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RESEARCH ARTICLE

An investigation on the role of electric vehicles in alleviating environmental pollution: evidence from five leading economies

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Abstract

The relationship between battery electric vehicles (BEV) and carbon dioxide emission (CO_2) has significant environmental outcomes. Notwithstanding, battery electric vehicles have not been extensively explored through econometric approach. For countries to meet their net zero targets, it is crucial to consider the role of battery electric vehicles, renewable energy consumption, and CO_2. As a result, it is critical to scrutinize a variety of variables that contribute to a sustainable future. This study therefore examines the dynamic correlation between BEV, gross domestic product (GDP), urbanization (URB), renewable energy consumption (REC), population (POP), and CO_2 in five leading countries (the United States of America (USA), China, France, Germany, and Norway) using panel data from 2010 to 2020. The study adopted the Westerlund cointegration method to ascertain the long-term nexus among the series. The cross-sectionally augmented autoregressive distributed lag CS-ARDL technique is adopted to evaluate the variables long-run elasticity. The study applied the common correlated effect mean group (CCEMG) and augmented mean group (AMG) approach to ascertain the robustness of the long-run relationships among the variables. Dumitrescu and Hurlin's panel causality analysis determines the extent of the significant causality linkage. The results demonstrate that increased economic growth, urbanization, and population growth accelerate carbon emissions and environmental depletion. However, BEVs were found to be more energy efficient and the adoption of renewable energy through the manufacturing and battery production process would reduce CO_2 emission especially in China and the USA. Finally, the research proposed several policy implications for policy and decision-makers in the five leading countries for combating climate change and increasing productivity in the electric vehicle market and renewable energy consumption.

Keywords Battery electric vehicle · Carbon emissions · Renewable energy · Urbanization

Introduction

The goal of keeping global climate change to less than 2 °C has become the de facto primary objective of international climate change policy. Such objectives necessitate regions around the world to implement transition policies. The drastic greenhouse gas (GHG) emissions such as CO_2 reductions necessitate the widespread adoption of low-carbon technologies in all aspects of the economy (Lamb et al. 2021). Although some industries, such as the electricity sector, are now making progress, others, such as transportation face considerable challenges (Xu et al. 2021). According to Hao et al. (2016), road vehicles account for most emission levels, and the latest estimates show that the passenger fleet of vehicles will be more than double by 2050. Although intervention is necessary across all energy industries to achieve carbon neutrality, reducing emissions, especially from the transportation industry, is critical to meeting the emissions reduction objectives (Xu et al. 2021).

However, a number of other factors contribute to the rise in CO_2 emissions. For instance, population growth, urbanization, and GDP are extensively researched in literature as

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some of the contributory factors (Salari et al. 2021; Koengkan et al. 2021). As a results, minimizing CO_2 emissions from transportation is expected to be particularly challenging, but technological advances such as electric vehicles, herein, refers to as battery electric vehicles (BEVs) tend to substantially improve CO_2 emission mitigation in the automobile industry (Hawkins et al. 2013; Andersson and Börjesson 2021). In addition, Xu et al. (2021) and Andersson and Börjesson (2021) have stated that limiting vehicle fuel and energy carbon densities provides the best opportunity for high-emitting regions to dramatically lower CO_2 emissions emitted by the transport industry.

This research examines the most recent developments of carbon emissions in the United States of America (USA), China, Germany, France, and Norway. These countries have been chosen based on the statistics on electric vehicle sales and CO_2 emissions over a period of time. The USA, China, France, and Germany are among the highest emitters of CO_2 and accounted for over 60% of final passenger car sales in 2016 (Statistics 2017), while Norway accounts for the highest shares of electric vehicles in the world (IEA 2022). Thus, examining the diversity across various automotive marketplaces helps to understand the transport industry's role in reducing vehicle CO_2 emissions.

Carbon emissions in China increased by 1.7% in 2020, well below the 3.3% average over the past decades, reaching almost a billion metric tons, an indication of China's high dependency on fossil fuel (Grant et al. 2021). In contrast to China, the second-highest CO_2 emission country, the USA, decreased by 11% in 2019, the lowest level since 1983, due to Covid 19 lockdowns and restrictions (EIA 2021). The EU countries such as Germany, France, and Norway also have been gradually declining in recent years especially in Norway where renewable energy mix is paramount; for instance, according to the European Environment Agency (2021) in 2020, CO_2 emissions in the European Union were lower than (31%) compared with 1990 levels, achieving the EU's climate objective by 11% indicating an ultimate decline of 124.9 million tons of CO_2 equivalents as indicated in Fig. 1.

The electric vehicle (EV) is a technological innovation that has the potential to change the global transportation industry by offering more eco-friendly and socially responsible transportation options, thereby improving air quality, greenhouse gas emissions, and health hazards. Recently, EVs have been regarded as an incredible option to the traditional transport system as countries worldwide, through policy instruments, are shifting towards BEVs (Ajanovic and Haas, 2019). According to the literature, BEVs have a much more productive powertrain, cheaper to maintain, and emit no chemicals into the environment, at least not while on the road (Hawkins et al. 2013; Bekel and Pauliuk 2019). For these characteristics, BEVs are seen as a viable alternative

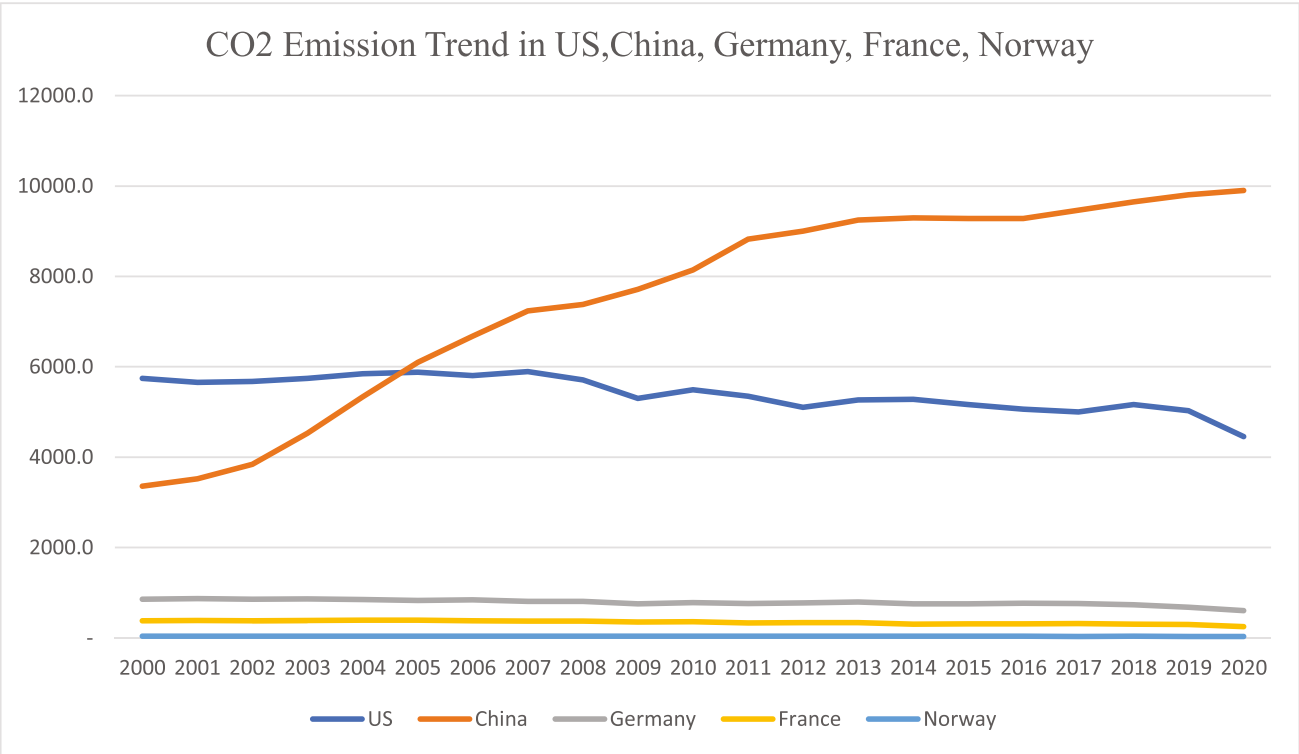


Fig. 1 Greenhouse gas emissions in the USA, China, Germany, France, and Norway between 2000 and 2020. (BP Statistical Review of World Energy, 2020) (Index 1990 = 100)

for limiting transportation-associated carbon emissions (Hawkins et al. 2013).

The penetration of battery electric vehicles in this study's sampled countries has prompted several scholarly works on integration into the power grid. However, a few studies use the macroeconomic and econometric methodology to measure the effect of CO_2 on BEVs and their related GHGs. These studies employ econometric approaches to determine the future increase in battery electric vehicles, as well their impact on energy utilization and the effect of gaseous emissions on the environment (Andersson and Börjesson 2021; Zhao et al. 2021; Gómez Vilchez and Jochem 2020). These econometric models as demonstrated in previous literature have shown that economic models can be reevaluated with multiple research variables. The implementation of these models in the current study, for instance, will guide the assessment of the correlation between carbon emissions, BEV adoption, GDP, urbanization, renewable energy demand, and population in this study.

Furthermore, including the sampled variables as inferential components of the environmental Kuznets curve (EKC) has attracted less interest from scholars. It is one of the most significant contributions of this study. This research is critical in determining the effect of CO_2-related GHG emissions. This is the first study to examine this impact in the USA, China, Germany, France, and Norway using macroeconomic indicators and an econometric method. The primary contribution of this research is to ascertain the role that battery electric vehicle penetration plays in the USA, China, Germany, France, and Norway and the implications it could have, with an emphasis on CO_2 emissions. The study also establishes a correlation between how CO_2 engages with BEV, urbanization, GDP, renewable energy consumption, and population in the five sampled countries, through an empirical assessment employing macroeconomic panel data from the countries mentioned above from 2010 to 2020. The research will benefit governments and decision-makers in developing additional measures to promote policies to reduce fossil fuel-based energy consumption, promote energy efficiency, and reduce environmental pollution. Lastly, this study can potentially expand a policy debate platform between governments, researchers, consultants, and industry, as an important step toward safeguarding that BEVs serve as a framework for combating climate change in the study countries and beyond. This survey seeks to bridge the gap by providing empirical evidence of how the sampled variables influence carbon footprint in the five countries. This study adopts the cutting edge second generational sectional dependence test (CSD) (Breitung 2000; Pesaran 2007). The study also employs three distinct techniques proposed by Westerlund (2007) to determine whether or not the variables have long-run relationships. The linear model cross-sectional-augmented autoregressive distributed lag (CS-ARDL) technique propounded by Chudik and Pesaran (2015) was adopted in the current study to assess the short- and long-run complexity estimators. The common correlated effect mean group estimator (CCEMG) and augmented mean group (AMG) proposed by Pesaran (2007) and Teal and Eberhardt (2010) as robustness check to the CS-ARDL technique were also used in this study. Finally, the novel technique (Dumitrescu and Hurlin 2012) was used to examine the correlation between the series.

We outline the remainder of the study as follows; related literature in the "Review of literature" section. The "Empirical methodology" section covers the methodology and data, and we explore the empirical results in the "Empirical results and discussions" section. The "Conclusion and policy recommendations" section includes a summary of the results and makes policy recommendations.

Review of literature

The literature will be discussed in this section exploring the linkage between carbon emissions (CO_2), battery electric vehicles (BEVs), GDP, population growth, urbanization, and renewable energy consumption.

Electric vehicles and CO_2 emissions

A body of research has explored the factors influencing the linkage between electric vehicles and CO_2 emissions, which comes in response to the exponential growth of electric vehicles in the last decade. Fuinhas et al. (2021) for instance, investigated GHG emissions and battery electric vehicles (BEVs) and discovered that BEVs could reduce CO_2 emissions compared to conventional vehicles. Furthermore, Xu et al. (2021) examined the causal relationship between the shares of electric vehicles and GHG emissions in eight electric vehicle markets using monthly data from 2009 to 2017 France, China, India, Germany, Japan, Norway, the Netherlands, and the UK. The authors adopted a quantile on-quantile regression technique, and the analytical results differed across the sampled countries. Overall, they observed that electric cars adversely influence GHG emissions, while CO_2 emissions have both a weak and positive effect on electric vehicles. As a result, there is mixed causality between the two variables. Kawamoto et al. (2019), however, using life cycle analysis to estimate CO_2 emissions from gasoline engines and battery electric vehicles (BEVs) in the USA, Japan, China, Australia, and the European Union, discovered that CO_2 emissions from BEVs manufacturing were higher than those from internal combustion engines vehicles as a result of the increased CO_2 emissions from battery production from nonrenewable sources. However, in geographic areas where renewable resources are highly utilized to generate electricity, the operating expense CO_2 emissions of

BEVs drop below those of ICEV as vehicle lifetime driving time increases (Gómez Vilchez and Jochem 2020).

Gross domestic product and CO_2 emissions

Economic growth necessitates energy to boost productivity; GDP contributes to CO_2 emissions and environmental pollution (Gong et al. 2020; Murshed et al. 2020). Based on Simon Kuznets' curve, the environmental Kuznets curve (EKC) hypothesis establishes a conceptual framework for investigating GDP and environmental degradation. According to the EKC, increases in GDP result in higher CO_2 emissions up to a particular threshold, where the increase in GDP after this tipping point results in environmental advancements. As a result, multiple investigations have examined the EKC hypothesis. For instance, Du et al. (2018) surveyed 71 countries from 1996 to 2012, confirming the EKC hypothesis. Similarly, Kacprzyk and Kuchta (2020) assessed the EKC for 161 countries, and the findings supported the EKC hypothesis. Investigations such as Munir et al. (2020) which used the fully modified ordinary least square (FMOLs) and the dynamic ordinary least square (DOLS) for five Asian countries, also supported the EKC hypothesis. Furthermore, an investigation conducted among the BRICS nations by Cheng et al. (2019) concluded that GDP growth is directly proportional to CO_2 emissions; as CO_2 emissions rise in tandem with economic activities. Furthermore, to investigate the EKC, Balsalobre-Lorente et al. (2018) evaluated the linkage between economic growth and CO_2 emissions in five EU countries from 1985 to 2016, and their empirical findings showed an N-shaped linkage between the countries' CO_2 emissions and economic growth.

Urbanization and CO_2 emissions

Several empirical pieces of research have analyzed the linkage between urban growth and carbon dioxide emissions in various geographical settings. In the existing literature, the EKC hypothesis, implying an inverted U-shaped linkage between economic growth and the environment, has indeed been extensively evaluated (Gokmenoglu and Taspinar 2018; Khan et al. 2019; Li et al. 2019; Usman et al. 2020). Similarly, a recent report by Xu et al. (2020) confirmed the EKC hypothesis by investigating an inverted U linkage between urbanization and greenhouse effects. According to Zhang et al. (2017), increased urbanization increases the energy demand for fossil fuels like coal and oil. Urbanization minimizes environmental efficiency by enhancing CO_2 emissions due to significant energy demand, particularly fossil fuel–based energy (Wang et al. 2020). According to Zhu et al. (2018), the negative impact of urbanization varies greatly across quantiles of urban growth, and in some investigations, the correlation between urbanization and carbon intensity is somewhat mixed or non-significant across geographic areas (Wang and Zhao 2018; Yu et al. 2020). These studies contentious results imply that the correlation between urban growth and the environment is not linear and may have a non-linear influence on environmental deterioration. Cui et al. (2017) explored the correlation between CO_2 emissions and socioeconomic factors, concluding that urbanization plays a significant role in CO_2 emissions.

Population growth and CO_2 emission

The universal popularity of growth in population and the associated energy demand and various environmental emissions are highly plausible. The enormous upsurge in population degrades biodiversity, reduces the quality of the environment, and reduces environmental capacity (Freedman 2014). Khan et al. (2021) explored the influence of population growth on GHG emissions in the USA employing data from 1997 to 2016; the results reveal population growth and CO_2 are unidirectional. Toth and Szigeti (2016), on the other hand, illustrated that population per se is not the source of air pollution and environmental hazards; instead, the population's components are to be blamed. Begum et al. (2015) on the contrary also ascertained the influence of population on CO_2 emissions by employing DOLS and the Sasabuchi-Lind-Mehleum U (SLM U) on Malaysia with data from 1970 to 1980 and observed that population growth had no substantial influence on environmental quality. However, they anticipated that the population growth might negatively influence CO_2 emissions in the Malaysian economy in the long term. Recent findings, such as Dong et al. (2018) and Mendonça et al. (2020), have revealed the positive relation between population and environmental pollution levels. According to Wood and Garnett (2009), on the Northern territory of Australia revealed that, urban population has a relatively higher environmental impact than the rural population. Another study in China used panel cointegration techniques to analyze data on CO_2 and population between 1999 and 2013. The results revealed an inverted U-shape nexus between population and CO_2. The study also discovered a positive correlation between the variables mentioned in the eastern part of the country and a negative one in China's western and central parts (Li et al. 2018).

Renewable energy use and CO_2 emissions

The influence of sustainable energy sources on ecological sustainability has become the center of energy policy debate across existing research scholarships (Hafeez et al. 2019). Bekun et al. (2019), for instance, employing the panel pooled mean group-autoregressive distributive lag technique (PMG-ARDL), discovered that renewable energy demand is inversely related to poor air quality in 16 EU countries. Also adopting the fully modified ordinary least squares (FMOL)

and the ordinary least squares (OLS) Sulaiman et al. (2020) study on 27 EU countries also found consistent outcomes, indicating that renewable energy has a positive effect on CO_2. Furthermore, Saidi and Omri (2020b) again adopted fully the FMOLS and vector error correction (VEC) models in investigating 15 OECD countries; the findings revealed that renewable energy demand, like nuclear mitigate CO_2 emissions. Dong et al. (2017) used the augmented mean group (AMG) technique for BRICS countries and found that a 1% increase in renewable energy consumption minimizes air pollution by 0.26%. The Eastern and Central European experience was investigated by Simionescu (2021) who, on the other hand, tested the EKC, and the econometric results demonstrated the non-linear relationship between renewables and CO_2 emissions. Renewable energy utilization is acknowledged to positively affect the environment by lowering CO_2 emissions in the atmosphere (Zafar et al. 2020).

Research gap

Several investigations have ascertained the influence of electric vehicles on carbon emissions in recent years; however, very few uses econometric approaches to examine the relationship between electric vehicles (BEV) and carbon emissions, particularly in the USA, China, Germany, France, and Norway. Only a few analyses have ascertained the role electric vehicle penetration plays in the USA, China, Germany, France, and Norway and the implications it could have on CO_2 emissions. Moreover, no studies have examined how CO_2 emissions engage the five variables: BEV, urbanization, GDP, population growth, and renewable energy consumption, through an empirical investigation using econometric series data from the sampled countries between 2010 and 2020.

The present investigation is a synthesis of the extant literature on energy growth and environmental degradation. However, integrating the battery-electric vehicle attribute into our econometric approach sets it apart from previous research. BEVs are predicted to improve environmental efficiency by minimizing CO_2 emissions. This research expands the EKC concept by investigating the link between the variables described above utilizing a linear relation centered on the economic expansion environmental pollution theory and the introduction of BEVs.

Empirical methodology

Theoretical underpinning

With the rapid penetration of electric vehicles and related carbon-cutting implications, it is widely assumed that electric vehicles generate fewer toxic emissions, particularly carbon dioxide emissions (CO_2) and enhance energy efficiency (Fuinhas et al. 2021). There is relatively sufficient verifiable research on the numerous advantages of electric vehicle adoption, and the benefits of battery electric vehicles (BEVs) have been generally acknowledged. Transportation-related emissions are rising in regions where mobility is still rising, and the power supply is fossil fuel–based (primarily in China, the USA, France, and Germany). Hofmann et al. (2016) assessed the influence of electric vehicles on CO_2 in China. According to the findings, electric vehicles can help lower CO_2, especially if the source of battery production is from renewable energy sources. In this study, the authors expect that the penetration of BEV will positively affect climate change and significantly reduce CO_2 emissions.

Empirical studies that use the Kuznets environmental curve assertions find a significant influence on economic growth and carbon emissions. In this scenario, Badulescu et al. (2020) on EU countries between 1995 and 2013, Panait et al. (2019) on 28 EU economies from 1995 through 2015, and Saqib and Benhmad (2021) on 22 EU member states all support the existing EKC theory. Others are opposed to this concept. For example, Sarkodie and Strezov (2018) found evidence verifying the EKC hypothesis using a linear model in their analysis of four major economies. Chen et al. (2019) found the model to be insufficient due to humans' limited rationality. Therefore, the present investigation examined the presence of EKC in the USA, China, Germany, France, and Norway using GDP and the quadratic term $(GDP)^2$. In this situation, we anticipate a U-shaped EKC hypothesis.

The linkage between economic growth and CO_2 emissions is complex, and such different research arrives at different conclusions; it has been discovered to come in the form of a line, an inverted U-shape, a U shape, and a variety of other shapes. A case in point is Sarkodie and Strezov (2019) who affirmed the EKC hypothesis as CO_2 and economic growth are linked in an inverted U shape in China and Indonesia. Balsalobre-Lorente et al. (2018) found an N-shaped EKC correlation between economic growth and CO_2 emissions using data from five EU countries from 1985 to 2016. However, in this study, we envisage that GDP would have a long-run positive impact on CO_2 emissions.

This research provides evidence for renewable energy consumption (REC) critical role in reducing carbon emissions and boosting economic growth. REC constituents such as solar photovoltaic, onshore and offshore wind energy, and hydroelectric power have been identified as the fastest innovative technologies and present a better alternative to fossil fuels such as coal. The Paris Agreement aims to address climate change over the next several decades through a combination of initiatives, including increased use of renewable energy (Anser et al. 2021, Anser et al. 2022; Khalid Anser et al. 2021). Saidi and Omri (2020a) in the case of 15 OECD economies from 1990–2018 concluded that renewable energy usage minimizes CO_2 in the

long run. As a result, the researchers of this study anticipate a positive linkage between REC and carbon emissions in the sample countries.

Ecological modernization hypotheses enhance the notion that it is hard to predict the long-term implications of urbanization. However, Salahuddin et al. (2019) investigated the influence of urbanization and globalization on South Africa from 1980 through 2017 revealed that urbanization increases CO_2. Using a panel data and macroeconomic model to estimate levels of CO_2 in the EU from 2000 to 2019, Busu and Nedelcu (2021) and Sampene et al. (2022) conclude that urbanization positively affects CO_2 emissions; thus, this study asserts that URB will have a positive interaction with CO_2.

Some studies such as Rehman et al. (2022) on Pakistan employing the Stochastic Impact by Regression on Population, Affluence and Technology (STIRPAT) and Asumadu-Sarkodie and Owusu (2016) on Ghana utilizing the VECM and the ARDL models from 1972 to 2013 concluded that population growth is critical to increasing CO_2 emissions. Recently, carbon emissions have become a major global issue, affecting food production and biodiversity and contributing to climate change. In most cases, regardless of which country of study, it is noted that population growth has a substantial influence on emissions. As a result, we anticipate POP to impact CO_2 positively.

Based on the EKC theory and consistent with previous literary works (Haldar and Sethi, 2022; Suki et al. 2020), the macroeconomic method used in this investigation is mathematically represented as follows (1):

$$CO2^{it} = f(BEV^{it}, GDP^{it}, GDP^{2it}, POP^{it}, URB^{it}, REC^{it}) \quad (1)$$

To improve the distribution and accuracy of the sample data, all study variables were converted to the natural log. The natural logarithmic conversion of the data sets aids in resolving heteroskedasticity and autocorrelation issues in the study data. The log-linear form of the CO_2 is represented mathematically as the follows:

$$InCO2^{it} = \phi_0 + \phi_1 InGDP^{it} + \phi_2 InGDP^{2it} + \phi_3 InBEV^{it} + \phi_4 InPOP^{it} + \phi_5 InURB^{it} + \phi_6 InREC^{it} \quad (2)$$

Such that, $\phi_1, \phi_2, \phi_3, \phi_4$, and ϕ_5 are the co-efficient of gross domestic product (GDP), square root of economic development (GDP^2), battery electric vehicle (BEV), renewable energy consumption (REC), urbanization (URB), and population (POP). *In* connote the data's natural log form, ϕ_0 serves as the constant term, and ε denotes the error terms of the model. Also, i represents cross-sections (USA, China, Germany, France, and Norway), and t denotes the study timeframe (2010 to 2020).

Variable and data source descriptions

Data spanning 2010 to 2020 for a panel of five leading EV and CO_2 countries: the USA, China, Germany, France, and Norway were collected for this study. The period was chosen according to data availability. The data for battery electric vehicles and carbon emissions were derived from IEA (2020) and BP (2020) respectively. Population, urbanization, renewable energy, and gross domestic product data were generated from WDI (2022). The approximate variables used in this study are economic growth (measured as GPD constant 2010 US$), total energy generated from renewable sources (calculated as million kilowatt-hours), and CO_2 emissions (quantified in units of metric tons equivalent per capita). The measuring system, symbols, and sources of data for the selected data sets are shown in Table 1.

Empirical estimation

Cross-sectional dependence test

The cross-sectional dependency (CSD) test must be explored during the first scenario of the panel survey to avoid spurious and misleading regression results. Growing associations cause CSD across sociodemographic frameworks and typical undisclosed shock, rendering traditional

Table 1 Variable and data source descriptions

Variable	Symbol	Description	Source
Carbon dioxide	CO_2	CO_2 emissions from fossil fuel (kt)	BP
Gross domestic product	GDP	Economic growth is the market value of the products and services produced within a country over a period of time	WDI
Urbanization	URB	Urban population (% of the entire population)	WDI
Renewable energy consumption	REC	% of total renewable energy consumption	WDI
Population	POP	% of the total population	WDI
Electric vehicles (BEV)	BEV	The total of registered BEV in the fleet	IEA

panel evaluation metrics ineffective. As a result, disregarding cross-sectional dependency test has serious consequences (Ertur and Musolesi 2017). Although unit root testing presumes cross-section dependency, it is preferable to work with CSD. Therefore, depending on approaches that accept cross-sectional dependency may result in erroneous outcomes. This study employs CSD to carry out this operation, pioneered by Pesaran (2007). The following is the CSD equation:

$$\mathrm{CSD}\sqrt{\frac{2T}{N(N-1)}}\sum_{i=1}^{N}\varphi_i\sum_{m=i+1}^{N}\partial_{im} \tag{3}$$

So that T denotes the time, N denotes the CSD in the model, ∂_{ij} indicates the statistical value of the m and i modules. Besides, the authors have employed a slope homogeneity test in our approach as propounded by Hashem Pesaran and Yamagata (2008). The test equation is tabulated as "adjusted delta-tilde and delta-tilde".

Second generation unit root test

The second-generation stationarity tests, named cross-sectional augmented Dickey-Fuller (CADF) and augmented cross-sectional Im Pesaran and Shin (CIPS) (Pesaran 2007), were employed in the study. The CADF and CIPS tests address CSD issues and spurious results in regression analysis. Furthermore, both stationarity tests assisted the researchers in determining the precision of the series' heterogeneity. The CADF equation is as follows:

$$\Delta x_{it}=\alpha_{it}+\beta_{it-1}+\delta_I T+\sum_{j=1}^{N}\gamma_{ij}\Delta x_{it-j}+\mu_{it} \tag{4}$$

Such that, x_{it} denotes the variables examined in the survey, Δ symbolizes the disparity between the variables, and μ_{it} portrays the error term.

The CIPS test statistics is mathematically represented in Eq. (5) as:

$$\mathrm{CIPS}=\frac{1}{N}\sum_{i=1}^{N}\varphi_i(N,T) \tag{5}$$

where $\varphi_i(N,T)$ implies CADF regression statistical test.

Panel cointegration test

A panel cointegration method is employed to calculate the long-run equilibrium linkage between two or more variables when the variables have a unit root.

The study employed the Westerlund (2007) cointegration technique to explore the series' cross-sectional dependency (CSD) and heterogeneity. The t statistics for the two major categories of this technique are defined by the Eqs. (6)–(8):

$$G_\tau=\frac{1}{N}\sum_{i=1}^{N}\frac{\eta_i}{S.E(\widehat{\eta}_i}} \tag{6}$$

$$G_a=\frac{1}{N}\sum_{i=1}^{N}\frac{T\eta_i}{1-\sum_{j=1}^{k}\widehat{\eta}_{ij}} \tag{7}$$

$$P_a=T\eta_i \tag{8}$$

As shown, G_τ and G_τ portray the group mean statistics, $P_\tau$and P_a stipulate the panel statistics, and $\widehat{\eta}_i$ suggests the change from short-run to long-run frequency symmetry.

Panel estimation approach

The study employed the CS-ARDL introduced by Chudik and Pesaran (2015) in the investigation to ascertain the short- and long-run projections. Compared with other forecasting models like the pooled mean group (PMG), the potency with the CS-ARDL produces more accurate outcomes, and the projections are robust. In addition, the CS-ARDL approach aid the resolution of heteroscedasticity, endogeneity, and linear relationship between the variables (Baydoun and Aga 2021; Huang et al. 2021). Chudik and Pesaran (2015) argued that the ARDL model is one of the most "heterogeneous panel data estimators." Still, the model typically did not find success to address CSD errors. In addition, various factors play a notable role in ascertaining the CSD, which may lead to some misleading output. In this regard, the methods entitled as CS-ARDL are feasible to apply whenever there is a presence of heterogeneity and the CSD among the variables of interest. (Chudik and Pesaran (2015) argued that CS-ARDL model basically grounds the ARDL model with the element of linear combination of average CSD. The reason is to capture CSD in error term. One of the key benefits in applying the CS-ARDL approach is that it deals with dynamic correlated effect estimator for various issues as expressed by Topcu and Çoban (2017). The CS-ARDL has a mathematical expression, which is shown in Eq. (9):

$$\Delta EVQ_{i,t}=\delta_i+\sum_{j=1}^{m}\delta'_{it}EVQ_{i,t-j}+\sum_{j=0}^{m}\delta'_{i}K_{i,t-j}+\sum_{j=0}^{1}\delta_i\overline{Z}_{i,t-j}+\mu_{it} \tag{9}$$

And so, the estimate of the cross-sections is depicted by $\overline{Z}_t=\left(\Delta EVQ_{i,t},\overline{X}_{t'}\right)'$ K denotes the model's descrip-

tive series, which includes CO_2, GDP, GDP^2, REC, BEV, URB, and POP.

Robustness test

The AMG and CCEMG models proposed by Teal and Eberhardt (2010) and Pesaran (2007) were also adopted in our research to ascertain the robustness of the short- and long-run estimation methods. In this investigation, the AMG and CCEMG modeling techniques are utilized as they are robust and produce unbiased and accurate estimates.

Panel causality testing

The study applied the Dumitrescu and Hurlin (2012) to ascertain the causality test among the variables under consideration, i.e., CO_2, urbanization, GDP, BEV, renewable energy consumption, and population. Therefore, the present study employed Dumitrescu and Hurlin (2012) who recognize the CSD challenge. The non-causality test for Dumitrescu and Hurlin (2012) considers the heterogeneous panels and CSD. In line with the panel causation test by Ahmad et al. (2022), the Dumitrescu and Hurlin was used to improve the causality diagnosis in this investigation. The panel causation testing technique is appropriate for exploring causal links in panel data because of its ability to evaluate and clarify heterogeneous challenges in panel data.

Empirical results and discussions

Descriptive statistics

Table 2 furnishes the general statistical information of the five leading BEV and CO_2 emissions countries for the data set between 2010 and 2020. The findings reveal the facts and figures comprising the median, minimum, mean, maximum, skewness, standard deviation, probability, kurtosis, etc. The total observation of the series is 567. The mean statistical results for the series indicate that $lnCO_2$ (6.713), lnGDP (9.024), In GDP^2(2.996) lnURB (72.820), lnBEV (3.031), lnREC(2.794), and InPOP (18.940). Furthermore, the variables investigated in this study had a relatively higher standard deviation depth. The normality of the data in this study was assessed using statistical results like Kurtosis, Jarque–Bera, and probability tests. Table 3 also shows all probability values are statistically relevant at 1%. As a result, it is advisable to reject the null hypothesis. Table 2 shows the survey's data sample is not normally distributed, indicating variations in the data collected.

Cross sectional dependency test

Existing research indicates that failing to address cross-sectional dependency (CSD) testing issues can result in inconsistencies, lack of credibility, prejudices, and ineffectiveness, all of which can lead to errors in the analysis (Baydoun and Aga 2021; Huang et al. 2021). As a result, this research utilizes three CSD testing approaches to test the dataset to answer the inherent problems of CSD in our study. Table 3 shows that all three CSD testing

Table 3 Summary of CSD test results

Series	Brecsch-Pagan LM	Pesaran-scaled LM	Bias-corrected scaled LM
$InCO_2$	158.450***	33.194***	25.90252***
InGDP	126.3986***	26.02752***	6.583***
$In(GDP)^2$	277.813***	59.884***	59.792***
InBEV	228.300***	48.813***	48.720***
InURB	95.884***	19.204***	19.111***
InREC	59.636***	11.098***	11.006***
InPOP	154.257***	32.257***	32.164***

***1% represents the significance level

Table 2 Descriptive statistics for countries and variables

Descriptive statistics	$INCO_2$	INGDP	INGDP2	INBEV	INPOP	INREC	INURB
Mean	6.713	9.024	2.996	3.031	18.940	2.794	72.820
Median	6.663	8.713	2.951	0.000	18.215	2.667	77.399
Maximum	9.200	11.541	3.397	12.720	21.087	4.348	82.900
Minimum	3.465	7.099	2.664	−4.605	17.893	1.064	35.877
Std. Dev	1.948	1.316	0.216	5.304	1.208	0.828	12.634
Skewness	−0.368	0.502	0.423	0.757	0.817	0.451	−1.691
Kurtosis	1.867	2.000	1.923	1.903	2.066	2.525	4.412
Jarque–Bera	7.987	8.787	8.199	15.290	15.516	4.5485	58.787
Probability	0.018	0.012	0.016	0.000	0.000	0.102	0.000
Observations	105	105	105	105	105	105	105

Table 4 The panel unit testing result for CADF and CIPS

Variables	CIP			CADF		
	Level	First-difference	P-Value	Level	First-Difference	P-Value
$InCO_2$	1.186	−3.897	0.000	0.291	−2.020	0.000
InGDP	0.151	−6.816	0.000	−0.978	−8.163	0.000
$InGDP^2$	0.066	−4.106	0.000	−1.333	−3.746	0.000
InBEV	1.676	−4.832	0.000	−1.310	−3.405	0.000
InURB	−1.419	−6.904	0.000	−0.104	−8.469	0.000
InREU	−1.549	−6.797	0.000	−0.110	−8.619	0.000
InPOP	1.501	−7.257	0.000	−0.542	0.8236	0.000

***1% represents the significance level

Table 5 Westerlund panel cointegration test

(Westerlund, 2007)		
	Z value	*P* value
G_τ	−5.022	0.000
G_a	2.164	0.332
P_τ	−6.064	0.000
P_a	0.528	0.752

approaches were significant at 1% based on the p-values, affirming that we must reject the null hypothesis concerning the validity of CSD among the cross-section of variables. The authors conclude that the sampled countries development have a relationship with GDP, CO_2, electric vehicles, urbanization, population, and renewable energy consumption, premised on these intriguing findings.

Panel unit root test

Furthermore, CIPS and CADF unit root testing were utilized due to their high performance in stationary checking, as demonstrated by several studies (Sun et al. 2021; Pesaran 2007; Westerlund 2007). Table 4 depicts the CADF and CIPS. It demonstrates that it is impossible to reject the null hypothesis at the level. All other series became stationary after the first difference I(1). The works of Adebayo et al. (2022) and Danish et al. (2019) have shown that it is crucial to analyze cointegration among the chosen variables after the cointegration.

Panel cointegration test

As shown in Table 5, this study utilizes the Westerlund panel cointegration testing procedure to combat cross-sectional dependence and heterogeneity among highly heterogeneous datasets from various countries. Table 5 shows the two categories of cointegration methods proposed by Westerlund (2007) and the corresponding two-panel statistics and probabilities. The findings show that both categories (G_t and G_a) are statistically significant, with an immensely substantial level of 1%. Nonetheless, these exciting findings show long-run cointegration between the variables in this research.

Panel long-run elasticity estimation

In switching to the core estimation of this study, Table 6 demonstrates the CS-ARDL approach employed in assessing the parameters. As shown in Table 6, the CCEMG and AMG estimators concur with the CS-ARDL result. Furthermore, the indications for all chosen variables are similar, confirming that the CS-ARDL findings employed in the analysis were robust. Table 6 shows a schematic description of the empirical findings from our research.

The EKC hypothesis is predicted to impact both GDP and CO_2 emissions. The findings of the coefficients in Table 6

Table 6 CS-ARDL, AMG, and CCEMG estimator panel regression estimation results

Parameters	CS-ARDL estimator		AMG estimator		CCEMG estimator	
	Coefficients	*P* value	Coefficients	*P* value	Coefficients	*P* value
InGDP	0.226	0.002	0.8671	0.001	0.207	0.001
$In(GDP)^2$	−3.148	0.000	−1.125	0.018	−6.506	0.000
InBEV	−0.105	0.000	−0.438	0.002	−0.541	0.000
InURB	0.121	0.000	0.208	0.000	0.628	0.000
InREC	−1.767	0.001	−1.178	0.001	−1.569	0.000
InPOP	5.247	0.000	3.155	0.000	6.051	0.000

show that GDP significantly affects CO_2 emissions at a 1% significance level. The estimates suggest that a 1% increase in LnGDP increases $LnCO_2$ by 0.226%. Again, the estimates indicate that a 1% increase in LnGDP squared minimizes $LnCO_2$ emissions by − 3.14%, respectively. The results show an inverted U-shaped EKC linkage between economic growth and CO_2 emissions in the sampled countries. Even though the sampled countries are mostly developed, overall economic activity is directly related to environmental degradation and climate variability as the tendency of energy demand mostly from nonrenewable sources generates more CO_2 emissions. Investigations by Fuinhas et al. (2021) on 29 European Union countries and Liu et al. (2020) on G7 countries also came to a similar conclusion; their works revealed that, growth in economic efficiency is statistically related to a rise in CO_2 intensity, compromising environmental quality.

The study discovered that increasing the share of electric vehicles on the road does not result in a massive increase in emissions; on the contrary, increasing the percentage of electric vehicles is advantageous for combating climate change. It is worth noting that CO_2 and BEVs have a negative correlation. Thus, the estimates indicate that a 1% increase in LnBEV will reduce $LnCO_2$ by 0.105%. The high penetration of BEVs in the sampled countries would mean achieving low-carbon emissions; however, the emission intensity of the energy consumed to power BEVs has a substantial influence on the perceived benefit and differs between the study countries. Adoption of BEVs, for instance, can result in significant savings in countries such Norway, where renewable energy makes for a significant share of the power mix. Nonetheless, as indicated by (Fuinhas et al. 2021) in countries where conventional source of energy makes for a significant component of the power mix, such as China and the USA. Pollution from charging BEVs might not mitigated whiles on the road. Therefore, the environmental consequences for these countries are likely to be negligible.

Ajanovic and Haas (2019) also share a similar view in their investigations that electric vehicles positively impact the environment; however, emissions vary depending on the vehicle's manufacturing and use. Again, Gómez Vilchez and Jochem (2020) in their research identified possible scenarios for the USA, Japan, China, India, Germany, and France. As a result, electric vehicles can help to reduce GHG emissions, but they must be powered by renewable energy.

Moreover, similar findings by Fuinhas et al. (2021) and Xu et al. (2021) indicate that BEV can reduce greenhouse gas emissions and energy consumption. The European Environment Agency, (2021), for instance, supports initiatives to minimize energy consumption and environmental pollution. According to the European Environment Agency (2021), the average BEV volume accelerated from 1200 kg in 2010 to 1700 kg in 2019. In contrast, average energy demand decreased from 264 to 150 Wh/km, implying that BEV is becoming significantly effective. Nielsen and Jørgensen (2000) in their study projected that between 2000 and 2030, electric vehicles would consume less energy (i.e., 0.23–0.10kWh/km) during this period. However, given the low participation, particularly in the sampled countries, the decrease in energy usage caused by BEVs is insufficient to combat GHG emissions. Therefore, regulations for electric vehicles should encourage high penetration among the populace, incentivize manufacturers, expand the shares of renewable sources, and increase the deployment of electric vehicles to mitigate carbon dioxide emissions.

Furthermore, the influence of URB can be understood by the concept that during the early phase of urbanization, the transport network of these countries has increased the market for electronic products and the total energy demand. These metrics raise the demand for conventional energy sources, which raises the country's carbon impact. Thus, the estimates indicate that a 1% increase in LnURB will maximize $LnCO_2$ by 0.105%. The findings support a significant linkage between urbanization and CO_2 emissions, implying that increasing urbanization levels significantly contribute to CO_2 emissions in the surveyed countries. The findings of this study is consistent with Adusah-Poku (2016) for 45 Sub-Saharan African countries and Ponce De Leon Barido and Marshall (2014) for 80 countries, both concluding that URB positively affects CO_2 emissions both in the long and the short run. Urbanization allows for the spread of technology and energy consumption, which accounts for the use of contemporary techniques in manufacturing processes, causing pollution and increasing CO_2 in the sampled countries. This necessitates a greater reliance on renewable energy demand and a more eco-sensitive approach to living, by advancing the campaign for higher penetration of BEV and sustainable form of living standards.

Again, regarding renewable energy consumption, the CS-ARDL estimator shows that this variable adversely influences CO_2 emissions as the study countries depend on coal and oil. Consequently, manufacturing companies in industrialized or semi-industrialized countries are more appealing and efficient in their production of goods and services and spur economic growth; however, this activity accelerates the use of non-renewable source of energy, thereby increasing pollution levels. Thus, the estimates suggest that a 1% increase in LnREC will minimize $LnCO_2$ by 0.105%. From an economical perspective, the fact that electric vehicles and renewable energy consumption reduce pollution necessitates immediate intervention by policymakers. Policymakers are encouraged to design and implement superior proportion of energy sources regarding environmental impact of fossil fuel consumption and the upsurge in greenhouse gas emissions. The rationale for this is because investing in renewable energy in the production of goods and services ensures that industries embrace fewer polluting technologies in their

manufacturing processes. It worth mentioning that, the policy consequence for the net zero ambition is that a better or maintained ecologically benign future would necessitate efficient renewable resource utilization (Koengkan et al. 2021). As a result, the study countries with renewable energy benefits and advantages should pursue a heterogeneous policy of increasing investment in BEV infrastructures and broadening the renewable energy resource base.

The study findings correspond with earlier studies that indicate that renewable energy consumption has a negative influence on CO_2 (Bekun et al. 2019; Saidi and Omri 2020a; Sulaiman et al. 2020).

Finally, the correlation between population growth and energy use explains the positive correlation between population and CO_2 emissions. Population growth raises energy usage in housing, industrial activities, transportation, and products and services, resulting in higher energy usage (Santamouris and Vasilakopoulou 2021). The estimates of this study showed that a 1% rise in LnPOP will increase $LnCO_2$ by 0.105%. The population and energy consumption correlation terms are inverse and significant, implying that CO_2 in regions with large populations, such as China and the USA grow more rapidly following energy consumption than in countries with a smaller population, such as Germany, France, and Norway. The results agree with Acheampong (2022) on Ghana, and Acheampong et al. (2019) on 46 sub-Saharan African countries, concluding that the rise in population growth is equivalent to high levels of carbon emissions (Fig. 2).

Dumitrescu and Hurlin causality test

The CS-ADRL technique offers the variables with short- and long-run estimates. Nonetheless, this approach fails to prove the linkage between the data series. The causality should be explored to prove organized and coordinated measures for stakeholders and policymakers. The study employed a new approach advocated by Dumitrescu and Hurlin (2012) to assess the causality between the employed variables as summarized in Table 7. The empirical findings show a unidirectional causal relationship between battery electric vehicles, urbanization, economic growth, and carbon emissions in the study countries. These results provide valid arguments that any policy path aimed at promoting economic growth and

Table 7 Results of D-H causality test

Null hypothesis	W-stat	Z-bar-Stat	Prob	Conclusion
InBEV ⇏ $InCO_2$	3.819	1.203	0.000	BEV → CO_2
In CO_2 ⇏ InBEV	1.041	-0.236	0.101	
InGDP ⇏ $InCO_2$	6.862	3.669	0.002	GDP → CO_2
$InCO_2$⇏ InGDP	3.810	1.196	0.231	
$InGDP^2$ ⇏ $InCO_2$	6.991	3.772	0.000	GDP^2 → CO_2
In CO_2 ⇏ $InGDP^2$	3.787	1.177	0.238	
InREC ⇏ $InCO_2$	5.24	2.355	0.000	REC ↔ CO_2
$InCO_2$⇏ InREC	4.177	1.493	0.000	
InPOP⇏ $InCO_2$	6.337	3.243	0.001	POP ↔ CO_2
$InCO_2$ ⇏ InPOP	4.634	4.261	0.000	
InURB⇏ In CO_2	6.201	3.132	0.000	URB → CO_2
$InCO_2$⇏ InURB	3.835	1.216	0.223	

→ reveal unidirectional causality, ↔ identifies bi-directional causality, and ⇏ indicates does not homogeneously cause

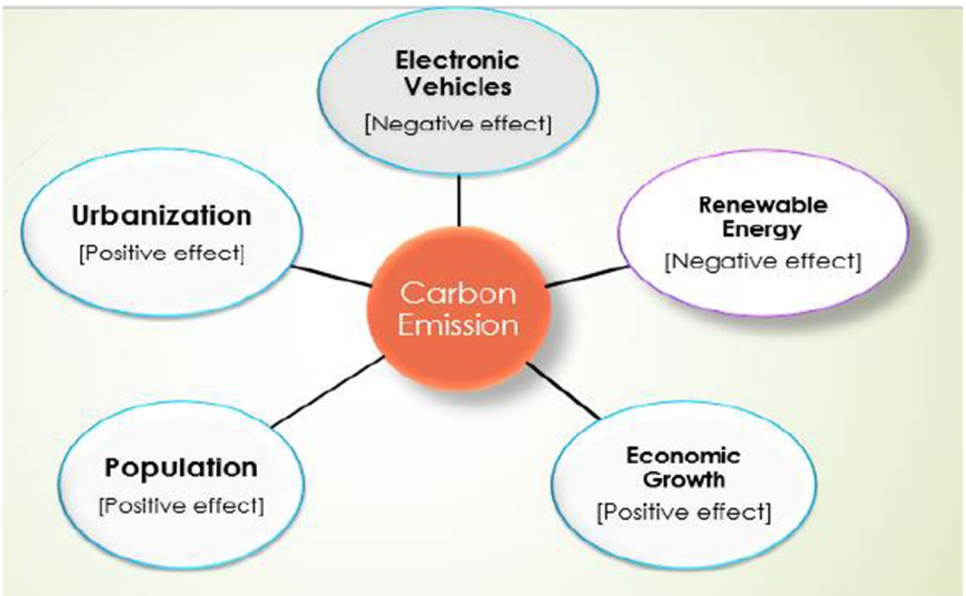


Fig. 2 Graphical representation of the outcome of the study

electric vehicles will remarkably minimize CO_2 emissions in China, the USA, Germany, France, and Norway. Furthermore, the D-H causality findings indicate a two-way causality between renewable energy consumption and CO_2 emissions, and population and CO_2 emissions respectively. The implication is that policy formulation focused on renewable energy consumption (REC), and population (POP), could mitigate CO_2 in the selected countries.

Conclusion and Policy recommendations

Conclusion

Decarbonization has emerged as a significant global challenge, attracting the attention of environmentalists, governments, and researchers to address this potential danger. Using annual data from five leading countries (USA, China, France, Germany, and Norway), this research explored the dynamic relationship between economic growth, battery electric vehicles, urbanization, renewable energy consumption, population, and CO_2. Theoretically, the research contributes to the growing knowledge on EKC and environment degradation indicators in the USA, China, Germany, France, and Norway. After acknowledging that cointegration exists among the series, the CS-ARDL approach was employed to predict the short- and long-run relations. This study summarized the findings as follows: (1) the study discovered a significant positive correlation between economic growth, population, and CO_2. (2) Battery electric vehicles, renewable energy consumption, and carbon dioxide emissions were discovered to have a negative relationship. (3) The panel D-H causality test demonstrates a unidirectional causal relationship that runs from economic growth, battery electric vehicles, and urbanization to carbon dioxide emissions. (4) The findings of D-H causality reveal a two-way causality among renewable energy consumption, population, and CO_2 emissions.

Policy implications

The following are the recommendations based on the empirical results of this survey to facilitate the adoption of sustainable technologies to ensure a more sustainable future. First, to build on the negative influence of BEVs on CO_2, the study proposes political ramifications for the five leading countries in increasing the commercial viability of BEVs and lowering CO_2. Furthermore, while the five leading countries have embraced a more sustainable transportation network, boosting BEV deployment still necessitates active stakeholders in planning in the short, medium, and long term to meet low-carbon emission pledges. Hence, to meet the objectives for decarbonizing the energy industry, BEVs have been recognized as a crucial technology for improving energy efficiency.

At the market level, the five countries should highly urge improved transformation of the automobile sector. Tax incentives and subsidies on purchasing battery electric vehicles can encourage mass adoption, resulting in enormous benefits. Furthermore, strategic national policy endorsement and constant improvement of businesses in the renewable energy industry are prerequisites for increasing battery-powered vehicle sales. As power-consuming devices, BEVs produce an electrical demand that renewable sources of electricity can fulfill. Furthermore, BEVs are an important storage option for fluctuating renewable energy sources such as wind and solar. Therefore, BEVs may be thought of as battery storage for stabilizing electric networks supplied by fluctuating renewable sources of energy, resulting in more sustainable power use. Another critical factor in increasing demand for BEVs is increasing investment in charging stations. Policymakers should also focus on raising consumer awareness about the benefits of adopting electric vehicles and decarbonizing power production.

Second, the study reported a positive and negative linkage between economic growth (GDP, GDP^2) and CO_2 emissions, respectively. The five countries utilize energy for production, and economic activities, to promote economic growth; however, increased production comes at the detriment of a sustainable environment. Therefore, we recommend governments, particularly in China, the USA, Germany, and France, to shift manufacturing operations and energy sources from fossil fuels toward sustainable energy and technologies if any constructive sustainable environmental objectives are to be met. This would promote cleaner and more sustainable environments while lowering carbon emissions.

Third, the findings indicate a negative correlation between REC and CO_2. Premised upon the discovery, the researchers propose that governments can mitigate the negative environmental impact of energy consumption by progressively transitioning to 100% renewable energy consumption. This is crucial for countries with high carbon dioxide emissions such as the USA and China. Larger organizations, for example automobile manufacturers, should establish and enforce laws to divert their portfolios to sustainable energies to replace fossil fuel usage, particularly in the USA and China, where oil and coal are the principal sources of primary energy. Furthermore, taxes on companies that consume large quantities of nonrenewable energy such as coal should be increased, which can be used as a cross-subsidy to limit dependence on coal and expedite the pace of renewable energy transition. Again, for the countries to attain their CO_2 emission objectives, policy initiatives such as energy efficiency and investment in low urban areas should be a top priority.

Fourth, as urbanization positively influence the environment, the study proposes smart infrastructure and electric drivetrains, which can help convert urban traffic to green transportation. This will also contribute to sustainable development through modern technological innovations and eco-friendly lifestyle habits such as solar lighting, battery-electric cars, e-bikes, and the use of more renewable power sources. It is crucial to decouple urbanization from CO_2 by increasing energy savings in residential and commercial spaces, particularly in the five countries.

Lastly, with the rapid population growth and considering the positive effect of population growth on carbon emissions in the sampled countries, this study suggest that the five countries should enforce energy efficiency. This could take effect at the household level, create suitable infrastructures, and policy response for sustainable population growth to mitigate the positive effect of URB on CO_2.

Limitation and future research

Although the present research has significant implications for policymakers, it also has some limitations which can be explored in future investigations. The current investigation only includes the top five global EV and CO_2 emitting countries, limiting the analysis. Again, our research design could not account for other important economic indicators such as electricity consumption, human development index, and research and development, which can influence CO_2 emissions to capture a broader contextual perspective. The authors intend to expand the research scope by integrating these variables and utilizing additional environmental concepts, like the STIRPAT model in future research. Relational variables like energy utilization and financial development could also be included to analyze the influence of these variables on carbon emissions in other territories.

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Declarations

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Consent to participate Not applicable.

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