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Research Article

Impact of economic growth, energy consumption, and trade openness on carbon emissions: evidence from the top 20 emitting nations

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ABSTRACT

The study focuses on the top 20 carbon emission-increasing nations across continents from 2000 to 2021 and the effects of gross domestic product, energy consumption, and trade openness on carbon emissions. The study uses a panel dataset and multiple linear regression analysis to pinpoint the significant factors influencing each nation's carbon emissions. The findings indicate that China, Kazakhstan, Saudi Arabia, and South Korea in Asia; Algeria, Egypt, Morocco, and the Seychelles in Africa; Antigua and Barbuda, Bolivia, Chile, and Panama in America; Albania, Belarus, Lithuania, and Russia in Europe; and Fiji, Samoa, Tonga, and Vanuatu in Oceania have a highly significant impact on carbon emissions in their respective regions. Energy consumption significantly increases carbon emissions in all countries except Panama and Kazakhstan, where it only significantly impacts GDP-related carbon emissions. These insights lay the groundwork for policymakers to prioritise sustainable development, reduce carbon emissions in their decision-making processes, and establish comprehensive strategies that reconcile ecological concerns with socioeconomic goals by understanding the intricate dynamics between gross domestic product, energy use, trade openness, and carbon emissions.

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Carbon emission; climate change; energy consumption; gross domestic product; sustainable development; trade openness

Introduction

Examining carbon emissions holds immense significance in understanding the path to sustainable development and identifying effective global mitigation strategies for carbon emissions (CE) (Andrew A. Alola, 2019; Khosla Radhika et al., 2017; Liu Lei et al., 2017; Peng & Deng, 2021; Sadiq et al., 2023). Due to the COVID-19 pandemic restrictions, CE from burning fossil fuels decreased in 2020; however, in 2021, CE increased by 6% annually, and global average carbon dioxide concentrations recently reached a new high of 413.2 parts per million (Lorente et al., 2023). In addition, given the historical data on countries contributions to CE, governments have recognised the need for differentiated responsibilities in addressing climate change (Althor Glenn et al., 2016; Dharmapriya et al., 2024). The Paris Agreement, in particular, highlights the significance of coordinated efforts and specialised strategies to cut carbon emissions while taking into account the specific conditions of each continent and nation (Ferreira Ana et al., 2019). Despite the emission reduction promises made in the Kyoto Protocol and the Paris Conference, CE in developing countries continues to rise (Pata, 2021). Gross domestic product (GDP), energy consumption (EC), and trade openness (TO) variations are all intimately related to the economic growth and development of countries (Nguyen Duc Khuong et al., 2017). It is essential to obtain a continent-by-continent understanding of the causes driving CE and develop focused policies to address the unique problems encountered by each region as the global community works to attain the goal of net-zero emissions.

The market value of the goods and services generated inside an economy's boundaries over a given period is known as the gross domestic product, or GDP (Asian Development Bank, 2023). Shifting from agriculture to the industrial sector, diversifying products, and expanding national growth and production contribute to environmental deterioration (Meysam Rafei et al., 2022). EC is another significant contributing factor to CE. Developed countries have a direct influence on CE since they utilise a larger percentage of non-renewable energy in their overall energy consumption (Dissanayake et al., 2023). Moreover, there has been an energy crisis recently, which has arisen from the ongoing conflict between Russia and Ukraine, raising geopolitical tension (Pata, Kartal, et al., 2023b). The need to reduce energy usage is widely recognised as a means of mitigating the continual changes in climate that result from it (Zaharia et al., 2019). TO is also a contributing factor to CE. By measuring a country's import and export openness, researchers typically determine how open a nation is to international trade (Fatima et al., 2020). Also, trade openness and economic policy uncertainty have a short-term negative impact on the ecological footprint (Esmaeili et al., 2023).

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Expanding trade has a significant effect on EC and CE since it raises global total output (Du et al., 2020). GDP, EC, and TO directly affect CE, leading to significant increases in total emissions.

Figure 1. illustrates the growth in CE over the past 22 years among the most significant carbon emitters on each continent. The barriers to sustainable growth are strengthened by emissions of greenhouse gases like carbon dioxide and nitrous oxide, which also have an impact on trade openness, energy consumption, income per capita, industrialisation, urbanisation, and financial development (Pata, 2018a). Focusing on economic aspects and CE in countries is critical because Asia's rapid economic progress has considerably increased the carbon footprint (Acheampong Alex, 2018; Zheng Zang et al., 2018). Agriculture, mining, and energy production are key drivers of economic growth. The continent's environmental problems are worsened because these activities frequently produce significant amounts of CE. Analysis of the particular causes of CE in African nations is crucial to solving this problem, as is the creation of policies that strike a balance between environmental sustainability and economic growth (Asongu Simplice et al., 2016; Bloom David E. et al., 1998). Policymakers can promote sustainable economic development while reducing their carbon footprint by adjusting measures to the various demands of African countries. The American region faces particular circumstances and difficulties when

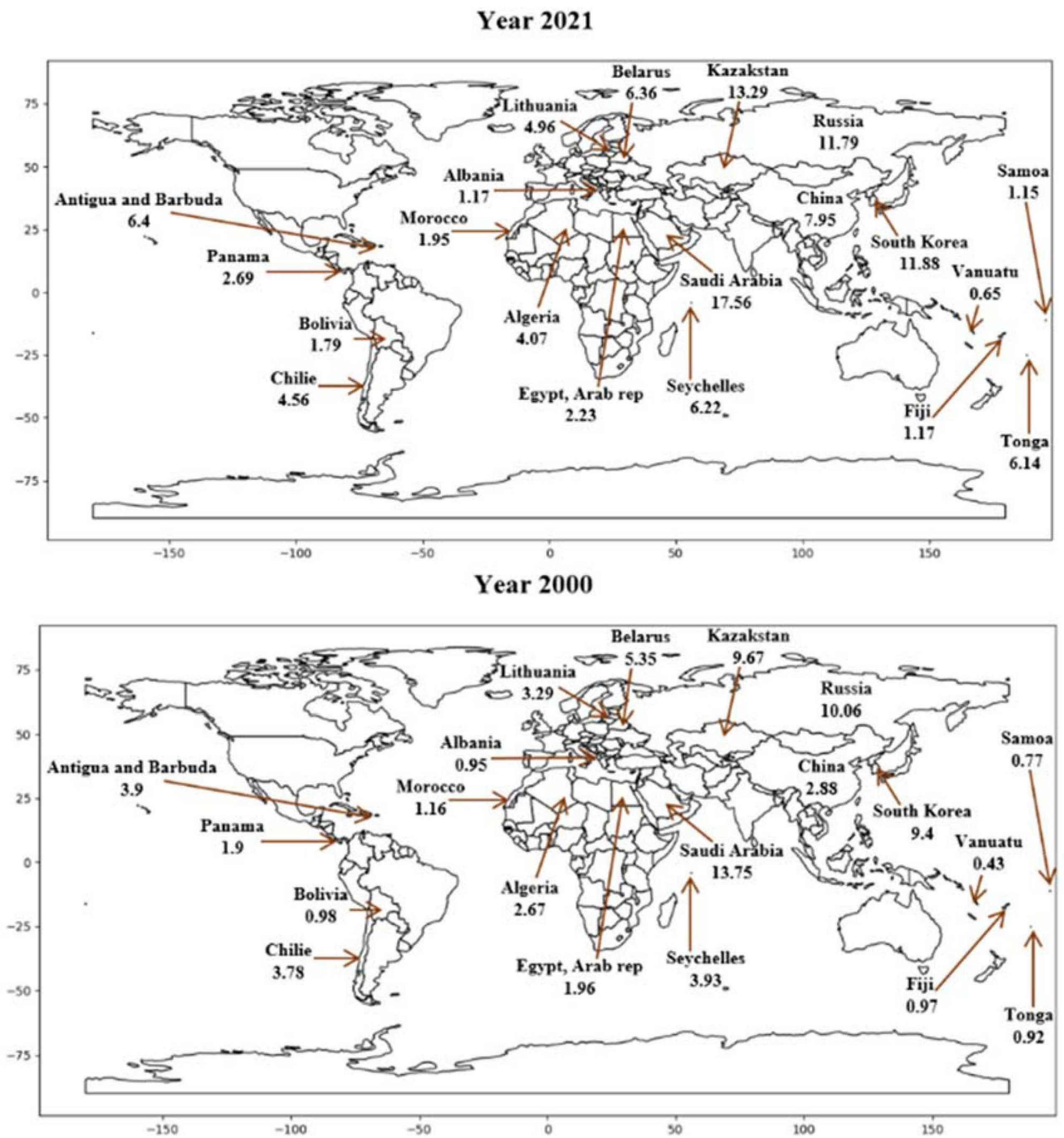

Figure 1. Carbon emissions in 2000 and 2021. Source: Authors' illustration based on Our World in Data (2023).

addressing sustainable development, climate change and lowering CE. Although renewable energy technologies have been adopted more widely in North America, the region still faces problems with high levels of EC and emissions from sectors like the oil and gas industry. Conversely, issues with deforestation, agriculture, and growing urbanisation are present in South America (Jorgenson Andrew K. & Clark Brett, 2013). By comprehending the relationship between GDP, TO and EC across Asian, African, and American regions, policymakers may create efficient strategies to further reduce CE in the economy and achieve the continent's sustainable development.

Europe and Oceania have advanced significantly in their shift to a low-carbon economy, with some nations putting sustainable practices and renewable energy regulations into place and the region still has much to be done to cut carbon emissions, notably in the heavy and transportation industries (Adedoyin Festus Fatai et al., 2021; Chen Lin et al., 2022; Kevin Lo, 2014; Markantoni Marianna, 2016; Yang Jinxuan et al., 2021). Policymakers may develop effective measures to 'decarbonise' the economy further and achieve the continent's climate goals by understanding the relationship between economic indicators, such as GDP and TO, and CE in European countries.

The intended objective of this study is to examine the impact of EC, GDP, and TO on CE in the top 20 carbon emission-increasing nations across continents by finding the four countries with the highest significant impact on carbon emissions in each continent from 2000 to 2021. This study's contributions differ from earlier studies in various ways, including the fact that it covers several research gaps. In order to provide a comprehensive understanding of the effect of GDP, EC, and TO on CE across continents, it first fills a significant knowledge vacuum by exploring their synchronous influence as independent variables. This study seeks to direct nations towards emission reduction strategies in line with the broader sustainable development goal of reaching carbon neutrality by 2050. Second, by drawing attention to the issue and employing the MLR model to conduct extensive research for all countries across continents, the methodology used in the research fills the methodological gap that implies the development of more comprehensive techniques that take regional country-level analysis into consideration. The results of this study have substantial implications for policy in nations under increasing pressure to reduce their carbon footprints. Policymakers can create focused initiatives to lessen CE's detrimental effects on the environment by identifying the primary drivers of CE in the top 20 CE-increasing countries in their respective regions.

Theoretical framework

The Environmental Kuznets Curve (EKC), the 3Ps Framework of Sustainability, and the Porter Hypothesis are the three theoretical frameworks that explain the relationship between CE, GDP, EC, and TO.

The EKC theory links per capita affluence to environmental degradation. The EKC states that there is an initial increase in environmental degradation in response to economic development, but that levels of environmental degradation eventually decrease as society begins to improve its relationship with the environment. Inverted "U" shapes are frequently used to symbolise the EKC (Balsalobre-Lorente et al., 2022; Balsalobre-Lorente et al., 2024a, b; Jahanger et al., 2022; Pata, Dam, et al., 2023a).

Three important components are included in the Sustainability 3Ps Framework, also referred to as the triple bottom line: people, profit, and planet. The social component of sustainability is highlighted in the "people" dimension, emphasising the effects of corporate operations on a range of stakeholders, such as workers, communities, and other relevant parties. Making sure that company activities take into account and positively contribute to social well-being is the main focus. The 'profit' dimension focuses on an action's economic feasibility, emphasising how crucial it is to make a profit in order to keep the organisation sustainable. But the pursuit of economic sustainability does not come at the expense of human welfare or environmental integrity. Achieving profits while upholding moral and socially conscious corporate practices is the aim. The third dimension, 'planet', highlights how decisions affect the environment. This part of the framework focuses on actions that actively support sustainability and actively try to minimise the negative impact on the environment. The goal is to guarantee that corporate operations are carried out with a great awareness of ecological factors, encouraging sustainable and environmentally responsible practices. The 'people' element of the 3Ps Framework draws attention to the societal impact of essential variables beyond only outlining the framework's boundaries. This requires careful analysis of the ways in which variables like rising GDP and EC can raise living standards while also causing CE, which has a negative impact on public health and overall well-being. The framework's "profit" component focuses on the financial outcomes, giving consideration to how these factors contribute to EG and profitability while also acknowledging their possible link to increased CE. On the other hand, the "planet" component requires an extensive evaluation of these factors' effects on the environment, especially with regard to CE. It supports intentional actions that can reduce emissions, like the use of renewable energy sources and the enactment of legislation encouraging ethical business practices. Furthermore, the only substance that can improve the condition of the environment is renewable energy and in order to lessen the effects of building energy consumption, renewable energy, especially solar energy, has been identified as a significant component of sustainable urban development (Adebayo et al., 2024; Erdogan et al., 2023). It is clear that in order to achieve sustainability in the top twenty carbon-emitting countries, equilibrium must be maintained across all three aspects (Dharmapriya et al., 2024; Gbejewoh et al., 2021).

According to the Porter Hypothesis, strong environmental laws can promote efficiency and innovations that boost EG and commercial competitiveness. According to this concept, rigorous environmental laws encourage the development and application of greener technologies and environmental innovations, which boost the productivity of production processes and finished goods in order to minimise CE. Environmental laws can also increase EG by improving people's quality of life and lowering health-related issues (Bitat, 2018; Dissanayake et al., 2023; Rubashkina et al., 2015).

Literature review

The literature evaluation thoroughly summarises the knowledge regarding carbon emissions across continents. Numerous studies have examined the connection between economic development, energy use, and carbon emissions in different nations and regions. These studies demonstrate the intricate interplay of variables affecting carbon emissions, including GDP growth, population dynamics, trade openness, and specific country settings (Khan Hayat et al., 2021; Phuc Nguyen Canh et al., 2020). This literature review endeavours to uncover common trends, knowledge gaps, and policy implications in the area of carbon emissions by analysing the findings from earlier studies.

Economic growth, EC, and environmental sustainability are all intricately linked, according to research on CE in Asian nations. Policymakers and governments can reduce pollution levels and encourage the use of cleaner energy thanks to a substantially increased understanding of the relationship between GDP development and environmental degradation (Muhammad Usman & Balsalobre-Lorente, 2022). According to studies, countries like China and India have experienced considerable increases in CE due to their rapid industrialisation and urbanisation (Nguyen Duc Khuong et al., 2017; Pata, 2018b; Sudharmma Vishwanathan Saritha et al., 2023; Yuan Chaoqing et al., 2017). The leading causes of CE in these nations have been recognised as energy use, population increase, and TO (Haider Salman & Adil Masudul Hasan, 2019). A context-specific approach is required to address CE in Asia because different countries' specific mechanisms and policy consequences vary.

Understanding the causes of CE is essential for sustainable development and environmental conservation in Africa. Research has examined how population expansion, EC, and economic growth affect CE in nations like Egypt. According to the study, economic factors like GDP growth and EC may be factors in these countries' CE (Hashem, 2021). However, the link between population increases and CE is still unclear, highlighting the need for additional research and specific policy changes in the African setting.

Studies on CE in North and South America have highlighted the region's difficulties and prospects for reducing CE. Past research has emphasised how specific country contexts, TO and economic factors affect CE. For instance, the connection between economic growth, TO, and CE has been studied in nations including Antigua, Barbuda, and Panama (OEC, 2021; Zeeshan Muhammad et al., 2022). The results imply that trade policies and sustainable economic development strategies must be customised to effectively adapt America to its circumstances.

Through several governmental initiatives, Europe has been at the forefront of efforts to decrease CE. The relationship between economic growth, EC, TO and CE has been studied in research on CE in European nations. Studies have shown that in some countries, CE is influenced by GDP growth, import and export, energy-related activities, and specific country circumstances (A. Ali & Ilhan, 2010; Kasman Adnan & Duman Yavuz Selman, 2015; Lee Jung Wan & Brahmasrene Tantatape, 2013). The results highlight the importance of implementing targeted regulations and switching to sustainable energy systems to reduce CE in Europe.

Due to Oceania's susceptibility to the effects of climate change, understanding the factors influencing CE is essential. Past research has examined how some countries' economic conditions, EC, and CE are related. CE in such countries is influenced by economic growth, energy-related activities, and unique country settings (Sayyed, 2015). The results of past studies emphasise the significance of implementing sustainable development policies, supporting renewable energy sources, and boosting climate change resistance in Oceania.

Only a few studies have typically examined how EC, GDP, and TO affect CE. South Asia has received the most attention in studies, with South Africa receiving the most attention in Africa. Most studies focused on the influence of global warming on specific continents, regions, or nations. The statistical link between CE, the dependent variable, and the independent variables, EG, EC, and TO, both worldwide and by continent, must be thoroughly explored in any study. Researchers conducted a study that included all continents to close the knowledge gap in this situation.

Data and methodology

The study relied on secondary data sources from Our World in Data. The Appendix section of this study has undergone considerable curation to ensure that only accurate and pertinent records have been added. The first phase of this section lists the facts, resources, and variables used within the investigation. These factors were selected for the study primarily based on how well they addressed the research topic. The second part of this section, thoroughly clarifies the research design, statistical techniques, and data evaluation methods used. This study aims to offer crucial insights into the research problem under examination and contribute them to the research discussion through a robust and inclusive methodological design.

Data

As indicated in Table 1, data was gathered from Our World in Data in four main categories: CE, GDP, EC, and TO from 2000 to 2021. The authors chose metric tons per capita as the unit of measure for CE, per capita as the unit of measurement for GDP, per capita kilowatt hours as the unit of measure for

Table 1. Data sources and variables.

Variable	Measure	Source and URL
CE	Metric Ton Per Capita	Our World in Data https://ourworldindata.org/grapher/co-emissions-per capita
GDP	Thousands of Dollars Per Capita GDP in Constant	Our World in Data https://ourworldindata.org/grapher/gdp-per-capita-worldbank
EC	Thousands of Kilowatt Hours Per Capita	Our World in Data https://ourworldindata.org/grapher/per-capita-energy-use
TO	Percentage of GDP	Our World in Data https://ourworldindata.org/grapher/trade-as-share-of-gdp

EC, and percentages of GDP as the unit of measure for TO, to guarantee consistency and comparability across data sets. GDP values are presented in constant 2017 USD. This study attempts to provide robust and comprehensive insights into the relationship between CE, EC, GDP, and TO by utilising a panel data collection spanning an extended time frame and a diverse range of nations. Consistent and standardised measurement units guarantee the data is accurate and dependable, allowing for meaningful comparisons and analysis. To reduce the decimals in multiple linear regression (MLR) estimations, the current study adapted the GDP and EC units of measurement to thousands of dollars per capita and thousands of kilowatt hours per capita, respectively, while CE is measured in metric tons per capita and TO is defined as a percentage of GDP.

To reduce the decimals in MLR estimations, the current study adapted the GDP and EC units of measurement to thousands of dollars per capita and thousands of kilowatt hours per capita, respectively.

Methodology

To conduct this study, data for all nations included in the analysis were collected from reliable sources, and Appendix S1 contains the dataset. This data encompassed EC, GDP, TO, and CE variables. To examine the relationship between these variables, scatter plots were generated, allowing for visual identification of trends and patterns. Appendix S2 contains the scatter plots for each country. Since certain countries had missing data for particular variables, this study used the backward forecasting approach to predict the values for the instances that were missing. The objective was to identify a constant slope for each country by utilising the coefficient and intercepts, indicating the strength and direction of the relationship. Furthermore, a single-country analysis was performed using MLR, considering the specific context of each nation, and test results are available in Appendix S3. Authors gained an in-depth insight into the factors influencing CE in each country, thus enabling a more precise and tailored approach to mitigate the environmental impact by applying Eq.1.

$$CE_t = \beta_0 + \beta_1 TO_t + \beta_2 EC_t + \beta_3 GDP_t + \varepsilon_t \quad (1)$$

This equation includes t, which stands for the year being considered, and ε, which stands for the standard error. This analysis aimed to determine how much EC, GDP, and TO influenced CE in each country. Finally, the countries were ranked based on the adjusted R-square value, which measures the goodness-of-fit of the regression model. The top 20 countries with high R-square values were identified, indicating a strong explanatory power of the independent variables in relation to CE.

The decision to utilise the MLR approach was deliberate, driven by its aptness for simultaneously examining the interplay between multiple independent variables (GDP, EC, and TO) and a dependent variable (CE). MLR presents distinct advantages that complement our study objectives. Firstly, it offers a versatile platform for modelling intricate relationships among variables. This adaptability enables capturing potential effects of GDP, EC, and TO on CE, which might be overlooked by alternative methods. Secondly, MLR enables the control of potential confounding factors and addresses multicollinearity between independent variables, thus bolstering the robustness of our analysis. Through this control, we achieve a more precise estimation of each variable's contribution to carbon emissions while mitigating the risk of spurious relationships. Moreover, MLR facilitates the assessment of statistical significance and quantification of the strength and direction of variable relationships, thereby enhancing result credibility and facilitating meaningful cross-regional comparisons. Overall, we affirm that the MLR approach effectively addresses our research questions and objectives by furnishing a rigorous, adaptable, and interpretable framework for scrutinising the intricate relationship between GDP, EC, TO, and CE within the context of sustainable development.

Results and discussion

The analysis of the impact of GDP, EC, and TO on CE in the top twenty carbon emission-increasing countries across continents has yielded significant insights. The findings reveal distinct patterns and varying degrees of influence in different continents. Trend lines depict these countries' regional distribution, highlighting their relative contributions to carbon emissions. Figure. 2 illustrates the four major carbon emitters in Asia, Africa, America, Europe, and Oceania, providing a short and instructive snapshot of the carbon emission landscape across different continents.

The single-country analysis of Asia's carbon emissions reveals interesting trends and offers novel insights into the continent's carbon impact. Figure 2(a) shows Saudi Arabia as one of the major carbon emitters in Asia. The nation's reliance on oil exports and production significantly contributes to its CE (H. Ali et al., 2022). Furthermore, Saudi Arabia's energy-intensive industries like petrochemicals and desalination are also important. The results emphasise the link between CE in the area and oil-dependent economies. Kazakhstan is another significant carbon emitter. Kazakhstan's energy-intensive industries, such as mining and oil refining, also add to the country's carbon footprint (Raihan Asif & Tuspekova Almagul, 2022). The nation's fossil fuel reserves, particularly oil and natural gas, are a factor in its high CE. South Korea is a significant Asian carbon emitter. The country's strong industrial sector, which includes shipbuilding, vehicles, and electronics, is a factor in its CE. South Korea's high energy usage and reliance on coal for electricity generation increase the country's carbon footprint (Park JaeHyun & Hong TaeHoon, 2013). China is a significant source of CE in Asia. The CE is a result of its firm reliance on coal for energy production, huge population, and rapid industrial growth (Nguyen Duc Khuong et al., 2017). The fact that China is the world's largest industrial hub and its substantial exporting activities also add to the country's carbon footprint. Increased CE in the electric heating sector is primarily caused by the industrial system's growing need for energy for electric heating (Tangyang Jiang et al., 2022). The results highlight how industrialisation and energy use significantly impact Asia's CE.

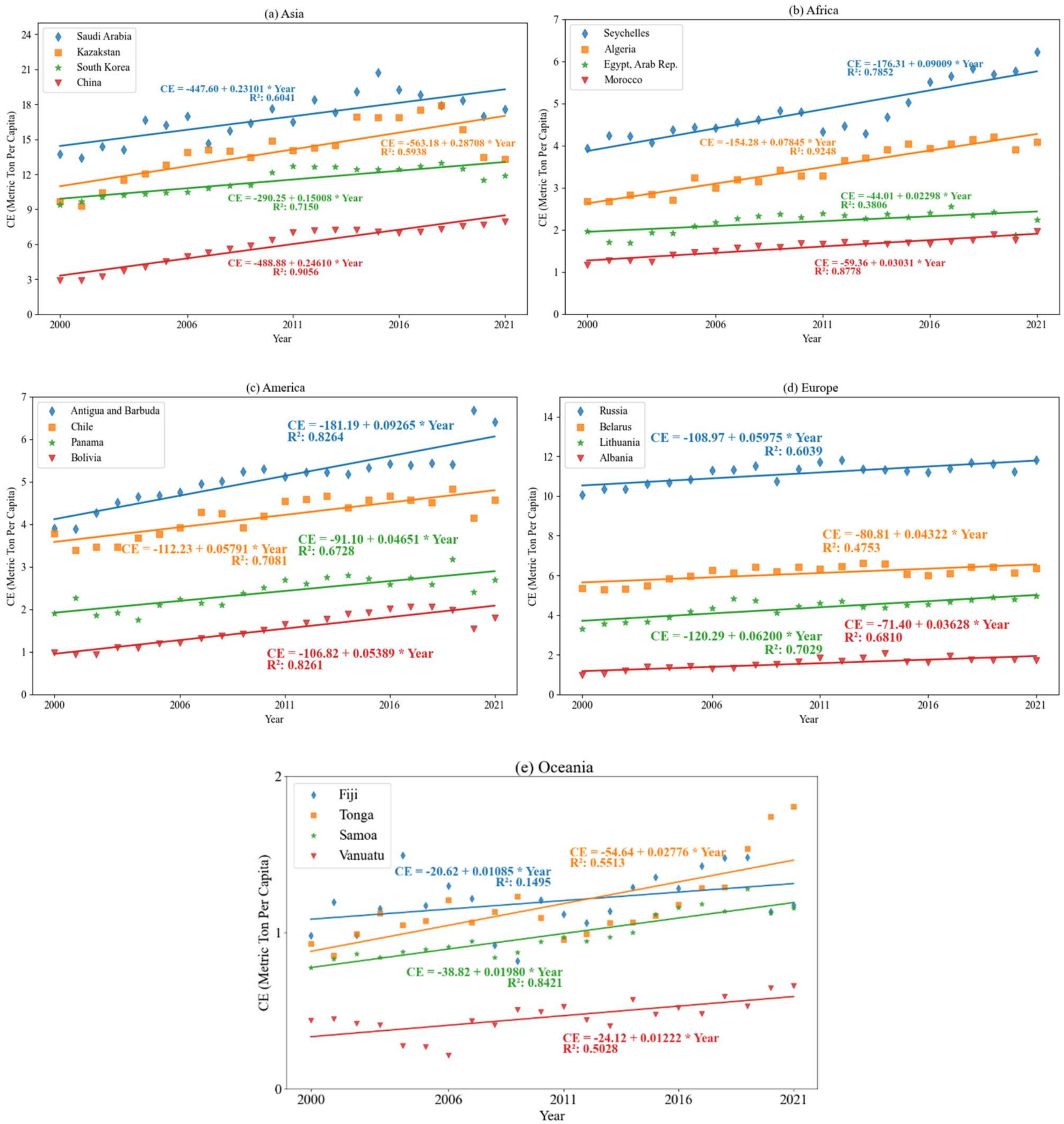

Figure 2. Linear Fit Scatter Plots of the Top 20 Carbon Emission-Increasing Countries. Source: Authors' illustration based on Our World in Data (2023).

Figure 2(b) illustrates that the Seychelles is the top African carbon emitter. Seychelles' tourism industry (Gössling Stefan & Schumacher Kim Philip, 2010) includes foreign travel and lodging and the country's reliance on imported fossil fuels for energy production, such as increased diesel and jet fuel consumption since 2015, adds to its carbon footprint. Algeria stands out as a significant carbon emitter in Africa. The country's reliance on fossil fuels, notably natural gas, for energy generation and industrial activity, adds to its carbon footprint. Furthermore, Algeria's growing population and developing industrial sectors, such as oil and gas extraction, contribute to the rising CE (Chekouri Sidi Mohammed et al., 2020). These findings show the interaction between African countries' energy sources, economic development, and CE. Egypt appears as another significant carbon emitter. The country's high energy demand, vast population, and reliance on fossil fuels for electricity generation contribute to its carbon footprint (Hashem, 2021). Petroleum refining and cement manufacturing also add to Egypt's carbon footprint. Morocco is a significant carbon emitter in Africa. The rising energy demand, fuelled by economic development and population increases, adds to its carbon footprint (Haq Ihtisham ul et al., 2016). Morocco's reliance on fossil fuels, such as coal and oil, for electricity generation and its developing industrial sectors, such as manufacturing, contribute to its carbon footprint. These findings highlight the importance of sustainable energy methods and diversity in countries experiencing rapid economic expansion to reduce CE. These findings underscore the unique difficulty that small island governments confront in regulating CE, particularly those that rely significantly on imported energy.

Figure 2(c) shows that Antigua and Barbuda stand out as significant carbon emitters in the region CE due to their small size and scarcity of natural resources (OEC, 2021). Hence, the nation's imports, which include refined petroleum, passenger and cargo ships, recreational boats, cars, and poultry meat, increased its reliance on fossil fuels for the production of power, transportation, and tourism-related activities. These results highlight the difficulties small island countries with few renewable energy options face in switching to a low-carbon economy. The figure shows considerable CE from Chile. Its carbon footprint is influenced by the nation's reliance on coal for power production, particularly in areas lacking access to renewable energy sources. CE is also a result of Chile's expanding transport and energy-intensive mining sectors. Panama is identified as another significant carbon emitter in the Americas. Due to its advantageous location as a centre of international trade, the nation's expanding transportation industry, particularly air and ocean transportation, contributes to its CE (Zeeshan Muhammad et al., 2022). Deforestation, land use changes, and Panama's reliance on fossil fuels for electricity production all increase the country's carbon footprint. Bolivia is another notable carbon emitter in the Americas. The nation's heavy reliance on natural gas and oil for transportation and energy production raises its CE (Kirikkaleli Dervis & Oyebanji Modupe Oluyemisi, 2022). The extensive agricultural sector in Bolivia, which includes cattle farming and deforestation for agricultural growth, also contributes to the rise in CE. These results demonstrate the intricate interactions among energy sources, land use, and farming methods that influence CE in South American nations. These results highlight the necessity for eco-friendly transport options and initiatives to save land in countries with significant logistical activity.

Figure 2(d) shows Russia as a major European carbon emitter. Russia is a significant player in the global energy market due to its plentiful natural resources, but it needs assistance switching to cleaner energy sources. As a result of its reliance on fossil fuels for energy production and exporting, Russia has a large carbon footprint (Yang Jinxuan et al., 2021). Additionally, CE is influenced by industrial processes like mining and heavy manufacturing. Belarus has a significant CE in Europe. The nation's massive carbon footprint results from its reliance on fossil fuels, notably coal and natural gas, for energy production and heating. The industrial sector in Belarus, which produces steel and makes chemicals, also contributes to the rise in CE. Lithuania is another significant carbon emitter in Europe. The nation's reliance on fossil fuels, like oil and natural gas, for energy generation and home heating adds to its CE. Manufacturing of chemicals and oil refining are two more industrial processes that contribute to CE in Lithuania. Furthermore, implementing sustainable energy practices has been difficult due to the nation's transition from a planned economy to a market-based structure. Albania is also a notable European carbon emitter. The country has a high dependence on coal for energy production and has seen little investment in renewable energy sources. Albania's industrial endeavours, including mining and manufacturing, further contribute to CE (Novikova Aleksandra et al., 2018).

In Oceania, Figure 2(e) shows Fiji as a significant carbon emitter. The nation's high reliance on fossil fuels, especially diesel and kerosene, for transportation, industry, and energy production increases its carbon footprint. The tourism sector in Fiji, which depends on accommodations and air travel, also adds to emissions (Becken Susanne, 2005). Further factors affecting CE are deforestation and land-use changes brought on by agricultural practices and urbanisation. Samoa is shown to have significant CE. The nation's dependency on imported fossil fuels, limited access to renewable and economical energy sources, and reliance on diesel generators for electricity generation add to its carbon footprint. Samoa's agricultural pursuits, such as cattle raising and deforestation, also contribute to emissions. Tonga is highlighted as a notable carbon emitter in Oceania. The nation's dependence on imported fossil fuels for transportation and energy generation raises its CE. Given Tonga's susceptibility to the effects of climate change, including sea level rise and extreme weather, adaptation and mitigation methods must be prioritised. Vanuatu is a strong carbon emitter in Oceania. The nation's dependence on fossil fuels, particularly diesel, for transportation and electricity production increases its carbon footprint (Wewerinke-Singh Margaretha & Salili Diana Hinge, 2020). Emissions are also influenced by agricultural practices in Vanuatu, such as deforestation and subsistence farming. The summary of MLR estimations for the top 4 carbon emitters on each continent is shown in Table 2.

China emerges as a significant source of CE in Asia. The negative GDP coefficient implies that CE emissions fall as China's GDP rises. However, higher levels of EC and TO result in higher levels of CE, as indicated by the positive coefficients for EC and TO. This research emphasises the complexity of China's CE and points to the necessity for focused policies that support energy efficiency and sustainable economic growth.

Table 2. Critical Insights from MLR Estimates.

Continent	Country	GDP	EC	TO
Asia	China	−0.3479***	0.4676***	−0.0331***
	Kazakhstan	0.0494***	0.3234	0.319
	Saudi Arabia	0.0853	0.1365***	−0.0362
	South Korea	−0.0914***	0.2932***	0.0040
Africa	Algeria	0.0440	0.2160***	−0.0022
	Egypt, Arab Rep.	0.0880***	0.2322***	0.0033**
	Morocco	−0.0318	0.2263***	0.0075
	Seychelles	0.1614***	0.0430***	0.0029
America	Antigua & Barbuda	−0.0096	0.1859***	−0.0186***
	Bolivia	0.2543***	0.0772*	0.0028*
	Chile	0.0599**	0.1487*	0.0021
	Panama	0. 0659**	−0. 0137	0. 0022
Europe	Albania	0.0670***	0.0698	0.0670
	Belarus	0.0271***	0.1159***	−0.0061***
	Lithuania	0.0344***	0.0423**	0.0122***
	Russia	−0.0433	0.1593**	−0.0135
Oceania	Fiji	0.1109***	0.0959***	0.0010
	Samoa	−0.0333	0.1967***	0.0012
	Tonga	−0.0060*	0.2928***	0.0046
	Vanuatu	−0.1223	0.2219***	0.0013

Note: *Significant at 10%, ** significant at 5%, and ***significant at 1% significance level.

Kazakhstan shows that GDP and CE are positively correlated. The negative but statistically negligible EC coefficient suggests that EC alone may not strongly influence the nation's carbon emissions. The fact that TO has a positive coefficient indicates that global commerce increases CE. These revelations illuminate the causes of Kazakhstan's CE and can help governments create plans for sustainable growth. The coefficients for GDP and EC in Saudi Arabia are statistically insignificant, indicating that neither economic expansion nor EC are likely reliable indicators of CE.

On the other hand, the positive coefficient for TO suggests that trade activities positively impact CE. Investigating the underlying causes of these conclusions can offer insightful information on the unique features of Saudi Arabia's CE profile. South Korea's GDP and CE show a negative correlation, indicating that CE declines as the nation's economy expands. The positive coefficients for EC and TO highlight the importance of EC and global trade in driving CE. These results highlight the need to encourage energy efficiency policies and environmentally friendly business practices to lower CE in South Korea.

Moving on to Africa, Algeria's GDP and TO coefficients are statistically negligible, indicating that these factors may only have a little impact on CE there. The fact that EC has a positive coefficient means that emissions are influenced by energy use. Potential tactics for lowering CE in Algeria include investigating alternate energy sources and implementing energy efficiency measures. GDP and CE have a favourable association in Egypt, an Arab Republic. According to the positive coefficients for EC and TO, the country's CE may be increased through energy use and trade. These results highlight Egypt's need for ecologically friendly energy options and green business practices to reduce CE. The coefficients for GDP and EC in Morocco are statistically negligible; however, the positive coefficient for TO points to a possible link between trade and CE. These observations underline how crucial Morocco's CE reduction initiatives are to consider trade-related emissions and embrace sustainable trade practices. GDP, EC, and TO all show positive coefficients for Seychelles, demonstrating the country's favourable impact on CE. To reduce CE, Seychelles must prioritise sustainable economic development and look into renewable energy options, according to the research.

Antigua and Barbuda in the Americas region exhibit statistically negligible coefficients for GDP and TO. However, the positive coefficient for EC indicates that the nation's energy use significantly contributes to CE. These results highlight how critical it is for Antigua and Barbuda to concentrate on energy efficiency initiatives and switch to renewable energy sources. All three factors in Bolivia have positive coefficients, which shows that they positively impact CE. This demonstrates the necessity for Bolivia to strike a balance between economic expansion and strategies for environmentally friendly development. Chile's GDP and EC coefficients are positive, indicating that economic growth and energy use increase CE. The fact that TO has a positive coefficient shows how trade activities affect emissions. These findings demand measures implemented in Chile to support sustainable trade and economic practices. Panama's GDP and TO show positive correlations, showing a favourable correlation between these variables with CE. Statistics show that the EC coefficient is not significant. These observations highlight the significance of considering the particular elements impacting Panama's CE and establishing focused efforts to minimise emissions.

Albania displays positive GDP and EC coefficients in Europe, indicating that these variables benefit CE. The fact that TO has a positive coefficient emphasises the importance of commerce in reducing emissions. These results can help Albania in its efforts to promote greener trade practices and embrace sustainable energy policies. All three variables in Belarus have positive coefficients, demonstrating a positive correlation with CE. These observations highlight Belarus's need to prioritise steps to minimise CE and achieve sustainable economic development. Lithuania has positive GDP and EC coefficients, indicating that these factors have a beneficial impact on CE. The fact that TO has a positive coefficient suggests that trade-related activities also increase emissions. The GDP and TO coefficients for Russia are statistically insignificant, whereas the positive EC coefficient indicates that EC significantly affects CE.

Fiji has positive coefficients for all three variables in Oceania, showing a positive correlation with CE. These results underline the necessity for Fiji to prioritise the development of renewable energy sources, energy-saving technologies, and environmentally friendly land-use strategies to reduce CE. Samoa's GDP and TO coefficients are statistically negligible. The positive EC coefficient indicates that the nation's CE is influenced by energy use. Tonga's GDP coefficient is negative, indicating that economic expansion can result in lower CE. The positive coefficients for EC and TO show a positive correlation between these variables and CE. These findings highlight the need for Tonga to reconcile economic growth with ecologically friendly energy practices and trade initiatives. Vanuatu demonstrates statistically insignificant coefficients for GDP and TO. The positive coefficient for EC suggests that energy consumption contributes to carbon emissions.

Conclusion

In conclusion, this study aimed to examine the impact of GDP, EC, and TO on CE in the top 20 carbon emission-increasing nations continent-wide. Using MLR analysis, the authors gathered critical insights into the factors influencing these nations' CE and the implications for sustainable development. The results portrayed various patterns and levels of effect among the various continents. Saudi Arabia has become a significant source of CE in Asia, while the Seychelles is the highest carbon emitter in Africa, emphasising the need for tailored policies that support the efficient use of energy and sustainable economic growth. As countries like Algeria and Egypt in Africa showed distinctive traits in their CE profiles, it is critical to look into alternative energy sources and adopt sustainable lifestyles. The region of America demonstrated various connections between economic expansion, EC, and CE. Bolivia and Antigua and Barbuda are two nations that have highlighted the need for sustainable development methods and energy efficiency initiatives. Meanwhile, Europe and Oceania provided insights into the importance of TO, the development of renewable energy sources, and energy conservation in reducing CE.

Europe serves as an example of the value of balancing economic growth with environmentally friendly practices to reduce CE. Countries like Albania, Belarus, Lithuania, and Russia provide examples of the necessity for focused policies that support energy efficiency and renewable energy initiatives while promoting economic growth. Fiji, Samoa, Tonga, and Vanuatu are examples of countries in Oceania that have demonstrated the possibility of using renewable energy sources to lower CE. These results highlight the value of regional cooperation and information exchange across Europe and Oceania to promote the adoption of sustainable energy practices. By exchanging experiences, technologies, and best practices, countries may cooperate to create a greener future where economic growth is not linked to CE, and sustainable development is a common goal.

These novel findings add to the existing knowledge on carbon emissions and significantly assist policymakers in developing successful policies for sustainable development. To reduce CE, nations must support renewable energy sources, prioritise sustainable economic growth, and implement energy efficiency policies. Achieving global climate targets also requires adopting ecologically beneficial trade practices and considering the distinctive features of each nation's CE profile.

Policy implications

The findings of this study highlight the importance of comprehensive and region-specific policy initiatives for reducing carbon emissions and promoting sustainable development. Policymakers should examine numerous targeted recommendations based on the specific requirements and contexts of each region. China and South Korea should lead the way in Asia by implementing energy efficiency standards for industrial sectors, encouraging the use of green technologies, and switching to renewable energy sources including solar, wind, and hydroelectric power. By lowering their dependency on fossil fuels, funding the development of alternative energy sources, and establishing laws that facilitate the integration of renewable energy sources into the national grid, CE can be significantly reduced by enacting stricter emissions rules for companies and encouraging sustainable urban development. The switch to a low-carbon industry should be given priority in South Korean policy. Promoting environmentally friendly urban planning can help reduce CE. Kazakhstan and Saudi Arabia can diversify their energy portfolios. To lower carbon footprints and help rural development, Algeria and Egypt should advocate for investments in renewable energy infrastructure, especially solar and wind power. They should also support sustainable agriculture practices. Further reducing CE can be accomplished by implementing sustainable land management techniques like reforestation and soil conservation. In addition to implementing educational efforts to increase public awareness of energy saving and environmental protection, the Seychelles should create legislation that supports sustainable tourism, minimising negative effects on the environment while optimising positive effects on the economy. To lessen its impact on the environment, the government can create waste management plans in hotels and resorts. Policies in these countries may focus on environmentally friendly tourism practices, such as promoting eco-tourism campaigns and implementing energy-saving techniques in hotels and resorts. The government can promote solar panels for hotels and electric buses to lower CE in the tourism industry. As Morocco is an ideal location for investments in renewable energies, they may adopt measures to encourage energy diversification, such as increasing the capacity for renewable energy.

Antigua and Barbuda and Bolivia ought to implement nationwide energy efficiency initiatives aimed at the residential and commercial sectors in the American region. These initiatives should offer tax breaks or subsidies for energy-efficient automobiles and appliances. In order to exchange best practices and cutting-edge carbon management technology, Antigua and Barbuda might implement laws encouraging environmentally friendly travel and lodging options. Chile and Panama should tighten their restrictions on industrial emissions, make investments in cleaner production technologies, and promote regional collaboration. Panama's government should encourage sustainable agricultural practices like agroforestry to reduce CE in the farming sector and implement forest protection measures to safeguard carbon sinks. Reducing CE can also be aided by stricter emissions standards for important industries like manufacturing and transportation. By investing in cleaner technology, such as renewable energy sources, regulations governing fossil fuel extraction and production emissions should be enhanced to lessen their detrimental environmental effects. This process can involve promoting energy conservation practices such as solar and wind farms.

In order to optimise energy distribution and consumption, Europe, Albania, and Belarus should intensify energy efficiency initiatives in all areas, such as upgrading buildings and enhancing public transport systems. They should also encourage the development of smart networks. Increased funding for renewable energy projects, support for public-private partnerships to spur innovation, and the creation of national carbon emission reduction plans that are in line with European Commission climate goals are all recommendations for Lithuania and Russia. The government can encourage the adoption of energy-efficient equipment, as can the promotion of sustainable building techniques like green building certifications. Feed-in tariffs are one type of incentive for renewable energy projects that can draw capital and promote the expansion of clean energy sources. CE can be further decreased by promoting environmentally friendly mobility solutions like electric cars. Promoting energy-efficient agricultural practices, such as precise irrigation and sustainable farming methods, can also help reduce CE. In order to lessen their dependency on imported fossil fuels, Fiji and Samoa should make use of their substantial renewable energy resources, such as ocean and geothermal energy, and form regional alliances to strengthen their resistance to the effects of climate change. In order to guarantee local involvement and benefit-sharing, Tonga and Vanuatu should establish community-based renewable energy projects. They should also bolster regulations meant to preserve natural ecosystems, which are essential for storing carbon.

Limitations and future research

Future studies on the interactions between EC, GDP, TO, and CE in the Asian region have a number of promising directions. Including more variables which directly impact CE apart from these variables would be beneficial. Examples of these variables include population growth, industrialisation level, urbanisation rate, and technological changes. Evaluating the efficacy of current CE reduction initiatives could be valuable. Another way to broaden the scope of the current research is to expand it to include new nations based on data availability. Future studies could examine the effects of carbon taxes and clean energy regulations in relation to rising GDP, TO, and EC. It would be useful to know how these actions affect or strengthen efforts to reduce CE. Further research could build on these results and explore other methodologies or additional analysis methods to circumvent these constraints and enhance our comprehension of the relationship between economic conditions and CE.

Data availability statement

All data generated or analysed during this study are included in this published article and its supplementary information files.

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