany, Saudi Arabia, South Korea, and the USA) over the period 1995 to 2019 is used for empirical estimation. CO_2 emission is the dependent variable whereas eco-innovations, renewable electricity and non-renewable electricity production, and economic growth are the independent variables of our study. Secondary sources are used to collect all the data of the variables. Measurement and data sources of the variables are provided in Table 2.

The functional form of the model is given as:

$$CO_{2it} = f(EINNOV_{it},\ RELEC_{it},\ NRELEC_{it},\ GDP_{it},\ GDP_{it}^2) \quad (1)$$

Where: i = cross-section, t = time

CO_2= Carbon dioxide emission

EINNOV = Eco-innovation

RELEC = Renewable electricity

NRELEC = Non-renewable electricity

GDP = Economic growth

GDP^2= Square of economic growth

The model in its econometric form is given as:

$$CO_{2it} = \beta_0 + \beta_1 EINNOV_{it} + \beta_2 RELEC_{it} + \beta_3 NRELEC_{it} + \beta_4 GDP_{it} + \beta_5 GDP_{it}^2 + \mu_{it} \quad (2)$$

3.2. Econometric methodology

3.2.1. Cross-sectional dependence (C.S.D.) test

Initially, this study employs the Pesaran (2004) C.S.D. technique to investigate the C.S.D. in the data because ignoring it in the analysis may increase the likelihood of forecasting errors and provide misleading findings. The H0 of the test is stated in eq (i) as follows;

$$H_0 \;=\; \rho_{ij} = corr\ (\mu_{it}, \mu_{jt}) = 0 \forall i \neq \quad \text{(i)}$$

Equations (a) and (b) express the Pesaran C.S.D. test as follows:

$$CSD = \sqrt{\frac{2T}{N(N-1)}}\left(\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\hat{\rho}_{ij}\right) \sim N(0,1)i,j \quad \text{(a)}$$

$$CSD = 1,\ 2,\ 3,\ 4\ldots\ldots\ldots10\ldots\ldots\ldots\mathrm{N} \quad \text{(b)}$$

$$M = \sqrt{\frac{2T}{N(N-1)}}\left(\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\hat{\rho}_{ij}\right)\frac{(T-k)\ \hat{\rho}_{ij}^2\ -E(T-k)\hat{\rho}_{ij}^2}{Var(T-k)\hat{\rho}_{ij}^2} \quad \text{(c)}$$

$\hat{\rho}_{ij}^2$ uses the Ordinary Least Square regression to investigate the residual pair-wise correlations from sample estimates (Usman et al., 2021).

3.2.2. Slopomogeneityety test

In panel data, slope heterogeneity is a significant issue that might undermine the panel estimator consistency. Therefore, before proceeding to empirical estimation, our study applies the slope homogeneity test proposed by Pesaran and Yamagata (2008). The equations of slope heterogeneity test for $\tilde{\Delta}$ and $\tilde{\Delta}_{adj}$ are as follows:

$$\tilde{\Delta} = \sqrt{N}\left(\frac{N^{-1}\tilde{S}-k}{\sqrt{2k}}\right) \quad \text{(d)}$$

$$\tilde{\Delta}_{adj} = \frac{\sqrt{N}[N^{-1}\tilde{S}-E\tilde{Z}_{it}]}{\sqrt{Var(\tilde{Z}_{it})}} \quad \text{(e)}$$

3.2.2.1. Panel unit root tests. The traditional tests for unit root assume no C.S.D. and slope heterogeneity in models and lead to erroneous conclusions. Therefore, our study applies a second-generation C.I.P.S. test (Pesaran, 2007), which addresses the issues of C.S.D. and heterogeneity of slope parameters. The following equation is used in the C.I.P.S. test:

$$\Delta y_{it} = \alpha_i + \rho_i^* y_{it-1} + d_0 y_{t-1} + \sum_{j=0}^{p} d_{j+1}\Delta y_{t-j} + \sum_{k=1}^{p} c_k \Delta y_{it-k} + \varepsilon_{it} \quad \text{(f)}$$

where, Δy_{it} indicates the averages of the cross-sections. The preceding equation yields a Cross-Section Augmented Dickey-Fuller (C.A.D.F.) test. We might get C.I.P.S. by using the C.A.D.F. value.

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

In addition, we also applied the second-generation test introduced by Bai and Carrion-I-Silvestre (2009) as this technique can handle many structural breaks in heterogeneous panels. Breaks are permissible at the slope, level, or both for different time periods for varying magnitudes of change. A modified Sargan-Bhargava (M.S.B.) test for each series is pooled by this technique. After including several breaks at the structure for every series and common elements, three pooling statistics result in three distinct test statistics: Z, individual statistics standardisation, P and Pm combining their p values. Monte Carlo simulations confirm that these tests perform well in infinite samples (Nasreen et al., 2020).

3.2.2.2. Cointegration analysis. The study applies the co-integration estimation offered by Westerlund and Edgerton (2008) and Banerjee and Carrion-i-Silvestre (2017). These estimators have the property of incorporating cointegration identification with breaks at the structure and deal with the issues of C.S.D., correlated error terms and slope heterogeneity. Similarly, Banerjee and Carrion-i-Silvestre (2017) developed a cointegration technique that ensures both weak and strong C.S.D., as well as other issues such as panel data non-stationarity, heterogeneity and the parameters consistently estimating the values in case of false regression constructs. The C.C.E.M.G. is the foundation for this technique (Shao et al., 2021).

3.2.2.3. C.S.-A.R.D.L. analysis. For long-run and short-run results, we select C.S.-A.R.D.L. approach developed by Chudik and Pesaran (2015) as for numerous reasons, this strategy is preferable to the common correlated mean group (C.C.E.M.G.), mean group (M.G.), pooled mean group (P.M.G.), as well as an augmented mean group (A.M.G.). However, the primary characteristics that set it apart from the previously described methodologies are: (1) it performs well both in endogeneity and heterogeneity; (2) It is beneficial to assure efficient results in C.S.D.; and (3) It is able to operate well when structural breaks are present. It includes a cross-sectional mean to deal with cross-section unit dependency. The following is the equation form of the model:

$$\Delta CO2_{it} = \emptyset_i + \sum\nolimits_{l=1}^{p} \theta_{il}\Delta CO2_{it-l} + \sum\nolimits_{l=0}^{p} \theta'_{il}X_{it-l} + \sum\nolimits_{l=0}^{1} \theta'_{il}Z_{it-l} + \mu_{it} \qquad \text{(h)}$$

where $Z_t = (\Delta CO2t, Xt)'$ and X_{it} is the set of independent variables (GDP, GDP^2_{it}, $RELEC_{it}$, $NRELEC_{it}$, $EINNOV_{it}$).

3.2.2.4. Common-Correlated Effects Mean Group and Augmented Mean Group estimation. For cross-validation of the coefficient estimation, A.M.G. and C.C.E.M.G. estimators are employed in our empirical analysis. However, these approaches can only forecast long-run elasticities and test the robustness only in the long run. Bond and Eberhardt (2013) presented the A.M.G. estimator, which is a two-step procedure that addresses C.S.D. and slopes heterogeneity concerns.

$$\text{AMG} - \text{stage 1}: \quad \Delta y_{it} = \alpha_i + b_i\Delta x_{it} + c_i f_i + \sum\nolimits_{t=2}^{T} d_t \Delta D_t + \varepsilon_{it} \qquad \text{(i)}$$

$$\text{AMG} - \text{stage } 2: \ \hat{b}_{AMG} = N^{-1} \sum_{i=1}^{N} \hat{b}_i \tag{j}$$

where, f_t denotes common factor (unobserved), while x_{it} and y_{it} represent the observables. Country specific coefficient estimation is represented by b_i, d_t are the time variable dummies, and $\hat{b}_{AMG}$ denotes A.M.G. estimator. C.C.E.M.G. estimation proposed by Pesaran (2006) takes C.S.D. into consideration.

Equation (i) is combined as follows before obtaining the coefficients:

$$y_{it} = \delta_0 + \delta_1 x_{it} + \varepsilon_{it} \tag{k}$$

where y_{it} represents unemployment, x_{it} is the explanatory variables vector and multifactor residual expression is denoted by the residual term (e_{it}). The residual terms for multifactor variables are built as follows:

$$\varepsilon_{it} = \lambda'_i UF_i + u_{it} \tag{l}$$

where, UF_t = m x 1 vector of unknown common factors. Pesaran (2006) also use cross-section means, $y_t = \frac{1}{N} \sum_{i=1}^{N} y_{it}$ *and* $x_t = \frac{1}{N} \sum_{i=1}^{N} x_{it}$ to deal with residuals as visible proxies for common causes with C.S.D. The slope coefficients and cross-sectional mean of slope coefficients are then regressed in the following way:

$$y_{it} = \delta_0 + \delta_i x_{it} + \alpha y_t + c x_t + \varepsilon_{it} \tag{m}$$

Pesaran (2006) denotes the computed Ordinary Least Square estimator. C.C.E. of the coefficients for slopes individually. Bi = (δ1, ., δn) as the C.C.E. estimator.

$$\hat{B}_{iCCE} = \left(Z_I \ \ D Z_i \right) Z'_i \widehat{DY}_i, \tag{n}$$

Where Z_i= (z_{i1} to z_{iT})′, z_{it}=(x_{it})′, y_i = (y_{i1} to y_{it})′, $D = I_T - H \ \ (H' H)^{-1} \ \ H H = (h_1, \ h_2, \ \ldots, \ h_t) = h_t = (1, y_t, \ x_t)$ are the CCE estimators. The average of the different estimators for C.C.E. gives the C.C.E.M.G. estimator, which is calculated as follows:

$$\hat{B}_{CCEMG} = \sum_{i=1}^{N} \hat{B}_{i,CCE} \tag{o}$$

4. Empirical findings and discussion

At the start of empirical analysis, we applied the C.S.D. test for the confirmation of the presence or absence of C.D.S. among the variables. Pesaran (2004) C.S.D. test results are provided in Table 3.

The p-values of the related variables are statistically significant confirming the existence of C.S.D. among the variables. Hence, H0 of no C.S.D. among variables can easily be rejected.

Table 3. CSD results.

Variable	Test statistics (*p*-values)
CO_2	16.133*** (0.000)
NRELEC	22.119*** (0.000)
EINNOV	19.232*** (0.000)
RELEC	21.118*** (0.000)
GDP	22.311*** (0.000)
GDP^2	23.178*** (0.000)

Notes: *, ** & *** shows significance at 10, 5, and 1% levels respectively, whereas P values are given in parentheses.

Table 4. Slope heterogeneity test results.

Explained variable: CO_2 emission	
Statistics	Test value (*p*-value)
Delta tilde (Δ)	45.189*** (0.000)
Adjusted delta tilde (Δ adj)	62.146*** (0.000)

Notes: Where, ***, ** & * shows significance at 1, 5 and 10% level, whereas parentheses contain P-value.

Next, we applied the slope homogeneity test to check the homogeneity of the slope parameters. For this, delta (Δ) and adjusted delta (Δ adj) is computed to estimate the H0 of the homogenous slope against the H1 of the heterogeneous slope. Table 4 shows that H0 of homogeneous slope can be rejected in favour of the H1 of the heterogeneous slope. As a result, there is a slope heterogeneity issue that varies throughout the top emitter countries.

After the confirmation of the presence of C.S.D. and heterogeneous slopes, we preferred to apply the second generation panel unit root test like the C.I.P.S. test and Bai and Carrion-I-Silvestre (2009) test that give the robust estimation in the presence of slope heterogeneity and C.S.D. among variables. Table 5 gives us the results of panel unit root tests.

Pesaran test results indicate that all variables are level stationary, while estimates of Bai and Carrion-I-Silvestre (2009) test indicate the non-stationarity of the variables at level that become stationary at first difference.

After knowing the order of integration, the next step is to test the cointegration among all the variables by Westerlund and Edgerton (2008) test which provide robust findings if the problems of heterogeneity and C.S.D. are present. Table 6 shows the cointegration test results indicating that all variables have the long-run cointegration (at intercept as well as at intercept and trend).

In addition, we carried out (Banerjee & Carrion-i-Silvestre, 2017) long run cointegration estimation and a steady relationship with constant and trend is confirmed for the entire sample as given in Table 7.

Next, we proceed to short-run and long run coefficients estimation through C.S.-A.R.D.L. model. Table 8 gives the long-run estimations of the C.S.-A.R.D.L. model. G.D.P., $G.D.P.^2$, R.E.L.E.C., N.R.E.L.E.C., and E.I.N.N.O.V. are evident to be the important determinants of CO_2 emissions in the top-emitting countries in the analysis.

Table 9 shows the short-run C.S.-A.R.D.L. coefficient estimation. Our results evidenced that all variables exert a statistically significant effect on CO_2 emission and except G.D.P. and N.R.E.L.E.C., all other variables have a mitigating effect on carbon

Table 5. Unit root test results: with and without structural break.

	I(0)			I(1)		
Variables	CIPS	M-CIPS			CIPS	M-CIPS
CO_2	−3.111***	−5.106**			–	–
GDP	−4.110***	−5.104**			–	–
REN	−4.100***	−7.012**			–	–
NREN	−3.148***	−6.204**			–	–
EINNOV	−4.010***	−8.709**				
GDP^2	−3.100***	−4.001**				
Bai and Carrion-I-Silvestre (2009)						
	Z	P_m	P	Z	P_m	P
CO_2	0.326	0.735	20.308	−4.055***	5.124***	54.043***
GDP	0.427	0.633	16.307	−3.025***	4.435***	64.047***
RELEC	0.493	0.567	14.075	−3.066***	5.298***	56.078***
NRELC	0.447	0.774	19.654	−4.470***	4.114***	73.047***
GDP^2	0.269	0.201	20.101	−5.065***	6.001***	80.011***
EINNOV	0.417	0.347	18.231	−3.210***	4.023***	57.051***

Notes: *, ** and *** shows the significance at 10, 5, and 1% level respectively.
Bai and Carrion-I-Silvestre (2009): for Z and Pm, the critical values 2.326, 1.645, and 1.282 for 1, 5, and 10% significance level respectively, whereas for P, critical values are 56.06, 48.60, and 44.90, separately.

Table 6. Westerlund and Edgerton (2008) cointegration results.

Test	Without break	Mean shift	Regime shift
Explained variable: CO_2 emission			
$Z_{\varphi}(N)$	−3.133***	−3.007***	−4.134***
P_{value}	0.000	0.000	0.000
$Z_{\tau}(N)$	−4.012***	−3.028***	−5.112***
P_{value}	0.000	0.000	0.000

Notes: Where, 10%, 5% and 1% significance level are denoted by *, ** and *** respectively, and parentheses contain P-value.

Table 7. Banerjee and Carrion-i-Silvestre (2017) cointegration results.

Economies	Without deterministic specification	With constant	With trend
Explained Variable: CO_2 emission			
Whole sample	−4.234***	−3.548***	−5.772***
China	−5.303***	−4.216***	−6.295***
Japan	−3.660***	−3.606***	−4.155***
Russia	−6.578***	−5.547***	−7.287***
South Korea	−4.103***	−3.364***	−5.276***
India	−3.016***	−3.000***	−4.176***
Canada	−5.663***	−4.721***	−6.278***
Iran	−6.355***	−5.350***	−7.120***
Germany	−4.038***	−3.496***	−5.123***
Saudi Arabia	−6.160***	−5.153***	−7.769***
United States	−3.019***	−3.001***	−4.246***

Notes: With constant, CV (critical value) at 10%* and 5%** is −2.18 and −2.32, whereas with trend CV are −2.82. and −2.92.

Table 8. C.S.-A.R.D.L. estimation (long-run results).

Variables	Coeff	t-stat	p-values
Explained variable: CO_2 emission			
GDP	0.200***	3.101	0.000
GDP^2	−0.273*	−1.696	0.091
RELEC	−0.342***	−4.517	0.000
NRELEC	0.253***	2.711	0.026
EINNOV	−0.244***	−3.010	0.043
CSD-Statistics	–	0.033	0.510

Notes: Where, *, ** and *** denotes significance at 10%, 5% and 1% respectively.

Table 9. C.S.-A.R.D.L. estimation (short-run results).

Variables	Coeff	t-stat	*p*-values
Explained variable: CO_2 emission			
GDP	0.187***	4.076	0.000
GDP^2	−0.035***	−3.011	0.000
RELEC	−0.085***	−4.732	0.000
NRELEC	0.103***	5.555	0.000
EINNOV	−0.056***	−4.089	0.000
ECT(−1)	−0.221***	−3.030	0.000

Notes: Where, *, ** and *** denotes significance at 10%, 5% and 1% respectively.

emissions both in the short and in the long run. Unlike, Mehmet et al. (2015), Al-Mulali et al. (2015), Jebli and Youssef (2015) and Mert and Bölük (2016), who did not find any evidence for the validity of E.K.C. hypothesis in their studies, an inverted U-shaped link between economic growth and environmental deterioration (E.K.C.) is found in our analysis as the coefficients for G.D.P. and G.D.P.^{2} change the sign from positive to negative. Our finding supports the argument that in the early development stages, countries focus on energy intensive productive activities that result in high rate of emissions. But, after reaching a particular development level, countries start focusing on environmental quality improvement and start spending a considerable sum of money on environment-friendly technologies and renewable energy resources that result in long-run lower emissions (Hao et al., 2021). From existing literature, Haseeb et al. (2018), Chien, Anwar et al. (2021), Bekhet et al. (2020) and Ahmad et al. (2021) validate our findings.

Next, green innovations are found to have negative impact on CO_2 emissions both in the short and long run C.S.-A.R.D.L. analysis, leading to argue that pollution is reduced by the adoption of environmentally friendly and efficient technologies which enhance environmental quality in turn. It indicates that all pollution prevention (harmful material discharge prevention), waste management, clean technologies (advanced techniques of production) and remediation technologies have a positive effect on the environment and these technologies potentially transform the manufacturing structure from non-renewable to renewable energy consumption and drop CO_2 emission level (Anwar, Sinha et al., 2021; Hao et al., 2021). Furthermore, the increased emphasis by state and industry on R&D aimed at generation of environmentally friendly capital goods enhances the efficiency of industrial technology that uses less energy (Salem et al., 2021; Sun et al., 2021). The findings of our study are in line with the findings of preceding empirical studies of Hao et al. (2021), Du et al. (2019), Liu et al. (2020), Mongo et al. (2021), Ji et al. (2021) and Ali, Dogan et al. (2021) but negate to Dauda et al. (2019) for B.R.I.C.S. countries as they concluded that overhead production cost of green technologies make it difficult for emerging economies to incorporate these technologies in their early phases of clean production development. Our findings are also in contrast with Khattak et al. (2020) who believed that the production-focused innovations, using unsustainable sources of energy as fuels for economic growth causes increase in CO_2 emission. Raiser et al. (2017), Ali et al. (2016) and Santra (2017) also negate our finding.

Finally, as expected, R.E.L.E.C. is found to reduce CO_2 emission whereas N.R.E.L.E.C. is found to increase CO_2 emission both in the short and in the long run

Table 10. Robustness analysis results (A.M.G. and C.C.E.M.G.).

	(AMG)			(CCEMC)		
Explained Variable CO_2 emission	Coeff	t-stat	*p*-values	Coeff	t-stat	*p*-values
GDP	0.045***	4.011	0.000	0.127***	7.110	0.000
GDP^2	−0.069**	−1.954	0.053	−0.247***	−5.142	0.000
RELEC	−0.126***	−3.547	0.000	−0.156***	−2.951	0.001
NRELEC	0.201**	2.323	0.041	0.258***	3.741	0.000
EINNOV	−0.092***	−2.537	0.000	−0.219***	−4.443	0.000
Wald test	–	22.42	0.000	–	15.055	0.000

Notes: *, ** and *** represent 10%, 5% and 1% significance level, respectively.

in contrast to Al-Mulali et al. (2015), Farhani and Shahbaz (2014), Mehmet et al. (2015) and Usama et al. (2020) but in line with Li et al. (2021), Oryani et al. (2021), Bento and Moutinho (2016) and Ng et al. (2019) for O.E.C.D. These studies claim that N.R.E.L.E.C. pollutes the environment, whereas R.E.L.E.C. is a vital cure for environmental concerns. This suggests that use of renewable energy, especially in the generation of electricity can be a feasible alternative to reduce CO_2 emissions in top emitter countries.

Last, the C.C.E.M.G. and A.M.G. methods are also employed for the robust estimation. The coefficient signs for the long run in A.M.G., C.C.E.M.G., and C.S.-A.R.D.L. techniques are strikingly similar but the magnitudes are rather dissimilar. The magnitudes of the C.S.-A.R.D.L. technique are greater than the A.M.G. and C.C.E.M.G. model. The A.M.G. and C.C.E.M.G. methods also show that all variables have a significant (positive or negative) impact on CO_2 emission. (Table 10)

5. Conclusion and policy recommendations

Energy is referred as a key driver of economic growth which is not without its deleterious environmental effects. Therefore, in the contemporary era of fast industrialisation and growing energy demand, environmental sustainability insurance has become an important macroeconomic agenda all over the world. In this regard, utilisation of renewable energy resources as the alternatives for the non-renewable resources is deemed necessary. Extensive research has been conducted on the energy generation, energy consumption, economic development, and environmental pollution. However, the current study differs by estimating a new factor, i.e., electricity production from renewable and non-renewable resources. To our knowledge, the world's top emitter countries did not get much attention in terms of electricity production and eco-innovations in the literature despite being the largest electricity producing and highest CO_2 emitting countries. Against this backdrop, our study estimated the effect of R.E.L.E.C., N.R.E.L.E.C. and E.I.N.N.O.V. on CO_2 emission in world's top emitter countries over the period from 1995 to 2019. The study also estimated the validation of E.K.C. hypothesis in the studied countries. Our study revealed that R.E.L.E.C. and E.I.N.O. are significantly and negatively but R.E.L.E.C. is positively related to CO_2 emission. Moreover the E.K.C. hypothesis is proved to be valid in these countries as the coefficient of G.D.P. and G.D.P. square changes the sign from positive to negative.

Our findings are robust to various policy implications. Because of the increase in population and income, energy demand is expected to double by 2030. As coal is responsible for almost 68% to 94% of global emissions, massive use of coal for electricity generation will have a severe negative effect on the environment. Thus, the governments should promote energy mix diversification not only on supply side, but on demand side also. Furthermore, the less utilisation of renewable energy to generate electricity in top emitting countries shows the slow pace toward a coal-to-renewable-energy shift. It necessitates that special arrangements must be made by the government and policy practitioners. For example green-energy measures, e.g., the New Policies Scenario (2000–2040) must be adopted to diversify the energy mix and minimise coal share of electricity production. Supportive packages must be launched including 'zero tax concessions'; i.e., governments should levy taxes on fossil fuels in order to minimise CO_2 emissions. There should be gradual fossil fuel price liberalisation (to become equal to international level), and reallocation of financial resources from subsidy reform for investment in clean electricity generation. Moreover, soft loan (with interest rate lower than the market), interest holidays and long payment periods must be offered in renewable electricity sector.

More specifically, government of each top emitting country should pay more attention to its most abundant renewable energy sector in order to ensure its maximum utilisation in electricity production. In this regard, reducing the cost of that renewable energy project installation can be a good initiative, along with transferring tax-related benefits from non-renewable to renewable power resources. This will lure not only the local companies but also attract foreign investors to increase their investments in the renewable electricity projects. Enough funds should be granted by the governments for renewable power sector. Banks should provide interest rebates on household loans for installation of renewable applications for example, solar water heaters, solar lights, P.V. panels in homes. Income tax rebates should also be given to the households for renewable applications. Moreover, policymakers should start paying more attention to R&D spending, which will result in significant innovations in the field of renewable electricity, which will help to reduce carbon emission. More funds should be allocated for research and education in renewable electricity sector. In developing high emitter countries, the required finance for the research activities can be obtained through joint venture agreements or other means (public private partnership) or getting financial support and technical assistance from international institutions such as the Organisation of Petroleum Exporting Countries (O.P.E.C.), the International Monetary Fund (I.M.F.), and the Asian Development Bank (A.D.B.). Another major finding of our research is the significance of eco innovation in improving environmental quality. As a result, policymakers should design policies that encourage investment in ecologically friendly technologies. Furthermore, the government should introduce new projects and support research and development in ecologically friendly technologies. Initialising new environmental innovative programs with the partnership of the private sector can also be a good initiative in this regard.

Notes

1. To attain a sustainable future, the U.N. developed the 2030 Agenda for Sustainable Development in 2015, which contains the S.D.G. The seventh goal, S.D.G.7, is to 'ensure

everyone has access to reliable, affordable, modern and sustainable energy'. It promotes a more widely available and more sustainable energy system. Five targets and seven indicators are defined by United Nations for S.D.G.7. The targets include: increase the renewable energy proportion in energy mix, energy efficiency improvement, and to encourage investment in clean energy technology, etc., by 2030 (Zhong et al., 2021).

2. Economic growth affects environmental quality through scale effect, composition effect and technique effect. According to scale effect, as the economy becomes more economically active, more resources are consumed and waste is generated that accelerate environmental damages. The composition of the economy also has an impact on environmental quality. Industry or manufacturing has more polluted activities than agriculture or services sector. The composition effect may exert a positive or negative effect on environmental quality, as evidenced by the economy's structure. Finally, because cleaner production processes are employed as income rises, the technique effect is helpful to the environment. As income rises, public spending on environmental regulation and cleaner innovations rises, causing the private sector to expand its spending on mitigation technologies (Bibi & Jamil, 2021).

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