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Investigating factors influencing CO_2 emissions in selected G20 countries

Mohammed Hakami *, Rozina Shaheen

College of Business, Effat University, Jeddah, Saudi Arabia

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ABSTRACT

This study aims at identifying the factors that influence CO_2 emissions in some G20 countries. It examines various possibilities such as electricity consumption, foreign investments, fuel and metal exports, economic growth, population growth, renewable energy consumption, trade, urbanization, and even the effects of the global economic crisis of 2008. The results show that increased electricity consumption, economic growth, and population increase result in higher levels of CO_2 emissions which demonstrates the environmental impact of industrialization and urbanization. Conversely, the use of renewable energy and foreign investment are correlated with lower emissions which proves that a shift towards cleaner energy and sustainable investments can be effective. The findings of the study also point towards the fact that the G20 countries need to shift towards the use of renewable energy, enhance energy efficiency, and encourage the development of sustainable urban environments. It provides a practical approach for the policymakers to follow for emission reduction along with promoting economic growth in a sustainable manner.

1. Introduction

The historical context of CO_2 emissions and their consequential impact on the climate is not merely an academic concern; it represents a critical challenge in today's world. As CO_2 levels continue to rise, the associated environmental repercussions have become increasingly severe, raising urgent alarms about sustainability and the long-term viability of our planet. Understanding the historical evolution of CO_2 emissions and their climate implications is essential for developing effective strategies to mitigate climate change impacts. This understanding is vital for academic researchers, policymakers, and stakeholders invested in climate change and environmental sustainability, as they collectively hold the responsibility for driving change. The urgency of addressing this issue cannot be overstated; it serves as a clarion call for immediate and concerted action. The collective efforts of various stakeholders are needed to confront this pressing challenge and to ensure a sustainable future for our planet.

In recent decades, the challenge of CO_2 emissions and their effects on global climate has emerged as a pressing concern. Numerous scientists and researchers have extensively explored the historical trajectory of CO_2 emissions and their climatic consequences. Their findings clearly indicate that human activities, particularly the burning of fossil fuels and deforestation, have been the principal contributors to the dramatic rise in atmospheric CO_2 concentrations since the Industrial Revolution of the 19th century. This sobering reality highlights the critical urgency for immediate and decisive action to combat climate change and mitigate its detrimental effects on the environment. The implications of these findings demand that stakeholders, including governments, industries, and individuals, prioritize sustainable practices and policies to address the root causes of CO_2 emissions and foster a healthier planet for future generations.

In industrialized nations such as Canada, Germany, Japan, the United States, and the United Kingdom, CO_2 emissions are significantly shaped by factors such as population growth, income levels, and emissions specific to various sectors. Research indicates that these interconnected variables contribute to the overall carbon footprint of these countries. As future projections highlight the urgency of implementing effective emission reduction strategies, it becomes increasingly evident that tailored policies are essential. Such measures must address the unique circumstances of each

* Corresponding Author.
Email Address: myhakami@effat.edu.sa (M. Hakami)
https://doi.org/10.21833/ijaas.2025.02.001
Corresponding author's ORCID profile:
https://orcid.org/0009-0004-5370-7576

nation while considering the distinct contributions of different sectors to greenhouse gas emissions (Mohmmed et al., 2019). By developing targeted approaches that consider demographic and economic factors, policymakers can more effectively mitigate CO_2 emissions and move toward achieving sustainability goals.

The impact of CO_2 emissions on industrialized nations, including Canada, Germany, Japan, the United States, and the United Kingdom, is complex and reflects the intricate interplay among economic development, industrial activities, energy consumption, and environmental policies. The Environmental Kuznets Curve (EKC) theory (Kuznets, 1955) suggests that as an economy progresses, environmental degradation may initially rise; however, it eventually declines after reaching a certain threshold of economic growth. This framework can be instrumental in examining the relationship between economic growth and CO_2 emissions in these industrialized countries. Furthermore, Wang et al. (2019) emphasized the time-varying nature of the relationship between carbon emissions and income, noting that developed nations such as Germany and Japan have experienced shifts in their EKCs over time. These changes indicate fluctuations in CO_2 emissions in relation to economic growth, suggesting that as these economies expand, a turning point may be reached where wealthier nations begin to reduce their carbon emissions. This trend is also observable in countries like Canada, the United States, and the United Kingdom, supporting the notion that economic advancement can eventually lead to more sustainable environmental practices.

This study seeks to explore the trends in CO_2 emissions over the past three decades in Canada, Germany, Japan, the United Kingdom, and the United States, while identifying the key drivers behind these trends. A significant focus of the research is to examine the role of renewable energy consumption in influencing CO_2 emission levels and its potential to alleviate the environmental impact of industrial activities. The main objectives include assessing the capacity of increased renewable energy adoption to reduce emissions and pinpointing the primary factors contributing to the observed changes in CO_2 emissions. Additionally, this study aims to enhance the discourse surrounding the role of renewable energy consumption in these G20 countries as a critical strategy for addressing climate change. By analyzing the interplay between renewable energy and CO_2 emissions, the research will provide valuable insights that can inform policy decisions and contribute to the development of effective strategies for mitigating climate change impacts.

The rest of the paper is organized as follows. In Section 2, we provide a comprehensive literature review, synthesizing existing research on CO_2 emissions and renewable energy consumption while identifying key gaps that this study aims to address. Section 3 outlines the data and methodology, detailing the econometric models used in the analysis, including the justifications for selecting panel fixed effects and generalized least squares (GLS) random effects models. Section 4 presents empirical results and analysis and discusses the implications of the findings in relation to the research questions and objectives, examining how increased renewable energy consumption can contribute to CO_2 emissions reduction. Following this, Section 5 concludes the research process by summarizing the main insights, discussing their relevance to climate policy, and suggesting areas for future research to further enhance understanding of renewable energy's impact on environmental sustainability.

2. Literature review

Climate change and its environmental impacts have emerged as a critical global concern (Xu and Ang, 2013), with carbon dioxide (CO_2) emissions being a primary contributor to global warming and climate change. Industrialized nations, particularly those within the G20, have historically been the largest emitters of CO_2, accounting for a significant share of global emissions (Chen and Jiang, 2023). As a result, the impact of CO_2 emissions on these countries has become a focal point of research. Several factors, including exports, imports, eco-innovation, gross domestic product (GDP), renewable energy consumption, and energy productivity, have been identified as drivers of consumption-based CO_2 emissions in these industrialized nations. Studies indicate that many of these countries are heavily reliant on imported goods, further contributing to their carbon footprints. This research seeks to analyze the effects of economic growth and foreign direct investment (FDI) on CO_2 emissions and to test the validity of the EKC hypothesis. By employing panel linear regression models that account for individual and distributional heterogeneity, the study aims to offer a nuanced understanding of these dynamics (Chen and Jiang, 2023). Importantly, it recognizes that the impact of CO_2 emissions may vary across different G20 nations, emphasizing the need for tailored approaches to mitigating emissions.

2.1. CO_2 emissions trends in the selected G20 countries

2.1.1. United States

The United States has experienced a notable reduction in CO_2 emissions, particularly within the power sector. This decline is mainly due to transitioning from coal to cleaner energy sources such as natural gas and renewables. Several key factors have driven this shift, including reduced energy demand following the 2007 recession, a surge in natural gas production, and the rapid growth of renewable energy industries. Additionally, the expansion of nuclear power has contributed to this downward trend in emissions (York, 2010). However, debates persist regarding the long-term effectiveness of natural gas as a cleaner alternative, as concerns over methane leakage and its role as a fossil fuel remain. Despite these positive advancements, the United States continues encountering significant obstacles in further reducing CO_2 emissions, particularly in sectors like transportation and energy production (Keerthana et al., 2023). Addressing these challenges will require sustained policy-making and technological innovation efforts to accelerate the transition to cleaner energy sources.

2.1.2. Canada

Canada's CO_2 emissions have been rising, driven by factors such as economic growth, population increase, and continued reliance on fossil fuels (Qingren, 2023). Transportation-related emissions account for a significant portion of the total, and projections suggest that these emissions will continue to rise unless alternative and low-carbon fuels are adopted (Abdulmalik and Srivastava, 2023). Despite this, there has been progress in reducing atmospheric nitrogen dioxide levels, primarily due to legal mandates to curb transportation emissions (Reid and Aherne, 2016). Technological advancements, particularly in carbon capture and storage (CCS), have been emphasized as cost-effective strategies for mitigating emissions. CCS plays a crucial role in reducing global CO_2 levels (Tontiwachwuthikul et al., 2011). However, despite these initiatives, Canada's emissions continue to exceed the targets necessary to remain within the 2°C global warming threshold, largely due to the expansion of unconventional oil production. This underscores the urgent need for policies addressing domestic emissions and reducing fossil fuel exports, ensuring that Canada contributes meaningfully to global climate change mitigation efforts.

2.1.3. Germany

Germany has committed to reducing its carbon emissions through various international treaties, including the Kyoto Protocol and the Paris Agreement. The German government set an ambitious goal of cutting emissions by 40% by 2020 compared to 1990 levels. However, in the years leading up to 2020, the country appeared to be off track to meet these targets. As a result, the government introduced a climate protection program aimed at accelerating emissions reductions, though it was criticized as inadequate. Early projections indicated that Germany would likely fail to meet its climate targets for 2020. Contrary to these initial projections, Germany experienced a significant and unexpected decrease in carbon emissions in 2019, bringing the 2020 targets within reach. Much of this reduction occurred in the power sector, with emissions falling by 40 million metric tons of CO_2, marking a 15% reduction from the previous year. This improvement highlights the impact of targeted energy policies and underscores the potential for rapid progress when sufficient action is taken. However, continued efforts will be essential to maintain this momentum and meet long-term climate goals.

2.1.4. United Kingdom

In the United Kingdom, affluence and technological advancements have significantly shaped the country's CO_2 emissions trend. Changes in global supply chains, driven by technological shifts, have contributed to increasing emissions, particularly in the transport sector, with car travel being a major source (Kwon, 2005). Despite these challenges, there have been notable improvements in certain areas, such as reducing carbonaceous aerosols and black carbon levels, which are linked to air quality improvements (Jafar and Harrison, 2020). However, despite these gains, the UK still faces difficulties meeting its CO_2 reduction targets, particularly in the freight transport sector, where emissions remain a persistent issue (Zanni and Bristow, 2010). This highlights the need for further policy intervention and technological innovations to address these ongoing challenges in the UK's efforts to combat climate change.

2.1.5. Japan

Japan's CO_2 emissions have exhibited a mixed trend over the years. While the industrial sector remains the largest contributor, it has successfully reduced its emissions by adopting environmentally friendly technologies and practices. In contrast, the residential and commercial sectors have seen a notable increase in emissions, driven by population growth, economic expansion, and technological advancement (Bai et al., 2019). To reverse this upward trend, energy efficiency improvements and carbon intensity reductions are crucial. Despite Japan's commitment to international agreements like the Kyoto Protocol, its overall emissions have continued to rise. The increasing number of households has also contributed to rising emissions, highlighting the need for more aggressive policy interventions to address these challenges effectively.

2.2. Renewable energy consumption

Various studies have examined the relationship between renewable energy consumption and the reduction of CO_2 emissions across various nations. Saidi and Omri (2020) highlighted that a combined approach of nuclear and renewable energy is particularly effective in reducing carbon emissions. Their findings show that nuclear energy investment can lower CO_2 emissions in Canada, Japan, and the UK, while renewable energy investments demonstrate positive impacts in Canada, Germany, the UK, the US, and Japan. The study also reveals that simultaneously using nuclear and renewable energy sources can lead to even more substantial emissions reductions. Furthermore, Nejat et al. (2015) affirmed the long-term effectiveness of nuclear and renewable energies in reducing CO_2 emissions. The growing trend of CO_2 emissions reduction in developed countries, driven by forward-thinking energy policies, has been widely noted. For instance, Shaari et al. (2020) emphasized that renewable energy consumption significantly curtails CO_2 emissions while also highlighting the contributing roles of economic and population growth. Similarly, Jebli et al. (2020) explored the potential for enhanced energy efficiency, finding that renewable energy consumption can negatively affect industrial value added in wealthier nations, underscoring the nuanced dynamics between energy sources and economic factors.

2.3. Population and urban population growth

The effects of population and urban growth on CO_2 emissions vary significantly between countries, reflecting differences in economic development and urbanization trends. In developed nations like the US, the UK, and Japan, both population and economic growth have been major contributors to the rise in CO_2 emissions, as noted by Chotia and Pankaj (2019). However, in upper-middle-income and highly developed countries, the influence of population growth on emissions is less pronounced (Martínez-Zarzoso and Maruotti, 2011). Urbanization also has a complex effect on emissions, with studies like Hwang and Lee (2016) identifying a non-linear relationship between urbanization and per capita CO_2 emissions, particularly in low-income countries, where rapid urbanization can either increase or mitigate emissions based on infrastructure and development policies. These findings underscore that while population and urban growth are crucial factors influencing emissions, their specific impacts vary widely across nations depending on their income levels and development trajectories.

2.4. The GDP growth effect on CO_2 emissions

The relationship between GDP growth and CO_2 emissions in developed countries is complex in nature, showing significant variation across different nations. Research indicates that GDP growth positively and significantly affects CO_2 emissions in G20 countries (Ramadhan et al., 2023). However, this relationship is not uniform across all G20 nations, as some countries may need to limit their economic growth to achieve emission reduction targets. The link between GDP growth and CO_2 emissions is shaped by several factors, including energy consumption, energy intensity, and the structure of energy sources (Dugu and Liu, 2011). In addition, renewable energy consumption, eco-innovation, and trade openness have been identified as potential mitigating factors in reducing CO_2 emissions (Olanrewaju et al., 2022). Thus, while a general trend of rising CO_2 emissions with GDP growth is observed, the nature of this relationship is complex and influenced by multiple dynamics, which this study aims to explore in detail (He et al., 2024).

2.5. Trade openness

The relationship between trade openness and CO_2 emissions is complex and varies significantly across countries. In nations like the USA and Canada, increased trade openness and economic growth have been linked to higher CO_2 emissions (Ansari et al., 2020). However, this effect is not uniform, as studies have shown that trade openness in high-income and upper-middle-income countries can reduce carbon emissions (Wang and Zhang, 2020). Various factors contribute to these differences, such as energy consumption patterns, per capita income, and the presence of a turning point in the EKC. Additionally, the influence of trade openness on CO_2 emissions is shaped by the ability of countries to substitute energy sources and leverage economic and technological advancements to reduce emissions (Chen et al., 2021). This variation underscores the need for country-specific strategies to balance trade growth and environmental sustainability.

2.6. Impact of ores and metals exports on CO_2 emissions

The effect of exporting ores and metals on CO_2 emissions varies considerably across different countries, reflecting the complexities of inter-sectoral trade. For instance, Japan's export of automobiles has been associated with increased CO_2 emissions within the country itself. Conversely, the United States has reduced its domestic emissions by relying on imported goods from China; however, this practice has inadvertently contributed to a rise in global emissions (Guo et al., 2010). The nature of CO_2 emissions embedded in international trade further complicates the issue, as evidenced by the fact that both China and the USA are significant exporters of carbon emissions (Zhua et al., 2018). In Canada, the mining industry has recognized the importance of environmental stewardship and has adopted measures to reduce air pollution. Additionally, the composition of export products, alongside factors such as income, urbanization, and economic complexity, significantly influences energy consumption and CO_2 emissions (Can et al., 2021). This multifaceted relationship emphasizes the need for nuanced policies that consider both domestic emissions and the global impact of trade practices

The existing literature highlights significant trends and disparities in CO_2 emissions across industrialized nations, yet it also reveals critical gaps in understanding the underlying factors driving these emissions. As such, this study seeks to address these gaps through two pivotal research questions. The first question focuses on the changes in CO_2 emissions trends over the past three decades in five major economies: Canada, Germany, Japan, the

United Kingdom, and the United States. The study aims to identify the primary drivers behind these trends by analyzing historical data. Factors such as economic growth, population dynamics, energy consumption patterns, and industrial activities will be examined to provide a comprehensive understanding of how each country's unique socio-economic context has shaped its emissions trajectory. This investigation will also consider the interplay between national policies, technological advancements, and market forces influencing emissions, aiming to paint a nuanced picture of the evolving relationship between economic development and environmental sustainability. The second research question delves into the role of renewable energy consumption in influencing national CO_2 emissions levels in the same five countries. This inquiry will assess the effectiveness of renewable energy in reducing emissions while considering additional variables like energy efficiency and technological innovation. By focusing on the potential of renewable energy as a key solution to climate change, the research aims to inform policymakers about viable strategies for achieving emissions reduction targets. Overall, addressing these research questions will contribute to a deeper understanding of the dynamics of CO_2 emissions in industrialized countries and the potential pathways for sustainable development.

2.7. Study objectives

The study aims to achieve two primary objectives. First, it seeks to assess the potential of increased renewable energy consumption in reducing CO_2 emissions and mitigating the environmental impact caused by industrial activities in the selected G20 countries. This objective highlights the critical role of renewable energy in addressing climate change and emphasizes the need for a transition towards more sustainable energy sources to lessen the ecological footprint of industrialization. Second, the study intends to investigate and identify the primary drivers behind the changes in CO_2 emissions within these G20 nations. It will explore various influencing factors, including economic growth, shifts in industrial practices, consumption patterns related to energy and renewable resources, demographic changes, urban population growth, technological advancements, policy implementations, and other relevant elements. By examining these drivers, the research aims to uncover the complex interactions influencing emissions trends in these countries.

Overall, this investigation into the impact of CO_2 emissions aims to provide valuable insights to enrich the ongoing discourse on renewable energy consumption in G20 nations. The findings are expected to serve as a crucial resource for policymakers, researchers, and industry stakeholders, guiding them toward developing more effective and sustainable strategies for reducing emissions. By highlighting the significant role of renewable energy, the research will facilitate the transition to cleaner energy sources and promote greater environmental sustainability. Additionally, this study seeks to enhance the understanding of the interplay between CO_2 emissions and various driving factors across different G20 countries. By examining the intricate relationships between economic growth, industrial practices, energy consumption patterns, and policy implementations, the research will illuminate pathways for significant reductions in greenhouse gas emissions.

3. Data and model specification

3.1. Data

This research investigates the factors that can influence CO_2 emissions in the selected sample of G20 countries from 1990 – 2014. In this context, this study considers variables such as electric power consumption, FDI, fuel exports (FUEL), the GDP, metal exports (ME), population, renewable energy consumption (RNEW), trade volume (TRD), urban population growth (URB) and is a dummy variable to capture the great recession of 2008. Current research includes electric power consumption (ELE) reflecting energy usage within a country. Higher electric power consumption indicates a greater dependence on energy-intensive activities and technologies, such as industrial manufacturing, transportation, and residential energy use. These activities and technologies often rely on fossil fuel-based energy sources, like coal, oil, and natural gas, which result in higher CO_2 emissions. Therefore, keeping track of electric power consumption to monitor their impact on the environment is essential. The variable FDI, measured as net inflows as a percentage of GDP, is also included, as it captures the role of international capital flows in economic activities The effect of FDI on CO_2 emissions is determined by multiple factors such as the type of investments, the technologies transferred, regulatory frameworks, and the industrial structure of the country hosting the investment. Effective government policies, regulations, and incentives are necessary to leverage the potential benefits of FDI for reducing CO_2 emissions and promoting sustainable development.

The study further accounts for FUEL expressed as a percentage of total merchandise exports, which highlights the role of fossil fuel-dependent economies in driving global CO_2 emissions. Fuel exports can affect global CO_2 emissions, but this impact can vary significantly depending on how the importing country utilizes the fuel. If it replaces dirtier energy sources, the impact may be less. However, the impact may be greater if the fuel contributes to overall energy consumption without replacing existing carbon-intensive fuels. International agreements and policies, such as carbon pricing and emissions trading, are designed to address these emissions and create incentives for reducing global CO_2 emissions.

The GDP, measured in current U.S. dollars, also captures the overall economic output, as economic growth often leads to increased energy consumption and emissions. Another important factor is ME, measured as a percentage of merchandise exports, which may also be linked to environmental degradation and CO_2 emissions, especially in resource-dependent economies. Metal exports constitute a significant portion of merchandise exports for many resource-rich countries. These exports contribute to CO_2 emissions through several stages; each stage can vary greatly depending on various factors, such as the type of metal, the extraction method, and the distance transported. Some ores, like those for rare earth elements, can be incredibly energy-intensive. In contrast, others, such as aluminum, are particularly energy-intensive to refine because of the electrolysis process. Countries that rely heavily on the export of ores and metals may have exceptionally high carbon footprints from these sectors, and their economic reliance on these exports can make transitioning to lower-carbon industries challenging. The demographic factor of the population (POP) is included to account for the scale of the population, as larger populations typically demand more energy and resources, which in turn can contribute to higher emissions. The impact of population on CO_2 emissions is complex and substantial. While the population's size does affect CO_2 emissions, consumption levels and technologies used to produce goods and services are equally, if not more, significant. Countries with smaller populations but higher levels of wealth can often have a larger carbon footprint per capita than larger, less wealthy nations. Therefore, focusing on the carbon intensity of economic activities and consumption patterns is crucial to addressing climate change effectively (Işık et al., 2024).

The study examines RNEW as a percentage of total final energy consumption to explore the transition towards sustainable energy. This variable helps to assess the extent to which renewable energy use has impacted CO_2 emissions over time. Increasing renewable energy use typically reduces CO_2 emissions. This is because renewable energy can replace fossil fuels, the main source of CO_2 emissions. Additionally, increasing renewable energy use signals to the economy that low-carbon technologies are preferred, which can lead to less investment in fossil fuel-based infrastructure (Shaheen, 2023). Furthermore, TRD, expressed as a percentage of GDP, is considered to understand the role of international trade in driving economic activity and its associated emissions. The relationship between trade as a percentage of GDP and CO_2 emissions is intricate and has several aspects. On the one hand, outsourcing, carbon leakage, and transportation missions can increase emissions. On the other hand, trade can provide opportunities to reduce emissions by promoting more efficient production, cleaner energy sources, and sustainable consumption patterns. The variable URB is included to capture the effects of increasing urbanization, which often leads to greater energy demand and emissions. Multiple factors, including urban planning, infrastructure development, transportation policies, and energy sources influence the correlation between CO_2 emissions and urban population growth. Sustainable development strategies that prioritize energy efficiency, renewable energy deployment, public transportation, and waste management should be implemented to reduce the carbon footprint associated with urbanization while accommodating growing populations. This will help cities reduce their environmental impact while supporting their growth. Lastly, a dummy variable (RECDM) is introduced to account for the effects of the 2008 global financial crisis, which had significant economic impacts worldwide, potentially influencing energy consumption and CO_2 emissions during the recessionary period. Data for all variables is extracted from the World Bank database (Table 1). Table 1 provides a detailed description of each variable.

Table 1: Variables description

Variables	Description	Source
CO_2E	CO_2 emissions	
ELE	Electric power consumption in kWh per capita	
FDI	Foreign direct investment, net inflows (% of GDP)	
FUEL	Fuel exports (% of merchandise exports)	
GDP	GDP (current US$)	
ME	Ores and metals exports (% of merchandise exports)	World Bank database
POP	Population, total	
RNEW	Renewable energy consumption (% of total final energy consumption)	
TRD	Trade (% of GDP)	
URB	Urban population growth (annual %)	
RECEDM	Dummy Variable for Recession in 2008	

3.2. Model specifications

To determine the factors influencing CO_2 emissions in selected G20 countries, this research specifies the model as follows:

$$\log(CO2E)_{i,t} = \beta_0 + \beta_1 ELE_{i.t} + \beta_2 FDI_{i.t} + \beta_3 FUEL_{i.t} + \beta_4 GDP_{i.t} + \beta_5 ME_{i.t} + \beta_6 POP_{i.t} + \beta_7 RECDM_{i.t} + \beta_8 RNEW_{i.t} + \beta_9 TRD_{i.t} + \beta_{10} URB_{i.t} + \varepsilon_{i.t} \quad (1)$$

where, CO_2E represents CO_2 emissions in metric tons per capita, while ELE refers to the electric power consumption for country i at time t. FDI denotes foreign direct investment, measured as net inflows as a percentage of GDP. FUEL corresponds to the percentage of fuel exports in total merchandise exports, and GDP is the gross domestic product measured in current US dollars. ME represents ore and metal exports as a percentage of merchandise exports, and POP refers to the total population. The variable RECDM is a dummy for the 2008 recession. RNEW captures renewable energy consumption as a percentage of total final energy consumption, TRD measures trade volume as a percentage of GDP, URB represents urban population growth and, finally, ε is the error term.

To investigate the impact of these selected variables on CO_2 emission in the sample of G20 countries, the current study employs panel fixed effects and GLS random effect models. The choice of econometric models for this study, specifically the panel fixed effects and GLS random effects models, is rooted in the objective of thoroughly analyzing the impact of various factors on CO_2 emissions in G20 countries. The panel fixed effects model is particularly suitable for this research as it effectively controls unobserved heterogeneity among countries, allowing for a more accurate assessment of the relationship between independent variables and CO_2 emissions. By focusing on variations within each country over time, this model mitigates the influence of time-invariant factors, such as geography and cultural characteristics, which may otherwise distort the results. This aligns with the research objective of identifying the primary drivers behind changes in CO_2 emissions, as it facilitates a clearer understanding of how specific variables, such as economic growth and renewable energy consumption, influence emissions trends over the study period.

On the other hand, the GLS random effects model is employed to capture both within- and between-country variations, offering a broader perspective on the determinants of CO_2 emissions. This model assumes that unobserved country-specific effects are uncorrelated with the explanatory variables, which allows for the inclusion of time-invariant variables that may be relevant to the analysis. By integrating both fixed and random effects, the study can provide a comprehensive examination of the impact of renewable energy consumption and other factors on CO_2 emissions across diverse G20 nations. This dual approach aligns with the research objective of assessing the potential of increased renewable energy consumption to reduce emissions and mitigate environmental impacts, as it facilitates a more nuanced exploration of the interplay between various drivers and emissions levels.

However, despite their advantages, both models come with inherent limitations that must be acknowledged. The fixed effects model, while effective in controlling unobserved heterogeneity, excludes time-invariant variables, potentially resulting in an incomplete understanding of all influences on CO_2 emissions. Additionally, this model may lead to a loss of degrees of freedom, reducing the statistical power of the analysis, particularly when the dataset has a limited number of time periods. Moreover, the assumption of homogeneity—where the impact of explanatory variables is considered uniform across all countries—may not hold true for the diverse G20, where nations exhibit varying economic structures and environmental policies. Conversely, the GLS random effects model relies on the assumption that unobserved country-specific effects are uncorrelated with the independent variables. If this assumption is violated, it can lead to biased estimates, affecting the validity of the conclusions drawn from the analysis. This model is also less robust to misspecification compared to fixed effects, meaning that inaccuracies in underlying assumptions may yield unreliable results. Additionally, while the random effects model captures both within- and between-country variations, it risks overgeneralizing findings that may not adequately reflect individual countries' specific contexts.

Both models also depend heavily on the quality and availability of data, as incomplete or inconsistent data can introduce bias and limit the robustness of the findings. Furthermore, they may struggle to capture dynamic relationships over time, such as the lagged effects of changes in renewable energy consumption on CO_2 emissions. External shocks, such as economic crises or natural disasters, can significantly impact emissions but may not be adequately accounted for in the analysis. While these econometric models provide valuable insights into the determinants of CO_2 emissions, recognizing these limitations is crucial for enhancing the validity and applicability of the research findings.

4. Results and analysis

This research begins by analyzing the descriptive statistics of the selected variables to provide an overview of the data used in the study. The descriptive analysis given in Table 2 reveals the mean level of CO_2 emissions is 1,676,459.4 metric tons, with a standard deviation of 1,868,232.1, indicating substantial variability in emissions across countries. The minimum value recorded is 413,298.6 metric tons, while the maximum reaches 5,775,807.2 metric tons, reflecting the differences in industrial activity and energy use among these nations. The average electricity consumption per capita is 9,983.987 kWh, with a standard deviation of 4,084.982 kWh. The minimum and maximum values are 5,130.39 kWh and 17,264.737 kWh, respectively, showcasing considerable variation in electricity usage across countries, likely due to differing energy infrastructures and economic development levels.

In addition, the average net inflows of FDI as a percentage of GDP is 2.081, with a standard deviation of 2.365. The minimum value is -0.725, indicating a net outflow of FDI in some instances, while the maximum reaches 12.732, highlighting significant variation in foreign investment levels across the sample. The mean percentage of FUEL as a share of merchandise exports is 6.518, with a standard deviation of 7.02. The minimum recorded value is 0.293, while the maximum is 29.136, suggesting that some countries in the sample are more dependent on fuel exports than others. The average GDP is 4.376 trillion USD, with a standard deviation of 4.078 trillion USD. The GDP ranges from a minimum of 579.1 billion USD to a maximum of 17.55 trillion USD, reflecting the significant differences in the economic size of the selected G20 countries. The average percentage of ore and ME as a share of merchandise exports is 3.287, with a standard deviation of 1.902. The minimum value is 0.81, and the maximum is 9.244, indicating variability in the reliance on metal exports across these nations. The average population across the selected countries is 117.2 million, with a standard deviation of 90.95 million. The population ranges from 27.69 million to 318.4 million, reflecting the wide population disparities between the G20 countries. The mean percentage of RNEW as a share of total final energy consumption is 8.036, with a standard deviation of 7.419. The minimum value is 0.61, while the maximum is 22.67, indicating a broad range in the adoption of renewable energy technologies.

Table 2: Descriptive statistics

Variable	Obs	Mean	SD	Min	Max
CO_2E	125	1676459.4	1868232.1	413298.6	5775807.2
ELE	125	9983.987	4084.982	5130.39	17264.737
FDI	125	2.081	2.365	-.725	12.732
FUEL	125	6.518	7.02	.293	29.136
GDP	125	4.376e+12	4.078e+12	5.791e+11	1.755e+13
ME	125	3.287	1.902	.81	9.244
POP	125	1.172e+08	90945467	27691138	3.184e+08
RNEW	125	8.036	7.419	.61	22.67
TRD	125	46.274	20.718	15.723	86.514
URB	125	.895	.578	-1.602	2.283

Obs: Observation; SD: Standard deviation

Table 3 provides the pairwise correlations between the variables, which provides insight into the relationships between CO_2 emissions (CO_2E) and other factors such as electricity consumption, FDI, fuel exports, GDP, and other variables. CO_2 emissions are significantly correlated with several variables. For instance, there is a positive and significant correlation with FUEL (0.353***), GDP (0.283***), and TRD (0.286***). This suggests that higher CO_2 emissions are associated with higher levels of fuel exports, economic output, and trade activity. Furthermore, there is a significant correlation between CO_2E and URB, indicating that urbanization shows a direct statistical relationship with emissions in this sample.

Table 3: Pairwise correlations

Variables	CO_2E	ELE	FDI	FUEL	GDP	ME	POP	RNEW	TRD	URB
CO_2E	0.008	0.004	1.000							
ELE	0.039	0.016	0.327***	1.000						
FDI	0.117	0.111	-0.169*	0.027	1.000					
FUEL	0.353***	0.122	-0.258***	0.530***	0.345***	1.000				
GDP	0.283***	0.063	0.890***	0.190**	-0.208**	-0.258***	1.000			
ME	0.229**	0.121	-0.231***	0.677***	0.242***	0.845***	-0.269***	1.000		
POP	0.059**	0.010	0.968***	0.166*	-0.252***	-0.391***	0.944***	-0.385***	1.000	
RNEW	0.185**	0.028	-0.203**	0.808***	0.082	0.667***	-0.242***	0.839***	-0.340**	1.000
TRD	0.286***	0.075	-0.597***	0.090	0.400***	0.479***	-0.588***	0.536***	-0.698**	0.551***
URB	-0.132**	0.023	0.358***	0.560***	-0.023	0.242***	0.168*	0.276***	0.259***	0.254***

***: p<.01, **: p<.05, *: p<.1

Table 4 provides the estimation results from the four alternate specifications of the model given in Eq. 1. These models are estimated through generalized least squares random effect and fixed effect models using robust standard errors. The estimates in Table 3 show a positive and statistically significant impact of electricity consumption on CO_2 emissions in the selected G20 countries across all estimated models. This finding suggests that higher levels of electricity consumption are strongly associated with increased CO_2 emissions, reinforcing the notion that energy usage, particularly from non-renewable sources, plays a crucial role in driving carbon emissions in industrialized nations. Given that many of these countries rely heavily on fossil fuels for electricity generation, the positive impact of electricity consumption on emissions aligns with expectations that greater energy use, without a substantial shift toward cleaner energy sources, will lead to higher carbon emissions. Furthermore, the estimate in Table 4 also indicates a positive and statistically significant impact of economic growth, population growth, larger trade volumes, and increased urbanization in the selected countries. Economic growth, measured through GDP, is positively correlated with higher emissions, suggesting that as these countries expand their economic activities, energy consumption and industrial output increase, leading to greater carbon emissions. This relationship highlights the environmental costs associated with economic development, particularly in industrialized nations where energy-intensive industries are prevalent.

Similarly, population growth contributes significantly to rising CO_2 emissions, as a larger population generally demands more energy for transportation, housing, and other essential services, thereby increasing the overall carbon footprint. The positive impact of trade volume highlights the role of global commerce in driving emissions, as higher trade activity often involves increased transportation, production, and energy use, all of which contribute to CO_2 output. In addition, urbanization, characterized by the expansion of cities and increased urban population growth, also shows a statistically significant relationship with rising emissions. Urban areas typically concentrate on economic activities and energy demand, leading to greater environmental pressure, particularly when cities are reliant on fossil fuels for energy and transportation. This finding emphasizes the challenges of managing environmental sustainability in rapidly urbanizing economies, where the infrastructure and energy systems may struggle to keep pace with the growing demand for resources. These combined factors underline the multifaceted drivers of CO_2 emissions in G20 countries, highlighting the need for comprehensive policy interventions that address economic, demographic, and trade-related determinants of environmental sustainability.

Conversely, the estimates in Table 2 reveal a negative and statistically significant impact of FDI, renewable energy consumption, and the 2008 global financial crisis (represented by a dummy variable for the great recession) on CO_2 emissions in the selected G20 countries. The negative relationship between FDI and CO_2 emissions suggests that foreign investment, particularly in more advanced and regulated economies, may lead to the transfer of cleaner technologies and more efficient production processes, thereby reducing the overall carbon footprint. This finding challenges the traditional "pollution haven" hypothesis, which posits that foreign investments tend to increase emissions in host countries, and instead points to the potential of FDI to drive sustainability initiatives.

Renewable energy consumption also has a negative and statistically significant effect on CO_2 emissions, underscoring the critical role that transitioning to renewable energy sources plays in reducing carbon output. As countries increase the share of renewable energy in their overall energy mix, the reliance on fossil fuels diminishes, leading to lower emissions. This result highlights the importance of scaling up investments in renewable energy technologies to mitigate the environmental impact of economic activities in G20 countries.

Additionally, the Great Recession of 2008 significantly negatively affected CO_2 emissions, reflecting the economic downturn's impact on energy consumption and industrial production (Table 3). During the recession, many countries experienced reduced economic activity, leading to lower energy demand and, consequently, a decline in emissions. This temporary reduction in emissions during a period of economic contraction illustrates the direct link between economic cycles and environmental outcomes, emphasizing the importance of decoupling economic growth from carbon emissions through structural changes in energy use and production.

Table 4: Model estimation

	FE	RE	RE	RE
	LCO_2E	LCO_2E	LCO_2E	LCO_2E
LELE	.057**	.989***	1.008***	.972***
	(.03)	(.071)	(.082)	(.05)
LFDI	-.004**	-.01**	-.009**	-.011*
	(.0002)	(.007)	(.0008)	(.009)
LFUEL	-.051	-.014	.005	
	(.031)	(.055)	(.033)	
LGDP	.157**	.139***	0.003**	.153*
	(.056)	(.09)	(.026)	(.012)
LME	-.026	.085		.064
	(.01)	(.004)		(.03)
LPOP	.354	1.352***	1.355***	1.37***
	(.213)	(.16)	(.163)	(.145)
LRNEW	-.207***	-.148***	-.138***	-.138***
	(.019)	(.052)	(.045)	(.029)
LTRD	.249***	.217**	.246*	.211**
	(.043)	(.095)	(.126)	(.094)
LURB	.002**	.014**	.01**	.015**
	(.001)	(.0009)	(.002)	(.007)
ReceDM	-.012**	-.042*	-.032*	-.04*
	(.003)	(.025)	(.038)	(.032)
_cons	2.914	-16.545***	-16.739***	-16.309***
	(2.78)	(1.536)	(1.641)	(1.09)
Observations	116	116	116	116
Within R^2	.846	.88	.89	.89

Robust standard errors are in parentheses; ***: p<.01, **: p<.05, *: p<.1; LELE: Log of electric power consumption; LFDI: Log of foreign direct investment; LFUEL: Log of fuel exports; LGDP: Log of gross domestic product; LME: Log of metal exports; LPOP: Log of population; LRNEW: Log of renewable energy consumption; LTRD: Log of trade volume; LURB: Log of urban population growth; ReceDM: Recession dummy variable; _cons: Constant term in regression models; FE: Fixed effect; RE; Random effect

5. Conclusion

The primary aim of this research was to investigate the key determinants of CO_2 emissions in selected G20 countries for the period 1990–2014, focusing on a range of economic, demographic, and energy-related variables. The study analyzed the impact of electricity consumption, FDI, FUEL, GDP, metal exports, population growth, renewable energy consumption, trade volume, urbanization, and the global recession of 2008. The findings offer valuable insights into the drivers of carbon emissions, providing a basis for policy recommendations aimed at mitigating environmental degradation while fostering sustainable development. The results confirm a strong, positive relationship between electricity consumption and CO_2 emissions, indicating that energy use remains a dominant factor in explaining emissions in the selected G20 countries. Economic growth, population size, and trade volume also show significant positive correlations with emissions, highlighting the environmental costs of industrial expansion, population pressures, and global trade. Urbanization, which is often associated with economic and industrial activities, similarly contributes to rising emissions, particularly as cities expand and energy demand increases. These findings underscore the need for these economies to decouple economic growth and urban expansion from carbon-intensive energy consumption.

On the other hand, the study also reveals that FDI, renewable energy consumption, and the 2008 global recession had a negative and significant impact on CO_2 emissions. Increased FDI, potentially through the introduction of more efficient technologies and sustainable practices, helped reduce emissions in the selected countries. Renewable energy consumption was found to have a mitigating effect on carbon emissions, further reinforcing the importance of transitioning toward clean energy sources. Additionally, the global recession of 2008 served as an economic shock that temporarily reduced emissions, likely due to a slowdown in industrial activities. These findings suggest that policy interventions promoting renewable energy adoption and sustainable foreign investments can play a vital role in reducing the environmental impact of economic growth.

From a policy perspective, the results emphasize the need for G20 countries to focus on energy-efficient technologies and the expansion of renewable energy infrastructures to reduce their dependency on carbon-intensive energy sources. Policies that incentivize the adoption of renewable energy, enhance energy efficiency, and facilitate green investments should be prioritized to achieve long-term reductions in CO_2 emissions. Urbanization policies must also promote sustainable city planning, including the development of energy-efficient transportation systems and infrastructure. Finally, measures to encourage trade practices with a lower environmental footprint are essential, as trade volumes are shown to exacerbate emissions in the context of energy-intensive sectors. In conclusion, this study provides evidence that addressing CO_2 emissions in the G20 countries will require a multifaceted approach that integrates energy efficiency, green technology adoption, and sustainable urban and trade policies. As these economies continue to grow, it is critical to implement strategies that mitigate the environmental impact of industrial activities and population growth, while promoting sustainable and inclusive economic development. The findings of this research contribute to the ongoing dialogue on balancing economic growth with environmental sustainability, offering actionable insights for policymakers working to reduce emissions and achieve long-term environmental goals.

This research's limitations include its focus on only five G20 countries and the use of linear regression models, which may not fully capture the complex relationship between CO_2 emissions and renewable energy consumption. The data is limited due to the time limit of this research; the data sample only covers up to 2014. Many developments and changes have happened in recent years, which is essential to capture and study. Further research opportunities could include expanding the scope to include more countries and utilizing different methods to understand better the factors influencing CO_2 emissions. Future research could also explore the effectiveness of specific policies and strategies in reducing emissions in these countries.

List of abbreviations

CCS	Carbon capture and storage
CO_2	Carbon dioxide
CO_2E	Carbon dioxide emissions
EKC	Environmental Kuznets curve
ELE	Electric power consumption
FDI	Foreign direct investment
FE	Fixed effect
FUEL	Fuel exports
GDP	Gross domestic product
GLS	Generalized least squares
ME	Metal exports
POP	Population
RE	Random effect
RECDM	Dummy variable for recession in 2008
RNEW	Renewable energy consumption
TRD	Trade volume
UK	United Kingdom
URB	Urban population growth
US	United States
USA	United States of America
USD	United States dollar

Compliance with ethical standards

Conflict of interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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