

RESEARCH ARTICLE

Renewable realities: Charting a greener course for the world's high-emitting nations through information technology insights

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Abstract

Carbon dioxide (CO₂) is the most abundant gas among all greenhouse gas emissions, severely impacting global warming. This study examines the impact of Information and Communication Technology (ICT), population dynamics, Per Capita Gross Domestic Product (PGDP), and Renewable Energy Consumption (REC) on CO₂ on a global scale, representing 38 countries selected using the Pareto principle. Results from the panel regression model indicate a significantly positive relationship between ICT, PGDP, and population on CO₂ emissions. In contrast, REC exhibits a negative relationship. The Multiple Linear Regression model shows that an increase in PGDP leads to higher CO₂ emissions, except in Uzbekistan. ICT increases emissions in the United States, Argentina, Australia, Canada, and Egypt. Population growth raises emissions, except in the United States, France, Germany, and Russia. REC reduces CO₂ emissions in most countries. Policymakers in individual countries can gain a precise understanding of how these variables impact CO₂ emissions, enabling them to mitigate the risks associated with global warming.

KEYWORDS

CO₂ emission, information and communication technology, panel regression, per capita gross domestic production, population, renewable energy consumption

1 | BACKGROUND

Global warming is the long-term warming of the earth's surface caused by human activity since the pre-industrial period (1850–1900), a critical issue that has been a global threat (NASA, 2023). Some atmospheric gases absorb and re-emit infrared radiation from the atmosphere to the earth's surface, contributing to global warming. The greenhouse effect causes a mean surface temperature of 33°C higher than normal (World Meteorological Organization, 2022). Out of the five major greenhouse gases, specifically carbon dioxide (CO₂) emissions are mentioned as one of the leading causes of climate change across the globe, and it has become one of the world's most concerning issues that highly impact the environment (Environmental Protection Agency, 2023; Li, Siu, & Zhao, 2021).

The current study focuses on CO₂ as one of the main study variables since it is the most abundant among the other greenhouse gases. CO₂ is released into the atmosphere mainly in two ways: by human activities and through natural incidences. Excessive CO₂ emission causes severe damage to the environment. CO₂ emissions stem from burning fossil fuels, consumption of solids, liquids, gas fuels, gas flaring, cement manufacture, deforestation, land clearing for agriculture, and degradation of soils. The primary sources of CO₂ emissions are fossil fuels such as coal, natural gas, and oil, which are the primary catalysts for climate change (Jahanger et al., 2023).

Climate change occurs due to CO₂ in the atmosphere, which warms the earth (NASA, 2023; Rezza, 2013). Due to humans' activities in under 200 years, the content of CO₂ has increased by 50% in the atmosphere. As of June 2023, the CO₂ rate is measured at 421 ppm, whereas in 1958, it was measured at 314.43 ppm, having

an expeditious growth rate of 133.89%, signalling potential warnings towards the environment (NASA, 2023). Further, the earth's global average surface temperature in 2020 tied with 2016 as being the hottest year on record, continuing a long-term warming trend caused by human activity. As of 2022, the global temperature has been measured as an annual average anomaly of 0.89°C (NASA, 2023).

Furthermore, the heat emitted from the ocean causes its water to expand, accounting for one-third to one-half of the global sea level increase. Much of the additional energy is stored at the surface, at depths ranging from zero to 700 m. The last 10 years have been the warmest decade in the ocean since 1800. The year 2022 was the ocean's warmest recorded year, with a value of 345 zettajoules and the highest global sea level (NASA, 2023). The increase in the surface temperature of oceans causes the heat stored in oceans, resulting in ice sheets melting, eventually increasing the global sea level. Antarctica loses ice mass (melts) at a pace of roughly 150 billion tons yearly, whereas Greenland loses about 270 billion tons annually, contributing to rising sea levels (NASA, 2023).

Moreover, global sea levels have risen unprecedentedly in the last 2500 plus years. As of February 2023, the sea level is 99 mm; 98.5 mm has risen since (NASA, 2023). Each September, the Arctic Sea ice is at its minimum. Compared to its average extent from 1981 to 2010, September Arctic Sea ice is now shrinking at 12.6% per decade (NASA, 2023).

Per Capita Gross Domestic Production (PGDP), ICT, Population, and Renewable Energy Consumption (REC) were selected as key variables for this study because they represent fundamental drivers of CO₂ emissions across nations. PGDP is a key indicator of a nation's economic development and is often associated with industrialisation and increased energy consumption, which tends to elevate CO₂ emissions. This variable was selected because economic growth plays a central role in shaping energy policies, industrial practices, and technological investments. As nations develop, their energy needs expand, often increasing emissions; however, a higher economic output can also support cleaner technologies and environmental regulations, making PGDP a crucial factor in emissions analysis. ICT was chosen due to its rapidly growing role in modern economies. The digital infrastructure and technological advancements in ICT sectors can increase energy demand, contributing to emissions. However, ICT also promotes energy efficiency and innovations in renewable technologies, offering a potential pathway for reducing emissions. The dual role of ICT as both a contributor to and mitigator of carbon emissions makes it an essential variable in this study. Population growth directly impacts energy demand, as a larger population requires more resources, transportation, and energy—especially in countries reliant on fossil fuels. Population pressure intensifies emissions through increased consumption and production activities. Given that demographic expansion is a global phenomenon, it was necessary to include population as a critical driver of CO₂ emissions in the study. REC was selected because it represents a key element in the transition towards low-carbon energy sources. Higher REC levels are typically associated with reduced reliance on fossil fuels, which are significant contributors to CO₂ emissions. As renewable energy production emits far less

carbon compared to traditional energy sources, understanding the role of REC is vital for assessing its effectiveness in reducing emissions.

Thus, the objective of the current study is to analyse the impact of Per Capita Gross Domestic Production (PGDP), ICT, Population, and Renewable Energy Consumption (REC) on CO₂ for the highest carbon-emitting 38 countries across the globe. This study differs from past studies in three ways. Firstly, this research addresses the knowledge gap by collectively examining the impact of PGDP, ICT, Population, and REC on CO₂ in 38 countries, which will be a recent addition to the literature. The 38 countries have been chosen based on the Pareto principle; this approach ensures a targeted investigation into the critical contributors to global carbon emissions, aligning with the 80–20 rule's insight that a concentrated effort on a minority of factors can yield substantial impacts on the observed phenomenon. The focus is on understanding the intricate relationship between economic development, technological progress, population dynamics, and environmental sustainability. Hence, the study aims to provide valuable insights into the interconnected factors influencing CO₂ emission.

Secondly, the study endeavours to narrow existing literature gaps through data analysis using the panel regression and the Multiple Linear Regression (MLR) models. By comprehensively investigating the environmental implications of the examined variables on a global scale, the research aims to elucidate the individual impacts of these factors on CO₂ emissions for each country. This enables researchers to uncover the varied effects and relationships of CO₂. The study could help determine what specific strategies or policies should be implemented to mitigate CO₂ emissions according to each country based on selected independent variables.

Lastly, the study provides each country's carbon emissions trend for a deeper understanding. Utilising scatter plot diagrams, the trends allow us to visualise the relationship between CO₂ and different time ranges for 38 countries. This helps to identify whether the emissions increase, decrease, or remain constant over time. Moreover, it helps to compare the patterns and fluctuations and the policymakers would be able to make decisions by identifying the outliers or which countries needed to be focused more on due to high and low emissions. This contributes to providing a clear impact on the representation of trends that assist in targeting reductions of CO₂ by innovative environmental projects and identifying areas for investments in the development of new sustainable energy and technologies.

2 | LITERATURE REVIEW

Several studies have been conducted to identify factors influencing CO₂ emission. These studies have been conducted based on regional and global contexts, income, and organisational levels. The current study determines the effects of PGDP, ICT, population, and REC on CO₂ emission in selected 38 nations. A substantial portion of countries from the 38 countries subjected to the current study has been examined previously by researchers. Moreover, many papers have been written based on prominent nations such as China, the US, India, BRICS countries and G7 countries. The study aims to deliver valuable

insights into the collective impact of how economic growth, technological advancements, population dynamics, and renewable energy affect CO₂ by synthesising the existing studies focused on different nations and organisations.

2.1 | Per capita GDP and CO₂

Among many factors discussed in prior studies, economic growth emerges as a pivotal factor closely linked to increased energy consumption, often leading to higher CO₂ emissions. As economies grow, they tend to consume more energy for various activities, such as manufacturing, transportation, and electricity generation, contributing to the increase in greenhouse gas emissions, including CO₂.

Countries with a low PGDP have shown a positive relationship between economic growth and environmental degradation, whereas it states a negative relationship exists between those high PGDP countries (Awan & Azam, 2022; Heidari et al., 2015). Indonesia, Australia, Japan, Canada, Chile, China, Malaysia, Russia, the US, and Mexico show a positive relationship between PGDP and CO₂ emission (Wang et al., 2020). Both in the short run and the long run, Pakistan has a positive relationship between CO₂ emissions and economic growth (Khan et al., 2020). Data collection from 70 countries proves a significant positive impact on economic growth and CO₂ emission, conducted through the Pooled Ordinary Least Squares (OLS) test (Osobajo et al., 2020). India has a positive relationship between economic growth and the CO₂ emission (Shahbaz et al., 2021). Economic growth will lead to environmental degradation, and other variables like renewable energy, international trade, and Foreign Direct Investment (FDI) inflow will lead to decreased CO₂ emission with a bidirectional impact on Middle East and North African (MENA) countries (Kahia et al., 2019).

The economic growth of seven countries of the Association of Southeast Asian Nations (ASEAN) reveals that with REC, CO₂ emissions in countries have been reduced (Vo & Vo, 2021). Since 2007, the economic growth of the US has been compatible with CO₂ emissions. Decoupling efforts reveal a contribution to decoupling economic growth of CO₂ emission from Research and Development (R&D) efficiency, sectoral carbon intensity, and energy intensity (Q Wang & Wang, 2019). In China, CO₂ emission hurts economic growth when upgrading industrial structures (Dong, Xu, & Fan, 2020). The South and Southeast Asia (SSEA) region has confirmed that the Environmental Kuznets Curve (EKC) has an inverted U-shaped curve. This means that, at first economic growth increases environmental degradation, but later, it will reduce the impact of carbon emissions on the environment (Arshad et al., 2020).

Economic growth, CO₂ emission, and energy consumption are related to one another (Muhammad, 2019). Accordingly, in emerging countries and Middle East and North Africa (MENA) countries, CO₂ emission is reduced. At the same time, energy consumption increases due to economic growth, suggesting that developed countries use more eco-friendly energy sources in energy generation. The growing economy will be seen as a solution to prevent environmental

deterioration (Fernandes et al., 2021; Xue et al., 2022). The relationship of the EKC hypothesis in the South Asian region illustrates a positive relationship between economic growth and CO₂ emission at the early stages of economic development in developing countries; however, it decreases gradually with the developed economies (Wen et al., 2021). Factors such as PGDP drive CO₂ emission, while carbon density and population affect emissions as specified (J Zhang et al., 2020). Energy intensity has reduced emissions in most countries. Countries like China and ASEAN require renewable energy policies and green development as long-term goals (Bai et al., 2022; Fang et al., 2022; Han et al., 2022; Islam et al., 2022).

2.2 | ICT and CO₂

Extensive research on the impact of ICT and CO₂ emission provides compelling evidence that ICT penetration from the mobile, internet, and fixed telephone is paramount in enhancing environmental quality. The adoption and utilisation of ICT have shown promising potential in achieving low-carbon development (Khan et al., 2022; Wang et al., 2023). The evaluation of technological advancement through internet penetration, increasing the usage of cellular and fixed telephones, sharing awareness regarding the adverse effects of greenhouse gases, and promoting sustainable practices have paved the way to reduce the carbon footprint for a greener and more sustainable future (Jahanger et al., 2023). ICT has a positive and influential role in effectively mitigating CO₂ emissions in Belt and Road countries (Khan, 2019). Data unequivocally supports that ICT is a potent tool in reducing CO₂ emissions, cutting across all industries (Haini, 2021). The robustness and consistency of these results emphasise the significant contribution of ICT in fostering sustainable practices and addressing environmental challenges worldwide. Promoting widespread use and penetration of ICT can support low-carbon development, achieving a per capita reduction in CO₂ emissions through a profound technical and structural transformation of the economy (Lahouel et al., 2021). Cutting-edge research supports the notion that ICT usage enhances environmental quality (Khan, 2019). The countries Indonesia, Malaysia, Philippines, Vietnam, Thailand, and Singapore have shown a 1% increase in ICT which tend to reduce CO₂ emission by 0.362% and 0.00545% which was employed using the Fully Modified Ordinary Least Square (FMOLS) and Dynamic Ordinary Least Square (DOLS) models (Ahmed & Le, 2021). Therefore, the aforementioned studies have proven a negative relationship between CO₂ emission and ICT, further clarifying that environmental quality can be increased with ICT penetration, reducing CO₂ emission.

Exploring the relationship between ICT and environmental quality, conducted in 21 Sub-Saharan African (SSA) countries using extended stochastic impact by regression model to estimate the effect and transmission channels of ICT on CO₂ emissions (Avom et al., 2020). Proving the effect in total is positive and indicates that ICT worsens the quality of the environment in the SSA countries. ICT use stimulates CO₂ emissions, indirectly positively affecting trade openness, financial development, and energy consumption (Atsu

et al., 2021). The relationship between ICT, energy consumption, and CO₂ emissions in South Africa from 1970 to 2019 is being examined. ICT will contribute to CO₂ emissions increase in the long term, with no threshold effect (Atsu et al., 2021). The countries Egypt, Chile, Argentina, Malaysia, Brazil, Indonesia, Iran, Pakistan, Mexico, Saudi Arabia, Vietnam, Thailand, South Africa, and the United Arab Emirates (UAE) have shown there is a positive relationship between ICT and emissions (Ke et al., 2022). From 43 countries, China, Mexico, Russia, and India have shown that the adaptation of ICT is positive in CO₂ emissions (Chatti, 2021). These studies emphasised the positive effect on CO₂ emission from ICT penetration.

Cointegration in variables across three panels, with ICT and energy consumption positively impacting CO₂ emissions where ICT goods and services are not energy-efficient in potential and advanced countries as per the findings (Arshad et al., 2020). The EKC inverted U-shaped curve suggests economic growth can deteriorate environment quality but mitigate emissions after reaching a threshold CO₂ emission increase, and afterward, a reduction will occur after reaching a certain level.

According to the Panel Quantile Auto Regressive Distributed Lag (PQARDL) model, there is a positive impact. In contrast, according to the Panel Auto Regressive Distributed Lag (PARDL) model, a negative impact has resulted in the long run based on the study's findings (Bildirci et al., 2022). ICT does not appear to have a noticeable effect on environmental quality in Africa (Awad, 2022). These findings underscore the complexity of the relationship between ICT, ecological quality, and economic growth, highlighting the need for further research and informed policies to foster sustainable development.

2.3 | Renewable energy consumption and CO₂

Renewable Energy plays a significant role in clean energy adaptation due to its lower carbon footprint and positive impact on climate change. There is a substantial contribution from CO₂ emissions to climate change, so it is necessary to understand the determinants and policies. With the increasing importance of renewable energies, research is now attempting to evaluate independently the impacts of the energies (Inglesi-Lotz & Dogan, 2018; Mamkhezri & Khezri, 2023).

Based on the cross-sectional dependence model, the relationship between the REC and carbon emission variables has affected 66 developing countries (Akram et al., 2020). Non-renewable Energy Consumption (NREC) increases CO₂ emissions while REC reduces environmental degradation (Sharif et al., 2019). Similarly, the coefficient of the REC is 1% and statistically significant, which has a negative relationship with CO₂ emissions of the SSA, which implies investments in REC will lower carbon emissions and enhance the environment quality (Adams & Acheampong, 2019). Malaysia has shown REC hurts CO₂ emissions, and economic growth and natural resources have a positive effect on CO₂ emission, which summarises that REC contributes to reducing CO₂ emissions (Aeknarajindawat et al., 2020).

Using more REC is a critical strategy for lowering CO₂ emissions (Adebayo et al., 2022). The EKC hypothesis in countries like the

United Kingdom (UK) finds that positive REC use reduces CO₂ emissions and vice versa, with a unidirectional causal impact between renewable energy, fossil fuels, and COVID-19 on CO₂ emissions. Relevant to the EKC curve and the Renewable Energy Kuznets Curve (RKC), a 10% increase in RKC leads to a 1.6% carbon emission reduction (Yao et al., 2019). This promotes the REC, which accelerates the EKC's turning points earlier. Also, this study suggests that the government should promote REC development to reduce CO₂ emissions while maintaining realistic energy policies.

Long-run projections demonstrate that increasing NREC and Gross Domestic Production (GDP) increases CO₂ emissions, which will decrease with the increased use of REC and overseas trade (Chen, Zhao, et al., 2019). Moreover, short-run Granger causality studies reveal bidirectional links between foreign trade, CO₂ emissions, NREC and REC long-term elasticity, which depends on the development stage (Nguyen & Kakinaka, 2019). In the early stages, lower-income countries face a decline in REC, which leads to an increase in NREC. This eventually leads to deterioration of the environmental quality or an increase in CO₂ emissions.

Western and Eastern regions positively impact CO₂ emissions in the NREC, while REC has a negative effect. In contrast, based on the results, the Central region has weak and statistically insignificant effects (Chen, Wang, & Zhong, 2019). The relationship between the utilisation of REC and NREC energy sources on CO₂ emissions and economic advancement across developed, developing, and Least Developed Countries (LDC) and economies in transition has been analysed (Dissanayake et al., 2023). Accordingly, developed countries consume more non-renewable energy, which may directly impact their CO₂ emissions. LDCs emit less CO₂ and use more RE and support, and a bidirectional causality between GDP and CO₂ in transitional economies was identified.

2.4 | Population and CO₂

The population is the total number of citizens in a country despite the legal status of the residents, which is a crucial variable impacting environmental degradation. A study done for 10 newly industrialised countries, namely India, China, Brazil, South Africa, Mexico, Malaysia, Thailand, Philippines, Indonesia and Turkey, also shows a positive impact explaining the increase in one unit of population increase CO₂ by 0.35 units (Ghazali & Ali, 2019).

Considering the Organisation for Economic Cooperation and Development (OECD) Countries, 29 OECD countries out of 35 have shown a positive relationship between CO₂ emission and population. Using the FE model, a 1% increase in population will increase CO₂ by 1.5% (Hashmi & Alam, 2019). This signifies that population is one of the critical drivers of CO₂. At the same time, the same and some other studies have found that the effects of population on CO₂ are elastic. Twenty-eight OECD countries also reveal the same impact between the two variables, implying that development in the economy through industrialisation has tended to increase CO₂ (Doğan et al., 2020).

TABLE 1 Data sources and definition of variables.

Variables	Measure	Source
CO ₂ emissions	Metric tons of CO ₂	https://data.worldbank.org/indicator
PGDP	Per capita GDP (Current US\$)	https://data.worldbank.org/indicator
ICT	Individuals using the internet (% of population)	https://data.worldbank.org/indicator
POP	Total population	https://data.worldbank.org/indicator
REC	Percentage of total final energy consumption	https://data.worldbank.org/indicator

In analysing the impact of population on CO₂ emission, the selected five South Asian Association for Regional Cooperation (SAARC) countries, namely India, Sri Lanka, Pakistan, Bangladesh, and Nepal, have revealed that there is a positive relationship between the population and CO₂ with an elasticity of 1.16% revealing that CO₂ emissions have grown faster than the population (Anser et al., 2020). Moreover, when the elasticity is more than one explanation, the impact on the environment is elevated in developing countries compared to developed countries. Findings show that the high combustion of fossil fuels in residential sectors tends to increase CO₂ emissions. There is a positive impact between CO₂ and the population analysed for 46 SSA countries (Acheampong et al., 2019). Hierarchical regression modelling and findings revealed that out of 50 countries, the US, Japan, China, the UK, and Germany, with high GDPs and populations, are the highest carbon emitters of greenhouse gas emissions Mendonça et al. (2020). Another study done for 130 countries categorising based on income levels also reveals population positively impacts CO₂, mostly in low-income countries. Further, they depict that the population contributes 18% of the growth by CO₂ (Dong, Hochman, & Timilsina, 2020).

The population and CO₂ in Pakistan have a positive impact in the long and short run (Hussain & Rehman, 2021). Further, a study based on the data in Malaysia stated that the model has found a positive effect on CO₂. Nevertheless, it shows an insignificant coefficient in population (Begum et al., 2015). Moreover, population and CO₂ positively impact China, the US, India, Iran, Canada, and Saudi Arabia, while they hurt Russia, Japan, Germany, and South Korea (Alnail Mohammed et al., 2019). Through the method of Logarithmic mean Divisia Index (LMDI), it was proven that population does have a significant impact on CO₂, especially in China and India.

The study differs from the existing literature due to its three main objectives. The first key objective addresses the knowledge gap by examining the impact of PGDP, ICT, Population, and REC on CO₂ emissions in 38 countries. Previous literature has primarily focused on either individual countries or specific groups, such as emerging countries, MENA countries, SSEA regions, SAARC or developing countries. However, beyond the scope of existing research, this study has selected 38 countries that contribute 80% of global carbon emissions, utilising the Pareto Principle. The second knowledge gap is that this

study employs panel regression and MLR models for data analysis, which differentiates it from the existing literature. Finally, to provide a deeper understanding, scatter plot diagrams have been drawn for each country, illustrating the relationships over different time ranges.

3 | METHODS

The study covers 38 countries for 25 years, (1996–2020). Data was extracted through secondary data sources and presented in Appendix S1. The measure and the relevant source of data extraction are summarised in Table 1.

Based on data availability, 190 countries were initially chosen, and examining the aggregate value of carbon emissions for the past 10 years, the countries have been thus ranked. The Pareto principle was used as the next step to select the countries with the highest carbon emissions. The 80–20 rule, or the Pareto Principle, is applied by Robati et al. (2021) to identify the primary sources of embodied carbon and capital cost. This explains why 80% of the carbon emission contribution is from the selected 38 countries, which is 20% from the total 190 countries. The reason for choosing the recent 10 years (2011–2020) was to neutralise the impact of CO₂ emissions during the COVID-19 impact; it was encouraged to analyse 10 years rather than 5 years, which will show a fair overview of each country's CO₂ emission rate.

Initially Equation (1) which represents the panel regression model has been developed to analyse the impact on how PGDP, ICT, REC, and POP impact on CO₂ for the selected 38 countries cumulatively, which represents the panel regression model, was initially developed to analyse how PGDP, ICT, REC, and POP impact CO₂ for the selected 38 countries. At the same time, Equation (2) represents the MLR model for each country individually.

$$\ln CO_{2it} = \beta_0 + \beta_1 \ln POP_{it} + \beta_2 \ln PGDP_{it} + \beta_3 \ln REC_{it} + \beta_4 \ln ICT_{it} + \varepsilon_{it}, \quad (1)$$

$$\ln CO_{2i} = \beta_0 + \beta_1 \ln POP_i + \beta_2 \ln PGDP_i + \beta_3 \ln REC_i + \beta_4 \ln ICT_i + \varepsilon_i. \quad (2)$$

The study model entails natural log values (ln) for all the variables in the study to ensure the normal distribution of data. The equation above, *i* depicts the country and *t* specifies the time. β denotes the coefficients of variables, and ε_{it} denotes the error term of the regression equation.

The descriptive statistic provides a comprehensive overview of the data gathered. To summarise the key features, mean, median, and standard deviation measures are used, offering valuable insights into demographic traits, distributional patterns, and core trends of the variables.

Two tests were done to identify the appropriate statistical model for the study out of, POLS, Random Effect (RE) and Fixed Effect (FE). The Breusch Pagan test selected the best model from POLS and RE. In contrast, the Hausman test was used to identify the preferred

application from RE and FE. Next, examining the impact of all the control variables on CO₂ for each country, MLR was used, and scatter plot diagrams with the linear fit were plotted to examine the effect on CO₂ to specify the trends for each selected country.

The study utilises the Fixed effects model over the Random effects model in the analysis. This choice was made based on Hausman test, a standard econometric technique for selecting between FE and RE models. The Hausman test results indicated that the Fixed effects model was more appropriate, as it provides consistent estimates even in the presence of potential endogeneity. To address concerns regarding endogeneity, the Fixed effects approach controls for time-invariant unobserved heterogeneity by eliminating any bias arising from omitted variables that do not change over time. Thus, by using the Fixed effects model, we ensured that the analysis is robust and reliable, offering a more accurate representation of the interactions within our dataset.

4 | RESULTS

The descriptive statistics of average CO₂, ICT, PGDP, REC, and POP values are 19.55, 2.80, 8.97, 1.83, and 17.92, respectively, in Appendix S2. Based on the summary, China holds the highest average for CO₂, and Chile remains the lowest. For PGDP, the US remains the highest, and Pakistan is the lowest. The Netherlands has the highest average for ICT, and Nigeria has the lowest. Meanwhile, China has the highest POP, and the UAE has the lowest. For REC, Nigeria remains the highest, and the lowest is Saudi Arabia.

To decide on choosing POLS or RE model, the Breusch Pagan test was applied, which conveyed the result $\chi^2(01) = 8721.33$ with a p value $<.01$, indicating that POLS is unsuitable. The Hausman test is used to take the decision $\chi^2(4) = 159.09$ with a p value $<.01$, which explains that RE regression is not appropriate, and the study utilises the FE regression.

The results of the FE and MLR are represented in Appendix S3, comprising the standardised coefficients for the entire model and selected countries. Based on the FE model, GDP, ICT, and POP show a positive impact, while REC negatively impacts CO₂ with a 1% significance level.

According to the MLR results, PGDP shows a substantial positive impact on the model at a significant level of 1%. Out of all the countries, the Philippines, Italy, UK, Kazakhstan, Chile, Ukraine, Netherlands, Poland, Argentina, Iran, Brazil, Algeria, Mexico, Malaysia, Thailand, Vietnam, and Indonesia indicate a positive impact with a 1% significance level, while Czechia, Australia, Spain with a 5% significance level and US, Russia, France with a 10% significance level. In contrast, Uzbekistan adversely affects PGDP with a 5% significance level.

Considering the impact of ICT on CO₂, it shows Argentina, Australia, Canada, Egypt, Indonesia, Iran, Italy, Malaysia, Spain, the US, and Vietnam have a positive impact at a significance level of 1% and Uzbekistan, Germany, with a 5% significance level. In contradiction, there is a negative impact for Poland, Turkey, India, Nigeria, and China

at a 1% significance level and Pakistan, Korea, and Algeria at a 5% significance level.

The coefficient of POP indicates that Algeria, Australia, Brazil, Chile, China, Egypt, India, Iran, Korea, Nigeria, Pakistan, Saudi Arabia, Turkey, and UAE have a significant positive impact at a significance level of 1%, Mexico, Canada, Vietnam, Ukraine, and the Netherlands with 5% significance level and Malaysia, Argentina with 10% significance level. Meanwhile, there is a negative impact on the U.S. at a 1% significance, France and Germany at a 5% significance, and Russia at a 10% significance level.

In addition, considering REC, almost every country negatively effect on CO₂ except Malaysia and Iran. Twenty-seven countries have a 1% significance level, and Kazakhstan, Thailand, and Japan have a 10% significance level. In contrast, Iran positively impacts CO₂ with a 10% significant level.

Furthermore, Appendix S4 illustrates the scatter plot diagrams and a plotted linear fit for the selected countries. Based on the results, all the independent variables are significant in the model with a 99% confidence level. However, when considering the countries individually, the results show that all the independent variables positively and negatively impact CO₂, with different significant levels of 1%, 5%, and 10%. In conclusion, the findings reveal that control variables do not impact CO₂ individually, but many other factors may cause the effect. The model runs through FE depicts that POP, PGDP, and ICT impact positively while REC negatively impacts CO₂. However, these results varied when the results were analysed individually for each country.

Based on factor multicollinearity, which is a standard diagnostic tool, the Variance Inflation Factor (VIF) test was employed to assess the presence of multicollinearity among the independent variables in the study. Multicollinearity occurs when independent variables are highly correlated, inflating the variance of the coefficient estimates and making it challenging to determine the precise effect of each variable. By calculating the VIF for each variable, the level of multicollinearity was measured. The results, with VIF values ranging from 1.30 to 2.22, indicate that multicollinearity is not a significant issue in the study's analysis. The values for each variable are presented in Appendix S5 of the study. The reason for multicollinearity not being problematic is that all VIF values are well below the commonly used threshold of 10, which is indicative of problematic multicollinearity. Therefore, we conclude that the study's independent variables do not exhibit a high degree of correlation, and multicollinearity does not adversely affect the regression estimates.

Furthermore, to address the causality between the aforementioned variables, pairwise Granger causality was examined in detail in the study (Caldera et al., 2024). The results revealed a variety of unidirectional and bidirectional causalities between CO₂ emissions and PGDP, REC, and NREC. Finland, Poland, Romania, and the Slovak Republic were found to exhibit bidirectional causality. In nations such as Albania and Libya, there were unidirectional linkages, where CO₂ emissions caused PGDP. Additionally, countries such as Uruguay, Qatar, and Trinidad and Tobago demonstrated bidirectional causality between CO₂ emissions and REC, while several other countries

showed unidirectional causality. Overall, all analysis indicated bidirectional causality between CO₂ emissions and PGDP, CO₂ emissions and REC, and CO₂ emissions and NREC across all countries.

5 | DISCUSSION

To support the results of PGDP, CO₂ emission and PGDP have a positive relationship due to the dependence on NREC used for industrial production and manufacturing (Rahman et al., 2020). High air pollution also occurs in emerging countries with the increase in PGDP Fields (Ozcan & Apergis, 2018). In contrast, there is a positive and negative (inverted U-shaped) effect in the countries Turkey, Australia, Canada, and France, which discovered a rise in PGDP which has led to an increase in CO₂ emission and subsequently a reduction caused by the rise in energy consumption led to increase in CO₂ emissions (Batool et al., 2022; Isik et al., 2021). According to the results, out of the top emitting countries, China is recognised as the highest carbon emitter (Li, Li, et al., 2021; Liu et al., 2022; Tang et al., 2021). Taking 2022 into account, it can be seen that the service sector, manufacturing sector and agriculture sector mainly impact the GDP of China with 52.8%, 39.9%, and 7.3%, respectively. This will mainly impact the service sector, including finance, retail, tourism, transportation, and the manufacturing industry, by producing machinery, garments, and electronics, which consume much energy. The USA is another prominent nation which emits the highest amount of carbon emissions, with 80% of GDP from the service sector and a 17% increase in health care and social care (Goldstein et al., 2020; Kartal, 2022; Salari et al., 2021). With the recovery signs of Covid-19 at the end of 2022 and 2023, India has made itself one of the fastest-growing economies in the world, which has led GDP to increase in the service sector by 60% and agriculture and manufacturing by 15% and 14%, respectively (Pradhan & Ghosh, 2021; Rathnayaka et al., 2023). These findings explain that increased production, economic development, and consumption in the economy with different innovations and advancements have increased high energy consumption and led to environmental deterioration.

In terms of ICT, more energy is being consumed by ICT products and different technologies, resulting in an increase in consumption, which has put a high pressure on CO₂ emission (Arshad et al., 2020). The environmental quality will decrease in emerging economies due to high energy consumption and the use of ICT equipment (Danish et al., 2018). The findings of our study imply that E-waste is one of the main reasons for the rise in CO₂. This explains the advanced technological improvements such as Robotic Process Automation, 5G, Virtual reality, Quantum computing, et al. that have led to shortening the life span of electronic devices and improper disposal and recycling, which will lead to environmental deterioration. In contrast, there is a negative impact between ICT and CO₂, signifying that prompt usage of internet and mobile cellular subscriptions along with highly efficient ICT devices has become the reason to reduce energy consumption and has tended to improve environmental quality in 77 developing countries and ASEAN countries, respectively (Haini, 2021; Ke

et al., 2022). Belt and Road countries reveal dematerialisation is a critical impact that mitigates CO₂, which has tended to save fossil fuel and lessen pollution (D Khan, 2019). The carbon capturing technologies in high emission industries was deployed in reducing greenhouse gas emissions which impacts the sustainability (Zhang et al., 2024). Considering the cement industry which highly impacts on carbon emission has this techno-economic feasibility to mitigate CO₂ (Ige et al., 2024).

Considering POP, the consumption patterns of the elderly population, such as the usage of public transportation, will reduce CO₂ emissions. At the same time, there is also an increase in demand for elderly-related products and services, leading to a rise in future CO₂ emissions. The increase in CO₂ emission results from China's ageing population, inadequate social security systems, and a severe support system (Yu et al., 2018). With the rise in the population, the demand for energy will increase, which will enhance CO₂ emissions (Xia et al., 2020). The author suggests that the new generation must be educated to adopt consumption patterns which generate low CO₂ emissions through public education and awareness programmes. Also, implementing suitable carbon taxes and pricing will be promising strategies for reducing carbon emissions. Two key drivers of CO₂ emission are population and GDP; population expansion and economic growth significantly positively impact the level of CO₂ emission both globally and regionally (Dong et al., 2018; Hashmi & Alam, 2019). Both these findings are compatible with the results of the study.

Inconsistent with the study, REC hurts CO₂ emission as a recent research (Saidi & Omri, 2020). Natural gases and REC have acted as the main mitigators of CO₂ emission in BRICS (Dong et al., 2017). Moreover, there is a negative relationship between REC and CO₂, indicating that production done using REC causes a decrease in CO₂ emissions for OECD countries (Cheng et al., 2019). According to recent data, even though China, the US and India are recognised as the highest emitting countries, it is also identified as the top three markets for REC since they initiated attempts to mitigate CO₂ and have net zero carbon emissions by 2030. Some leading causes would be greenhouse gas emissions, reducing the cost of REC and the growth of solar energy and the electric vehicle market, which led to the mitigation of CO₂ emissions. Study done for developed countries has estimated that REC and technological process contributed to mitigation of CO₂ (Hasanov et al., 2021). Similarly, for the MENA countries the impact shows negative from REC to CO₂ (Xiaoman et al., 2021).

6 | CONCLUSIONS

The study has explored the impact of ICT, POP, PGDP, and REC on CO₂ emissions across 38 selected countries from 1996 to 2020. By ranking countries based on their recent 10 years' CO₂ emissions and applying the Pareto principle, the study focused on the top carbon-emitters. The findings, derived from both panel regression and MLR analyses, reveal varied relationships between these factors and CO₂ emissions. Specifically, PGDP, ICT, and POP generally exhibit positive

correlations with CO₂ emissions, while REC shows a predominantly negative relationship, except in Malaysia and Iran.

The positive relationship between GDP and CO₂ emissions, as observed in most countries, suggests that higher economic activity and industrial production contribute to increased carbon emissions. Similarly, the role of ICT indicates that advancements and increased usage of digital technologies may lead to higher energy consumption and, consequently, greater CO₂ emissions in most countries. In contrast, the negative relationship between REC and CO₂ emissions highlights the importance of renewable energy in reducing carbon footprints. These findings provide valuable insights for policymakers focusing on sustainable economic growth and CO₂ mitigation.

7 | POLICY IMPLICATIONS

Based on the study's findings, several policy implications emerge for mitigating CO₂ emissions in the examined countries:

1. *Promotion of renewable energy:* The negative impact of REC on CO₂ emissions suggests that increasing the share of renewables in the energy mix is crucial. Policies should incentivise investments in renewable energy sources, such as solar, wind, and hydroelectric power, to reduce reliance on fossil fuels and lower carbon emissions.
2. *Encouraging sustainable ICT practices:* Given the positive relationship between ICT and CO₂ emissions, governments should promote energy-efficient technologies and encourage practices that reduce energy consumption in the ICT sector. This includes the adoption of green data centres, improved e-waste management, and the use of energy-saving devices.
3. *Managing population growth and urbanisation:* Population dynamics significantly impact CO₂ emissions. Policies aimed at managing urbanisation, promoting sustainable urban planning, and enhancing public transportation could mitigate the adverse effects of population growth on carbon emissions.
4. *Economic policies for sustainable growth:* Policymakers should develop strategies that decouple economic growth from carbon emissions. This could include promoting green technologies in industrial processes, enhancing energy efficiency standards, and encouraging low-carbon innovation in key economic sectors.
5. *Strengthening regulatory frameworks:* Robust regulatory frameworks are needed to enforce CO₂ emission reduction targets and encourage sustainable practices across all sectors. This includes setting ambitious CO₂ reduction targets, implementing carbon pricing mechanisms, and providing subsidies or tax incentives for companies that adopt green technologies.

By integrating these policy recommendations derived from the study's findings, countries can develop more effective strategies to reduce CO₂ emissions while balancing economic growth and environmental sustainability.

7.1 | Limitations and future research directions

While this study provides a comprehensive analysis of the factors influencing CO₂ emissions across multiple countries, several limitations must be acknowledged: The analysis is based on data from 1996 to 2020. The lack of more recent data (2021–2023) may limit the understanding of current trends and the impact of recent policy interventions, especially in the context of post-COVID-19 economic recovery. The study focuses on a limited number of variables (ICT, POP, PGDP, REC) to explain CO₂ emissions. Other potentially influential factors, such as technological innovation, policy changes, and cultural shifts, were not included. Future research could expand the scope by incorporating these variables to provide a more nuanced understanding. The use of panel regression and MLR models, while robust, may not capture all the complexities of the relationships between variables. Future studies could explore non-linear models or employ machine learning techniques to better understand the dynamics at play. The study is limited to 38 countries. Expanding the geographical scope to include more countries, particularly those from underrepresented regions, could provide a more comprehensive view of global CO₂ emission trends.

CONFLICT OF INTEREST STATEMENT

The authors confirm that there are no known financial or interpersonal conflicts that would have appeared to have an impact on the research presented in this study.

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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REFERENCES

- Acheampong, A. O., Adams, S., & Boateng, E. (2019). Do globalization and renewable energy contribute to carbon emissions mitigation in sub-Saharan Africa? *Science of the Total Environment*, 677, 436–446. <https://doi.org/10.1016/j.scitotenv.2019.04.353>
- Adams, S., & Acheampong, A. O. (2019). Reducing carbon emissions: The role of renewable energy and democracy. *Journal of Cleaner Production*, 240, 1–13. <https://doi.org/10.1016/j.jclepro.2019.118245>
- Adebayo, T. S., Awosusi, A. A., Rjoub, H., Agyekum, E. B., & Kirikkaleli, D. (2022). The influence of renewable energy usage on consumption-based carbon emissions in MINT economies. *Heliyon*, 8(2), 1–10. <https://doi.org/10.1016/j.heliyon.2022.e08941>
- Aeknarajindawat, N., Suteerachai, B., & Suksod, P. (2020). The impact of natural resources, renewable energy, economic growth on carbon dioxide emission in Malaysia. *International Journal of Energy Economics and Policy*, 10(3), 211–218. <https://doi.org/10.32479/ijeepp.9180>

- Ahmed, Z., & Le, H. P. (2021). Linking information communication technology, trade globalization index, and CO₂ emissions: Evidence from advanced panel techniques. *Environmental Science and Pollution Research*, 28(7), 1–12. <https://doi.org/10.1007/s11356-020-11205-0>
- Akram, R., Chen, F., Khalid, F., Ye, Z., & Majeed, M. T. (2020). Heterogeneous effects of energy efficiency and renewable energy on carbon emissions: Evidence from developing countries. *Journal of Cleaner Production*, 247, 1–33. <https://doi.org/10.1016/j.jclepro.2019.119122>
- Anser, M. K., Alharthi, M., Aziz, B., & Wasim, S. (2020). Impact of urbanization, economic growth, and population size on residential carbon emissions in the SAARC countries. *Clean Technologies and Environmental Policy*, 22(4), 1–8. <https://doi.org/10.1007/s10098-020-01833-y>
- Arshad, Z., Robaina, M., & Botelho, A. (2020). The role of ICT in energy consumption and environment: An empirical investigation of Asian economies with cluster analysis. *Environmental Science and Pollution Research*, 27(26), 1–10. <https://doi.org/10.1007/s11356-020-09229-7>
- Atsu, F., Adams, S., & Adjei, J. (2021). ICT, energy consumption, financial development, and environmental degradation in South Africa. *Heliyon*, 7(7), 1–10. <https://doi.org/10.1016/j.heliyon.2021.e07328>
- Avom, D., Nkengfack, H., Fotio, H. K., & Totouom, A. (2020). ICT and environmental quality in sub-Saharan Africa: Effects and transmission channels. *Technological Forecasting and Social Change*, 155, 1–12. <https://doi.org/10.1016/j.techfore.2020.120028>
- Awad, A. (2022). Is there any impact from ICT on environmental quality in Africa? Evidence from second-generation panel techniques. *Environmental Challenges*, 7, 1–12. <https://doi.org/10.1016/j.envc.2022.100520>
- Awan, A. M., & Azam, M. (2022). Evaluating the impact of GDP per capita on environmental degradation for G-20 economies: Does N-shaped environmental Kuznets curve exist? *Environment, Development and Sustainability*, 24, 11103–11126. <https://doi.org/10.1007/s10668-021-01899-8>
- Bai, X., Wang, K.-T., Tran, T. K., Sadiq, M., Trung, L. M., & Khudoykulov, K. (2022). Measuring China's green economic recovery and energy environment sustainability: Econometric analysis of sustainable development goals. *Economic Analysis and Policy*, 75, 768–779. <https://doi.org/10.1016/j.eap.2022.07.005>
- Batool, Z., Raza, S. M. F., Ali, S., & Abidin, S. Z. U. (2022). ICT, renewable energy, financial development, and CO₂ emissions in developing countries of east and South Asia. *Environmental Science and Pollution Research*, 29(23), 1–10. <https://doi.org/10.1007/s11356-022-18664-7>
- Begum, R. A., Sohag, K., Abdullah, S. M. S., & Jaafar, M. (2015). CO₂ emissions, energy consumption, economic and population growth in Malaysia. *Renewable and Sustainable Energy Reviews*, 41, 594–601. <https://doi.org/10.1016/j.rser.2014.07.205>
- Bildirici, M. E., Castanho, R. A., Kayikçi, F., & Genç, S. Y. (2022). ICT, energy intensity, and CO₂ emission nexus. *Energies*, 15(13), 1–15. <https://doi.org/10.3390/en15134567>
- Caldera, Y., Ranthilake, T., Gunawardana, H., Senevirathna, D., Jayathilaka, R., Rathnayake, N., & Peter, S. (2024). Understanding the interplay of GDP, renewable, and non-renewable energy on carbon emissions: Global wavelet coherence and granger causality analysis. *PLoS One*, 19(9), e0308780. <https://doi.org/10.1371/journal.pone.0308780>
- Chatti, W. (2021). Moving towards environmental sustainability: Information and communication technology (ICT), freight transport, and CO₂ emissions. *Heliyon*, 7(10), 1–8. <https://doi.org/10.1016/j.heliyon.2021.e08190>
- Chen, Y., Wang, Z., & Zhong, Z. (2019). CO₂ emissions, economic growth, renewable and non-renewable energy production and foreign trade in China. *Renewable Energy*, 131, 208–216. <https://doi.org/10.1016/j.renene.2018.07.047>
- Chen, Y., Zhao, J., Lai, Z., Wang, Z., & Xia, H. (2019). Exploring the effects of economic growth, and renewable and non-renewable energy consumption on China's CO₂ emissions: Evidence from a regional panel analysis. *Renewable Energy*, 140, 341–353. <https://doi.org/10.1016/j.renene.2019.03.058>
- Cheng, C., Ren, X., & Wang, Z. (2019). The impact of renewable energy and innovation on carbon emission: An empirical analysis for OECD countries. *Energy Procedia*, 158, 3506–3512. <https://doi.org/10.1016/j.egypro.2019.01.919>
- Danish, K., Baloch, M. A., Saud, S., & Fatima, T. (2018). The effect of ICT on CO₂ emissions in emerging economies: Does the level of income matters? *Environmental Science and Pollution Research*, 25(23), 1–10. <https://doi.org/10.1007/s11356-018-2379-2>
- Dissanayake, H., Perera, N., Abeykoon, S., Samson, D., Jayathilaka, R., Jayasinghe, M., & Yapa, S. (2023). Nexus between carbon emissions, energy consumption, and economic growth: Evidence from global economies. *PLoS One*, 18(6), 1–27. <https://doi.org/10.1371/journal.pone.0287579>
- Doğan, B., Driha, O. M., Lorente, D. B., & Shahzad, U. (2020). The mitigating effects of economic complexity and renewable energy on carbon emissions in developed countries. *Sustainable Development*, 29(1), 1–12. <https://doi.org/10.1002/sd.2125>
- Dong, B., Xu, Y., & Fan, X. (2020). How to achieve a win-win situation between economic growth and carbon emission reduction: Empirical evidence from the perspective of industrial structure upgrading. *Environmental Science and Pollution Research*, 27(35), 1–15. <https://doi.org/10.1007/s11356-020-09883-x>
- Dong, K., Hochman, G., & Timilsina, G. R. (2020). Do drivers of CO₂ emission growth alter overtime and by the stage of economic development? *Energy Policy*, 140, 1–12. <https://doi.org/10.1016/j.enpol.2020.111420>
- Dong, K., Hochman, G., Zhang, Y., Sun, R., Li, H., & Liao, H. (2018). CO₂ emissions, economic and population growth, and renewable energy: Empirical evidence across regions. *Energy Economics*, 75, 180–192. <https://doi.org/10.1016/j.eneco.2018.08.017>
- Dong, K., Sun, R., & Hochman, G. (2017). Do natural gas and renewable energy consumption lead to less CO₂ emission? Empirical evidence from a panel of BRICS countries. *Energy*, 141, 1–56. <https://doi.org/10.1016/j.energy.2017.11.092>
- Environmental Protection Agency. (2023). United States Environmental Protection Agency. <https://www.epa.gov/ghgemissions/overview-greenhouse-gases>
- Fang, W., Liu, Z., & Putra, A. R. S. (2022). Role of research and development in green economic growth through renewable energy development: Empirical evidence from South Asia. *Renewable Energy*, 194, 1142–1152. <https://doi.org/10.1016/j.renene.2022.04.125>
- Fernandes, C. I., Veiga, P. M., Ferreira, J. J. M., & Hughes, M. (2021). Green growth versus economic growth: Do sustainable technology transfer and innovations lead to an imperfect choice? *Wiley Online Library*, 30(4), 2021–2037. <https://doi.org/10.1002/bse.2730>
- Ghazali, A., & Ali, G. (2019). Investigation of key contributors of CO₂ emissions in extended STIRPAT model for newly industrialized countries: A dynamic common correlated estimator (DCCE) approach. *Energy Reports*, 5, 242–252. <https://doi.org/10.1016/j.egypr.2019.02.006>
- Goldstein, B., Gounaridis, D., & Newell, J. P. (2020). The carbon footprint of household energy use in the United States. *Social Sciences*, 117(32), 19122–19130. <https://doi.org/10.1073/pnas.1922205117>
- Haini, H. (2021). Examining the impact of ICT, human capital and carbon emissions: Evidence from the ASEAN economies. *International Economics*, 166, 116–125. <https://doi.org/10.1016/j.inteco.2021.03.003>
- Han, M. S., Yuan, Q., Fahad, S., & Ma, T. (2022). Dynamic evaluation of green development level of ASEAN region and its spatio-temporal patterns. *Journal of Cleaner Production*, 362, 132402. <https://doi.org/10.1016/j.jclepro.2022.132402>

- Hasanov, F. J., Khan, Z., Hussain, M., & Tufail, M. (2021). Theoretical framework for the carbon emissions effects of technological Progress and renewable energy consumption. *Sustainable Development*, 29(5), 810–822. <https://doi.org/10.1002/sd.2175>
- Hashmi, R., & Alam, K. (2019). Dynamic relationship among environmental regulation, innovation, CO₂ emissions, population, and economic growth in OECD countries: A panel investigation. *Journal of Cleaner Production*, 231, 1100–1109. <https://doi.org/10.1016/j.jclepro.2019.05.325>
- Heidari, H., Katircioğlu, S. T., & Saeidpour, L. (2015). Economic growth, CO₂ emissions, and energy consumption in the five ASEAN countries. *International Journal of Electrical Power & Energy Systems*, 64, 785–791. <https://doi.org/10.1016/j.ijepes.2014.07.081>
- Hussain, I., & Rehman, A. (2021). Exploring the dynamic interaction of CO₂ emission on population growth, foreign investment, and renewable energy by employing ARDL bounds testing approach. *Environmental Science and Pollution Research*, 28(29), 1–11. <https://doi.org/10.1007/s11356-021-13502-8>
- Ige, O. E., Von Kallon, D. V., & Desai, D. (2024). Carbon emissions mitigation methods for cement industry using a systems dynamics model. *Clean Technologies and Environmental Policy*, 26(3), 579–597. <https://doi.org/10.1007/s10098-023-02683-0>
- Inglese-Lotz, R., & Dogan, E. (2018). The role of renewable versus non-renewable energy to the level of CO₂ emissions a panel analysis of sub-Saharan Africa's Big 10 electricity generators. *Renewable Energy*, 123, 1–27. <https://doi.org/10.1016/j.renene.2018.02.041>
- Isik, C., Ongan, S., Ozdemir, D., Ahmad, M., Irfan, M., Alvarado, R., & Ongan, A. (2021). The increases and decreases of the environment Kuznets curve (EKC) for 8 OECD countries. *Environmental Science and Pollution Research*, 28(22), 1–9. <https://doi.org/10.1007/s11356-021-12637-y>
- Islam, M. M., Ali, M. I., Ceh, B., Singh, S., Khan, M. K., & Dagar, V. (2022). Renewable and non-renewable energy consumption driven sustainable development in ASEAN countries: Do financial development and institutional quality matter? *Environmental Science and Pollution Research*, 29, 34231–34247. <https://doi.org/10.1007/s11356-021-18488-x>
- Jahanger, A., Zaman, U., Hossain, M. R., & Awan, A. (2023). Articulating CO₂ emissions limiting roles of nuclear energy and ICT under the EKC hypothesis: An application of non-parametric MMQR approach. *Geoscience Frontiers*, 14(5), 1–19. <https://doi.org/10.1016/j.gsf.2023.101589>
- Kahia, M., Jebli, M. B., & Belloumi, M. (2019). Analysis of the impact of renewable energy consumption and economic growth on carbon dioxide emissions in 12 MENA countries. *Clean Technologies and Environmental Policy*, 21(4), 1–15. <https://doi.org/10.1007/s10098-019-01676-2>
- Kartal, M. T. (2022). The role of consumption of energy, fossil sources, nuclear energy, and renewable energy on environmental degradation in top-five carbon producing countries. *Renewable Energy*, 184, 871–880. <https://doi.org/10.1016/j.renene.2021.12.022>
- Ke, J., Jahanger, A., Yang, B., Usman, M., & Ren, F. (2022). Digitalization, financial development, trade, and carbon emissions: implication of pollution haven hypothesis during globalization mode. *Frontiers in Environmental Science*, 10, 1–15. <https://doi.org/10.3389/fenvs.2022.873880>
- Khan, D. (2019). Effects of information and communication technology and real income on CO₂ emissions: The experience of countries along belt and road. *Telematics and Informatics*, 45, 1–28. <https://doi.org/10.1016/j.tele.2019.101300>
- Khan, M. K., Khan, M. I., & Rehan, M. (2020). The relationship between energy consumption, economic growth and carbon dioxide emissions in Pakistan. *Financial Innovation*, 6(1), 1–13. <https://doi.org/10.1186/s40854-019-0162-0>
- Khan, S. A. R., Godil, D. I., Yu, Z., Abbas, F., & Shamim, M. A. (2022). Adoption of renewable energy sources, low-carbon initiatives, and advanced logistical infrastructure—An step toward integrated global progress. *Wiley Online Library*, 30(1), 275–288. <https://doi.org/10.1002/sd.2243>
- Lahouel, B., Béchir, T., Zaied, Y. B., & Managi, S. (2021). Does ICT change the relationship between total factor productivity and CO₂ emissions? Evidence based on a nonlinear model. *Energy Economics*, 101, 1–15. <https://doi.org/10.1016/j.eneco.2021.105406>
- Li, S., Siu, Y. W., & Zhao, G. (2021). Driving factors of CO₂ emissions: Further study based on machine learning. *Frontiers in Environmental Science*, 9, 1–16. <https://doi.org/10.3389/fenvs.2021.721517>
- Li, Z.-Z., Li, R. Y. M., Malik, M. Y., Murshed, M., Khan, Z., & Umar, M. (2021). Determinants of carbon emission in China: How good is green investment? *Sustainable Production and Consumption*, 27, 392–401. <https://doi.org/10.1016/j.spc.2020.11.008>
- Liu, Z., Deng, Z., He, G., Wang, H., Zhang, X., Lin, J., Qi, Y., & Liang, X. (2022). Challenges and opportunities for carbon neutrality in China. *Nature Reviews Earth and Environment*, 3(2), 141–155. <https://doi.org/10.1038/s43017-021-00244-x>
- Mamkhezri, J., & Khezri, M. (2023). Assessing the spillover effects of research and development and renewable energy on CO₂ emissions: International evidence. *Environment, Development and Sustainability*, 1–30, 1–30. <https://doi.org/10.1007/s10668-023-03026-1>
- Mendonça, A. K. S., Barni, G. A. C., Moro, M. F., Bornia, A. C., Kupek, E., & Fernandes, L. (2020). Hierarchical modeling of the 50 largest economies to verify the impact of GDP, population and renewable energy generation in CO₂ emissions. *Sustainable Production and Consumption*, 22, 58–67. <https://doi.org/10.1016/j.spc.2020.02.001>
- Mohammed, A., Li, Z., Arowolo, A. O., Su, H., Deng, X., Najmuddin, O., et al. (2019). Driving factors of CO₂ emissions and nexus with economic growth, development and human health in the top ten emitting countries. *Resources, Conservation and Recycling*, 148, 157–169. <https://doi.org/10.1016/j.resconrec.2019.03.048>
- Muhammad, B. (2019). Energy consumption, CO₂ emissions and economic growth in developed, emerging and Middle East and North Africa countries. *Energy*, 179, 232–245. <https://doi.org/10.1016/j.energy.2019.03.126>
- NASA. (2023). Global climate change—Vital signs of the planet. <https://climate.nasa.gov/global-warming-vs-climate-change/>
- Nguyen, K. H., & Kakinaka, M. (2019). Renewable energy consumption, carbon emissions, and development stages: Some evidence from panel cointegration analysis. *Renewable Energy*, 132, 1–31. <https://doi.org/10.1016/j.renene.2018.08.069>
- Osobajo, O. A., Otitoju, A., Otitoju, M. A., & Oke, A. (2020). The impact of energy consumption and economic growth on carbon dioxide emissions. *Sustainability*, 12(19), 1–9. <https://doi.org/10.3390/su12197965>
- Ozcan, B., & Apergis, N. (2018). The impact of internet use on air pollution: Evidence from emerging countries. *Environmental Science and Pollution Research*, 25(5), 1–16. <https://doi.org/10.1007/s11356-017-0825-1>
- Pradhan, B. K., & Ghosh, J. (2021). COVID-19 and the Paris agreement target: A CGE analysis of alternative economic recovery scenarios for India. *Energy Economics*, 103, 1–13. <https://doi.org/10.1016/j.eneco.2021.105539>
- Rahman, M. M., Saidi, K., & Mbarek, M. B. (2020). Economic growth in South Asia: The role of CO₂ emissions, population density and trade openness. *Heliyon*, 6(5), 1–9. <https://doi.org/10.1016/j.heliyon.2020.e03903>
- Rathnayaka, I. W., Khanam, R., & Rahman, M. M. (2023). The economics of COVID-19: A systematic literature review. *Journal of Economic Studies*, 50(1), 49–72. <https://doi.org/10.1108/JES-05-2022-0257>
- Rezza, A. A. (2013). FDI and pollution havens: Evidence from the Norwegian manufacturing sector. *Ecological Economics*, 90, 140–149. <https://doi.org/10.1016/j.ecolecon.2013.03.014>
- Robati, M., Oldfield, P., Nezhad, A. A., Carmichael, D. G., & Kuru, A. (2021). Carbon value engineering: A framework for integrating embodied

- carbon and cost reduction strategies in building design. *Building and Environment*, 192, 1–17. <https://doi.org/10.1016/j.buildenv.2021.107620>
- Saidi, K., & Omri, A. (2020). The impact of renewable energy on carbon emissions and economic growth in 15 major renewable energy-consuming countries. *Environmental Research*, 186, 1–11. <https://doi.org/10.1016/j.envres.2020.109567>
- Salari, M., Javid, R. J., & NoghaniBehambari, H. (2021). The nexus between CO₂ emissions, energy consumption, and economic growth in the U.S. *Economic Analysis and Policy*, 69, 182–194. <https://doi.org/10.1016/j.eap.2020.12.007>
- Shahbaz, M., Sharma, R., Sinha, A., & Jiao, Z. (2021). Analyzing nonlinear impact of economic growth drivers on CO₂ emissions: Designing an SDG framework for India. *Energy Policy*, 148, 1–13. <https://doi.org/10.1016/j.enpol.2020.111965>
- Sharif, A., Raza, S. A., Ozturk, I., & Afshan, S. (2019). The dynamic relationship of renewable and nonrenewable energy consumption with carbon emission: A global study with the application of heterogeneous panel estimations. *Renewable Energy*, 133, 1–17. <https://doi.org/10.1016/j.renene.2018.10.052>
- Tang, K., Liu, Y., Zhou, D., & Qiu, Y. (2021). Urban carbon emission intensity under emission trading system in a developing economy: Evidence from 273 Chinese cities. *Environmental Science and Pollution Research*, 28(5), 5168–5179. <https://doi.org/10.1007/s11356-020-10785-1>
- Vo, D. H., & Vo, A. T. (2021). Renewable energy and population growth for sustainable development in the southeast Asian countries. *Energy, Sustainability and Society*, 11(1), 1–15. <https://doi.org/10.1186/s13705-021-00304-6>
- Wang, Q., & Wang, S. (2019). Decoupling economic growth from carbon emissions growth in the United States: The role of research and development. *Journal of Cleaner Production*, 234, 702–713. <https://doi.org/10.1016/j.jclepro.2019.06.174>
- Wang, X., Wang, G., Chen, T., Zeng, Z., & Heng, C. K. (2023). Low-carbon city and its future research trends: A bibliometric analysis and systematic review. *Sustainable Cities and Society*, 90, 104381. <https://doi.org/10.1016/j.scs.2022.104381>
- Wang, Z., Rasool, Y., Zhang, B., Ahmed, Z., & Wang, B. (2020). Dynamic linkage among industrialisation, urbanisation, and CO₂ emissions in APEC realms: Evidence based on DSUR estimation. *Structural Change and Economic Dynamics*, 52, 1–29. <https://doi.org/10.1016/j.strueco.2019.12.001>
- Wen, J., Mughal, N., Zhao, J., Shabbir, M. S., Niedbała, G., Jain, V., & Anwar, A. (2021). Does globalization matter for environmental degradation? Nexus among energy consumption, economic growth, and carbon dioxide emission. *Energy Policy*, 153, 1–8. <https://doi.org/10.1016/j.enpol.2021.112230>
- World Meteorological Organization. (2022). World Meteorological Organization. <https://public.wmo.int/en/our-mandate/focus-areas/environment/greenhouse-gases#:~:text=Some%20atmospheric%20gases%20absorb%20and,would%20be%20in%20its%20absence>
- Xia, Q., Wang, H., Liu, X., & Pan, X. (2020). Drivers of global and national CO₂ emissions changes 2000–2017. *Climate Policy*, 21(5), 604–615. <https://doi.org/10.1080/14693062.2020.1864267>
- Xiaoman, W., Majeed, A., Vasbieva, D. G., Yameogo, C. E. W., & Hussain, N. (2021). Natural resources abundance, economic globalization, and carbon emissions: Advancing sustainable development agenda. *Sustainable Development*, 29(5), 1037–1048. <https://doi.org/10.1002/sd.2192>
- Xue, C., Shahbaz, M., Ahmed, Z., Ahmad, M., & Sinha, A. (2022). Clean energy consumption, economic growth, and environmental sustainability: What is the role of economic policy uncertainty? *Renewable Energy*, 184, 899–907. <https://doi.org/10.1016/j.renene.2021.12.006>
- Yao, S., Zhang, S., & Zhang, X. (2019). Renewable energy, carbon emission and economic growth: A revised environmental Kuznets curve perspective. *Journal of Cleaner Production*, 235, 1338–1352. <https://doi.org/10.1016/j.jclepro.2019.07.069>
- Yu, Y., Deng, Y.-r., & Chen, F.-f. (2018). Impact of population aging and industrial structure on CO₂ emissions and emissions trend prediction in China. *Atmospheric Pollution Research*, 9(3), 1–9. <https://doi.org/10.1016/j.apr.2017.11.008>
- Zhang, J., Fan, Z., Chen, Y., Gao, J., & Liu, W. (2020). Decomposition and decoupling analysis of carbon dioxide emissions from economic growth in the context of China and the ASEAN countries. *Science of the Total Environment*, 714, 1–8. <https://doi.org/10.1016/j.scitotenv.2020.136649>
- Zhang, T., Zhang, M., Jin, L., Xu, M., & Li, J. (2024). Advancing carbon capture in hard-to-abate industries: Technology, cost, and policy insights. *Clean Technologies and Environmental Policy*, 1–18, 2077–2094. <https://doi.org/10.1007/s10098-024-02810-5>

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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