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CO_2 EMISSIONS IN G20 ECONOMIES: A DYNAMIC PANEL ANALYSIS OF ECONOMIC AND ENERGY-SECTOR DRIVERS

Abstract

Mitigating the effects of climate change has emerged as a crucial global need, with carbon dioxide emissions serving as the principal driver of greenhouse gas accumulation. This paper analyzes the factors influencing CO_2 emissions in G20 countries from 2000 to 2021, emphasizing the effects of renewable energy consumption, trade openness, economic growth, and energy intensity. The study utilizes advanced dynamic panel econometric techniques, namely, the Augmented Mean Group (AMG) Estimator and the Common Correlated Effects Mean Group (CCEMG) Estimator, which address cross-sectional dependence and parameter heterogeneity among nations. The analysis indicates that the use of renewable energy noticeably decreases CO_2 emissions, with elasticity values between –0.15 and –0.16. The effect is especially significant in lower-income G20 countries and during the post-2005 era. Economic growth indicates a strong positive correlation with CO_2 emissions, characterized by elasticity values ranging from 0.83 to 0.89, whereas energy intensity also displays positive effects with coefficients between 0.69 and 0.82. Trade openness exhibits insignificant statistical effects in both models. The heterogeneity study reveals that the emission-reduction potential of renewable energy is significantly greater in emerging nations than in advanced economies, with coefficients of –0.25 and –0.08, respectively. The results highlight the essential role of renewable energy transitions and enhancements in energy efficiency for meeting climate goals, especially when aligned with specific policies for various income levels and timeframes within the G20 context.

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INTRODUCTION

Climate change has become a critical worldwide challenge, with carbon dioxide (CO_2) emissions as the principal factor in the accumulation of greenhouse gases in the atmosphere. As global initiatives to address climate change escalate via frameworks such as the Paris Agreement, comprehending the primary determinants of CO_2 emissions is essential for sustainable policy development. The Group of Twenty (G20) economies, representing a substantial share of global CO_2 emissions, almost 80% of global GDP, and nearly two-thirds of the world's population, are crucial in shaping the direction of international climate change mitigation initiatives (IEA, 2023).

The intricate association between economic growth and environmental quality has been thoroughly examined through multiple theoretical frameworks. In particular, the Environmental Kuznets Curve (EKC) hypothesis suggests that the association between economic growth and environmental degradation follows an inverted U-shape.

Comprehending these relationships is especially crucial within the framework of G20 economies, which display considerable diversity regarding energy systems, climate policy, and economic development. One of the crucial fundamentals of sustainable development initiatives is renewable energy, providing the capacity to dissociate economic expansion from carbon emissions. Trade openness affects emissions via composition, scale, and method effects, while energy intensity directly impacts the environmental consequences of economic activities. These interactions are intricate and may differ across various temporal frameworks and economic settings.

1. LITERATURE REVIEW

The impact of economic and energy-sector indicators, namely, renewable energy, trade openness, economic growth, and energy intensity, on CO_2 emissions has been thoroughly examined in environmental economics literature, with varied results across distinct theoretical and empirical frameworks.

Studies investigating the influence of renewable energy on CO_2 emissions have consistently shown a reduction in emissions; however, the extent varies by environment. Dogan and Seker (2016) presented foundational evidence corroborating the Environmental Kuznets Curve theory in European Union nations, demonstrating that renewable energy reduces CO_2 emissions, but non-renewable energy exacerbates them. This conclusion was corroborated by later research conducted in various regions and employing diverse methodologies. Dong et al. (2018) utilized the Augmented Mean Group estimator for BRICS countries and discovered that a 1% rise in renewable energy consumption results in a 0.26% reduction in emissions. Chen et al. (2019) employed vector error correction models and autoregressive distributed lag techniques in China, illustrating that renewable energy promotes CO_2 reduction. Apergis et al. (2023) recently examined Uzbekistan with the ARDL technique and discovered that hydropower consumption consistently reduces CO2 emissions per capita in both short- and long-term, demonstrating unidirectional causality.

The relationship between trade openness and emissions reveals a more intricate and disputed scientific landscape. Theoretical models present contrasting viewpoints via the pollution haven hypothesis, which posits that trade openness may increase emissions in emerging economies as pollution-intensive firms relocate from nations with stringent environmental regulations (Cole & Elliott, 2003), and the pollution halo hypothesis, which asserts that trade facilitates the spread of environmental standards and cleaner technologies (Frankel & Rose, 2005). Empirical studies have yielded inconsistent outcomes that illustrate this theoretical uncertainty. Managi et al. (2009) employed a panel instrumental variables methodology across 88 countries and discovered that the technique effect of trade decreases emissions in richer countries. In contrast, Al-Mulali and Ozturk (2015) examined 14 MENA countries employing the fully modified ordinary least squares method and concluded that trade openness intensifies environmental degradation in the long term. Gozgor and Can (2017) re-evaluated the Environmental Kuznets Curve for China and showed that improved export product quality is associated with reduced CO_2 emissions, hence refining the trade-environment nexus. Acheampong (2019) discovered no long-term correlation between trade openness and CO_2 emissions in Morocco from 1971 to 2014, pinpointing energy consumption and economic growth as the primary explanatory factors. Udeagha and Breitenbach (2023) employed nonlinear ARDL models across Southern African Development Community (SADC) nations from 1960 to 2020, revealing varied and frequently statistically insignificant outcomes for trade openness, indicating the necessity for a country-specific study.

The relationship between economic growth and emissions is one of the most thoroughly examined topics in environmental economics, predominantly through the Environmental Kuznets Curve framework. Initial studies, such as Grossman and Krueger (1995), offered evidence in favor of the Environmental Kuznets Curve (EKC); however, later research has uncovered more intricate patterns. Zhu et al. (2016) employed panel quantile regression methods for ASEAN-5 nations, illustrating that the impact of economic growth on

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emissions varies throughout emission levels, with more significant effects observed at higher emission quantiles. Zoundi (2017) employed panel cointegration analysis across 25 African countries, demonstrating that economic growth significantly affects emissions, although renewable energy exerts a minimal moderating effect. Aye et al. (2017) utilized dynamic panel threshold models for 31 developing countries, demonstrating that economic growth adversely influences emissions in low-growth contexts but positively influences emissions in high-growth contexts. Recent research by Alaganthiran and Anaba (2020) and Onofrei et al. (2022) has substantiated the enduring positive correlation between economic growth and emissions in several regional contexts.

Research on energy intensity has established a definitive scientific consensus on its positive correlation with CO_2 emissions, although the extent and temporal variations differ among studies. Hamdi and Sbia (2012) examined Gulf Cooperation Council countries through panel vector error correction models, demonstrating long-term relationships between energy consumption and CO_2 emissions, as well as short-term bidirectional causality. Saidi and Hammami (2015) analyzed 58 countries employing dynamic simultaneous-equation panel data models and established that heightened energy consumption leads to increased CO_2 emissions, while urbanization and trade openness may mitigate these impacts. Liu et al. (2019) conducted a panel analysis of Chinese provinces and discovered that energy-intensive industries significantly contribute to CO_2 emissions, exhibiting considerable regional disparities. Namahoro et al. (2021) analyzed African regions across various income levels and found that reductions in energy intensity are associated with lower CO_2 emissions, with variations depending on regional and economic contexts. Recent studies by Mahapatra and Irfan (2023) and Al Mamun et al. (2025) have validated that energy consumption is a primary determinant of CO_2 emissions, exhibiting diverse temporal and spatial impacts.

The current scientific environment identifies multiple research gaps that require attention. Parameter variability among nations has often been overlooked, despite significant differences in energy systems and economic frameworks. The aggregate effects of renewable energy, economic expansion, trade liberalization, and energy intensity have not been thoroughly examined within the G20 framework, a vital element of global climate mitigation initiatives. Furthermore, the majority of research has insufficiently considered cross-sectional dependency and temporal fluctuations in relationships, which may result in skewed estimations and policy recommendations.

This study seeks to examine the determinants of CO_2 emissions in G20 economies from 2000 to 2021, focusing on the impacts of renewable energy consumption, trade openness, economic growth, and energy intensity, utilizing advanced dynamic panel econometric methods that account for cross-sectional dependence and parameter heterogeneity, based on a thorough review of prior scientific findings.

To guide the empirical analysis, the study proposes a set of testable hypotheses grounded in the theoretical and empirical literature. These hypotheses aim to assess the relationships between renewable energy, trade openness, economic growth, and energy intensity in the context of CO_2 emissions across G20 economies.

Study hypotheses are as follows:

H1: *The transition to renewable energy significantly reduces CO_2 emissions in G20 economies.*

H2: *The impact of trade openness on CO_2 emissions differs among various income categories within G20 economies.*

H3: *Economic growth exerts a significant positive influence on CO_2 emissions in G20 economies.*

H4: *Energy intensity shows a substantial positive influence on CO_2 emissions within G20 economies.*

2. METHODS

This study examines the factors influencing CO_2 emissions in G20 nations from 2000 to 2021. The dataset includes annual observations for 19 countries which are Argentina, Australia, Brazil, Canada, China, France, Germany, India, Indonesia, Italy, Japan, Mexico, Russia, Saudi Arabia, South Africa, South Korea, Turkey, the United Kingdom, and the United States, omitting the European Union as an entity to prevent double-counting of member states already represented individually in the G20 grouping. The analysis encompasses the following variables: carbon dioxide (CO_2) emissions per capita (t CO_2e/capita) abbreviated as CO_2 (World Bank, 2023a), energy intensity level of primary energy (MJ/$ 2017 PPP GDP) (EI) (World Bank, 2023b), GDP per capita (constant 2015 USD) (GDP) (World Bank, 2023c), renewable energy consumption (% of total final energy consumption) (REN) (World Bank, 2023d) and trade openness quantified as the sum of exports and imports relative to GDP (Trade) (World Bank, 2023e). The data for all variables are obtained from the World Development Indicators. All variables in the study are transformed to natural logarithms (indicated by the prefix "ln") to mitigate heteroscedasticity and enhance the comprehension of coefficients as elasticities.

This paper employs a systematic empirical analysis to address critical concerns in panel data analysis, such as tests for cross-sectional dependency, unit roots, and parameter heterogeneity. The subsequent subsections delineate the methodological framework utilized.

Cross-sectional dependence (CD) in panel data may result from unobserved common factors, spillover effects, and common shocks. Neglecting to consider confounding variables can result in skewed estimations and erroneous conclusions. Pesaran (2004) CD test is utilized to assess the presence of cross-sectional dependence in the panel data. The test statistic is calculated as:

$$CD = \sqrt{\frac{2T}{N(N-1)}}\left(\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\hat{p}_{i,j}\right), \quad (1)$$

where $\hat{p}_{i,j}$ is the pair-wise correlation of the residuals from individual OLS regressions. Under the null hypothesis of cross-sectional independence, a standard normal distribution is followed by the CD statistic.

Considering cross-sectional dependence, the Cross-sectionally Augmented Im, Pesaran, and Shin (CIPS) test developed by Pesaran (2007) was employed to examine the stationarity properties of the included variables. This test tackles cross-sectional dependence by augmenting the conventional ADF regressions with the cross-sectional averages of the lagged levels and first differences of the individual series. The test statistic is calculated using the following equation:

$$CIPS = N^{-1}\sum_{i=1}^{N} t_i(N,T), \quad (2)$$

where $t_i(N, T)$ is the t-statistic for the lagged dependent variable in the cross-sectionally augmented ADF regression for country *i*. CIPS statistics' critical values are provided by Pesaran (2007).

Pedroni (2004) panel cointegration test is used to analyze the long-term connection between the variables, accommodating diverse cointegrating vectors among panel members. Pedroni introduces seven test statistics, four derived from pooling inside the dimension (panel statistics) and three from pooling between dimensions (group statistics). Panel v, panel rho, panel t, and panel ADF statistics are provided for the within-dimension, as well as the group rho, group t, and group ADF data for the between-dimension.

By considering parameter heterogeneity and cross-sectional dependence, the following estimation methods are applied:

2.1. Common Correlated Effects Mean Group (CCEMG) estimator

The CCEMG estimator is introduced by Pesaran (2006), takes into consideration cross-sectional dependence by augmenting the regression model with cross-section averages of the dependent and explanatory variables. The model is specified as:

$$y_{it} = \alpha_i + \beta_i X_{it} + \gamma_i \overline{y_t} + \delta_i \bar{X}t + \varepsilon_{it}, \quad (3)$$

where $\bar{y}_t$ and $\bar{X}_t$ are the cross-section averages of the dependent and independent variables, respectively. The CCEMG estimator is the mean of the individual country estimations:

$$\hat{\beta}CCEMG = N^{-1}\sum i = 1^N \widehat{\beta_i}. \quad (4)$$

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2.2. Augmented Mean Group (AMG) estimator

The AMG estimator established by Bond and Eberhardt (2009) and Teal and Eberhardt (2010) accounts for cross-sectional dependence by including a common dynamic process extracted from year dummies in the regression model. The model is assessed in two steps:

1. A pooled regression with year dummies is estimated in first differences:

$$\Delta y_{it} = \Delta X_{it}\beta + \sum_{t=2}^{T} c_t \Delta D_t + e_{it}, \quad (5)$$

where D_t are the year dummies and the estimated coefficients $\hat{c}_t$ represent the common dynamic process.

The group-specific regressions include the common dynamic process: $y_{it} = \text{á}_i + \text{â}_i X_{it} + c_i \hat{\text{î}}\, t + eit$ (6)

where µ̂t is the common dynamic process derived from the first step.

The AMG estimator is then calculated as the mean of the individual country estimations:

$$\hat{\text{â}}AMG = N^{-1} \sum i = 1^N \widehat{\text{â}_i} \quad (7)$$

3. RESULTS

Table 1 represents the descriptive statistics for the variables included in the investigation.

Table 2 shows the correlation matrix for the logarithmic conversions of the variables, offering preliminary insights into their interrelations.

The correlation matrix indicates numerous significant trends. Initially, renewable energy consumption has a strong negative association with CO_2 Emissions, which is –0.6455, indicating that increased consumption of renewable energy correlates with reduced CO_2 emissions. Secondly, there is a strong positive association between economic growth and CO_2 emissions, which is equal to 0.7648, signifying that elevated income levels correspond with increased emissions. Third, Energy Intensity exhibits a modest positive association with CO_2 emissions (0.3323), indicating that increased energy intensity correlates with elevated emissions. Ultimately, Trade Openness has a weak positive association with CO_2 emissions by showing 0.2203, indicating a potentially constrained link between trade openness and emissions.

Table 3 displays the outcomes of the Pesaran (2004) CD test for each variable analyzed.

Table 1. Descriptive statistics

Variable	Obs.	Mean	Std. Dev.	Min	Max
CO_2	418	8.772138	5.580216	0.9386827	21.01262
REN	418	14.03268	12.58947	0.18	50
Trade	418	51.52801	16.98468	19.5596	105.5663
GDP	418	23463.66	17538.2	756.7041	62996.29
EI	418	5.005455	2.026034	2.2	12.06

Table 2. Correlation matrix

Variable	$lnCO_2$	lnREN	LnTrade	lnGDP	lnEI
$lnCO_2$	1.0000	–	–	–	–
lnREN	–0.6455	1.0000	–	–	–
lnTrade	0.2203	–0.3213	1.0000	–	–
lnGDP	0.7648	–0.3943	0.0990	1.0000	–
lnEI	0.3323	–0.1903	0.0729	–0.2400	1.0000

Table 3. Cross-sectional dependence test results

Variable	CD-test	p-value	Mean ρ	Mean abs(ρ)
$lnCO_2$	5.282	0.000	0.09	0.66
lnREN	3.347	0.001	0.05	0.60
lnTrade	7.306	0.000	0.12	0.46
lnGDP	42.818	0.000	0.70	0.81
lnEI	36.328	0.000	0.59	0.78

The CD test findings demonstrate substantial evidence of cross-sectional dependency among all variables, with all test statistics exhibiting high significance at the 1% level. The mean absolute correlation coefficients (mean abs(ρ)) vary from 0.46 for Trade Openness to 0.81 for Economic Growth, signifying considerable cross-country relationships. These findings highlight the necessity of utilizing estimation techniques that consider cross-sectional dependence, such as the AMG and CCEMG estimators.

Table 4 displays the findings of the CIPS panel unit root test for both the level and first-differenced series.

Table 4. Panel unit root test results

Variable	CIPS Statistic	Critical Values		
		10%	5%	1%
$\ln CO_2$	–1.012	–2.11	–2.20	–2.38
lnREN	–1.124	–2.11	–2.20	–2.38
lnTrade	–1.387	–2.11	–2.20	–2.38
lnGDP	–1.672	–2.11	–2.20	–2.38
lnEI	–2.592*	–2.11	–2.20	–2.38
ΔlnCO2	–3.797*	–2.11	–2.20	–2.38
ΔlnREN	–4.183*	–2.11	–2.20	–2.38
ΔlnTrade	–3.605*	–2.11	–2.20	–2.38
ΔlnGDP	–3.009*	–2.11	–2.20	–2.38
ΔlnEI	–4.556*	–2.11	–2.20	–2.38

Note: * indicates rejection of the null hypothesis of unit root at the 5% significance level.

The CIPS test findings demonstrate that all variables, with the exception of Energy Intensity, are non-stationary in levels, since the test statistics are higher than the critical values at standard significance levels. All variables attain stationarity following first-differencing, as the test statistics for the first-differenced series fall below the critical values at the 5% significance level. The results conclude that the variables are viewed as integrated of order one, I (1), prompting the investigation of cointegration connections.

Table 5 summarizes the results of the Pedroni (2004) panel cointegration tests.

Table 5. Panel cointegration test results

Test Statistics	Panel	Group
V	–1.354	–
Rho	1.097	2.775
T	–5.679*	–5.188*
Adf	–1.165	0.6212

Note: * indicates rejection of the null hypothesis of no cointegration at the 5% significance level.

The findings of the Pedroni cointegration test yield inconclusive evidence concerning the occurrence of a long-term connection between the variables. The panel t and group t statistics decisively reject the null hypothesis of no cointegration at the 5% significance level, whereas the other statistics fail to present evidence against the null hypothesis. Nonetheless, as the panel t and group t statistics are deemed the most dependable in small samples (Pedroni, 2004). It is concluded that there is evidence of cointegration among the variables. This discovery validates the assessment of long-term relationships with suitable methodologies.

Table 6 displays the long-term estimation outcomes utilizing the CCEMG and AMG estimators, which consider cross-sectional dependence and parameter heterogeneity.

Table 6. Long-run estimation results

Variable	CCEMG	AMG
lnREN	–0.1542***	–0.1626***
	(0.0533)	(0.0471)
lnTrade	0.0012	0.0204
	(0.0287)	(0.0275)
lnGDP	0.8277***	0.8870***
	(0.0702)	(0.0846)
lnEI	0.6940***	0.8221***
	(0.0806)	(0.0969)
Constant	–4.3338	–7.4293***
	(2.7055)	(0.8907)

Note: Standard errors in parentheses. *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

The CCEMG and AMG estimators produce qualitatively analogous results, serving as a robustness verification for the model. The coefficient of Renewable Energy is statistically significant and negative in both models, corroborating Hypothesis *H1* that renewable energy usage decreases CO_2 emissions. The CCEMG estimator demonstrates that a 1% rise in renewable energy consumption correlates with a 0.15% reduction in CO_2 emissions, whereas the AMG estimator implies a marginally greater benefit of 0.16%. The Trade Openness coefficient is positive, but it lacks statistical significance in both models, suggesting that trade openness exerts a minimal influence on CO_2 emissions across G20 economies collectively. These data do not offer definitive support for Hypothesis *H2*, which proposed a differential ef-

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fect of trade openness among various income categories. Additional examination of heterogeneous effects is required to comprehensively evaluate this theory. In both models, the coefficient of economic growth is statistically significant and positive, corroborating Hypothesis *H3* that economic expansion elevates CO_2 emissions. The CCEMG estimator indicates that a 1% increase in GDP per capita correlates with a 0.83% rise in CO_2 emissions, whereas the AMG estimator implies a little greater effect of 0.89%. The findings suggest that, on average, economic development in G20 economies has not adequately decoupled from carbon emissions. Energy intensity exhibits a positive and statistically significant coefficient in both models, corroborating Hypothesis H4 that energy intensity elevates CO_2 emissions. The CCEMG estimator indicates that a 1% rise in energy intensity correlates with a 0.69% increase in CO_2 emissions, whereas the AMG estimator indicates a greater effect of 0.82%. These findings underscore the significant impact of energy efficiency enhancements in reducing carbon emissions.

Table 7 displays the short-run estimation results using the CCEMG estimator with lagged variables to capture dynamic effects.

Table 7. Short-run estimation results

Variable	Coefficient	Std. Error	Z	P > z
ΔlnREN	–0.0976	0.0697	–1.40	0.161
ΔlnTrade	–0.0906	0.1739	–0.52	0.602
ΔlnGDP	0.7578*	0.4532	1.67	0.095
ΔlnEI	0.5615***	0.1838	3.05	0.002
ΔlnREN_L1	0.0167	0.0667	0.25	0.802
ΔlnTrade_L1	0.0763	0.1064	0.72	0.473
ΔlnGDP_L1	0.4365	0.4393	0.99	0.320
ΔlnEI_L1	–0.0246	0.1300	–0.19	0.850
Constant	–0.0033	0.0106	–0.31	0.757

Note: *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

The short-run estimation outcomes indicate significant dynamism in the link between the variables and CO_2 emissions. The coefficient of ΔlnREN is negative yet statistically negligible, indicating that fluctuations in renewable energy consumption do not exert an immediate effect on CO_2 emissions. This conclusion is consistent with the view that the advantages of adopting renewable energy may require time to manifest. The coefficient of ΔlnTrade is negative yet statistically insignificant, further corroborating the conclusion that trade openness exerts a minimal effect on CO_2 emissions in the case of G20 economies. The coefficient of ΔlnGDP is positive and slightly significant, suggesting that short-term economic expansion correlates with heightened emissions. A 1% rise in GDP per capita can lead to a 0.76% increase in CO_2 emissions in the short term. The coefficient of ΔlnEI is statistically significant and positive, signifying that short-term fluctuations in energy intensity considerably affect CO_2 emissions. A 1% increase in energy intensity correlates with a 0.56% rise in CO_2 emissions in the short term. This discovery highlights the significance of enhancing energy efficiency as an urgent approach to mitigate emissions. All lagged variables lack statistical significance, indicating that the impacts of fluctuations in renewable energy, trade openness, economic growth, and energy intensity do not endure beyond one year. This discovery underscores the necessity of continuous policy interventions to attain enduring emission reductions.

To investigate the variability in the associations between the variables and CO_2 emissions, distinct analyses are performed for two subsamples: (1) pre-2005 versus post-2005 periods, reflecting the phases before and after the implementation of the Kyoto Protocol; and (2) High-income versus Low-income G20 economies, determined by the median GDP per capita for each year.

Table 8. CCEMG estimation results by time period

Variable	Pre-2005	Post-2005
lnREN	–0.0229 (0.1536)	–0.1853*** (0.0630)
lnTrade	0.0410 (0.0824)	–0.0136 (0.0305)
lnGDP	0.1667* (0.0974)	1.0379*** (0.1303)
LnEI	0.2534** (0.1035)	0.6583*** (0.0919)
Constant	0.9735 (1.7385)	–3.3728 (5.0155)

Note: Standard errors in parentheses. *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

Table 8 displays the CCEMG estimation outcomes for the periods preceding and succeeding 2005. The findings demonstrate considerable changes in the connections between the factors and CO_2 emissions across the two time periods. The coefficient of renewable energy usage shows a negative but statistically insignificant relationship in the pre-2005 period, while it is negative and extremely significant in the post-2005 period. The data imply that the influence of renewable energy on emissions has been more pronounced in recent years, presumably due to technological breakthroughs, regulatory backing, and economies of scale in renewable energy deployment. The coefficient of trade openness is statistically negligible in both periods, affirming the minimal influence of trade liberalization on emissions. The coefficient of economic growth rises significantly from 0.17 in the pre-2005 period to 1.04 in the post-2005 period, with both estimates demonstrating statistical significance. This study indicates that the emission intensity of economic expansion has escalated in recent years, perhaps attributable to the swift industrialization of emerging nations within the G20 group. The coefficient of energy intensity rises from 0.25 in the pre-2005 period to 0.66 in the post-2005 period, with both estimates being statistically significant. This discovery signifies that energy intensity has increasingly influenced emissions in recent years, underscoring the necessity for improved energy efficiency policies and initiatives.

Table 9 displays the CCEMG estimation outcomes for the low-income and high-income G20 economies, derived from the median GDP per capita for each year.

Table 9. CCEMG estimation results by income group

Variable	Low-Income	High-Income
lnREN	−0.2496*** (0.0878)	−0.0773*** (0.0282)
lnTrade	−0.0207 (0.0271)	−0.0226 (0.0605)
lnGDP	0.8792*** (0.0910)	0.8353*** (0.1219)
lnEI	0.6940*** (0.0792)	0.6213*** (0.2010)
Constant	−6.2471*** (1.9427)	−5.8960* (3.2011)

Note: Standard errors in parentheses. *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

The findings indicate significant disparities in the correlations between the factors and CO_2 emissions among socioeconomic levels. Renewable energy consumption has a negative and statistically significant effect in both income categories, with a notably greater size in low-income nations (−0.25) than in high-income economies (−0.08). This discovery indicates that renewable energy's capacity to diminish emissions is more pronounced in developing economies, likely owing to their elevated carbon intensity and increased opportunities for technological leapfrogging. There is no statistically significant relationship between trade openness and the dependent variable in either income group, further substantiating the minimal effect of trade openness on emissions in G20 economies. The coefficients for economic growth and energy intensity are both positive and statistically significant across both income levels, exhibiting comparable magnitudes. The data indicate that economic growth and energy intensity are concluded to be significant determinants of emissions throughout various phases of economic development.

4. DISCUSSION

This study's empirical findings offer significant insights into the factors influencing CO_2 emissions in G20 countries and enhance the current scientific discourse across numerous major aspects. The findings indicate both alignment and deviation from other studies, while uncovering novel trends pertinent to the G20 environment.

The findings on renewable energy are in strong agreement with the general scientific consensus formed by Dogan and Seker (2016), Dong et al. (2018), and Apergis et al. (2023), all of whom consistently identified negative correlations between the utilization of renewable energy and CO_2 emissions. This study surpasses past research by demonstrating substantial variation in the effects of renewable energy across different income levels and time periods within the G20 context. The observation that renewable energy's influence is more significant in low-income G20 economies (−0.25 elasticity) than in high-income economies (−0.08 elasticity) contradicts the findings of Chen et al. (2019), which indicated more substantial effects in high-income countries. This discrepancy shows that the G20's distinctive assembly of rapidly industrializing nations engenders dynamics that vary from those found in individual countries or smaller regional analyses. The temporal analysis indicating more pronounced effects after 2005 corroborates the assertions made by IRENA (2021) concerning technology progress and governmental support related to reductions in renewable energy costs and increases in implementation.

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The results of trade openness exhibit a significant divergence from the inconclusive findings in prior studies. While Managi et al. (2009) revealed that trade's technical effect diminishes emissions in affluent nations and Al-Mulali and Ozturk (2015) determined that trade openness intensifies environmental degradation in MENA countries, this study reveals statistically insignificant effects across all G20 economies, irrespective of income level or temporal context. This deviation from other studies may indicate the distinctive attributes of G20 economies, where the scale, content, and method effects of trade may be more equilibrated than in other regional contexts. The results show that the pollution haven and pollution halo hypotheses posited by Cole and Elliott (2003) and Frankel and Rose (2005) may effectively negate one another within the G20 context, leading to a neutral net impact.

The findings on economic growth robustly corroborate the existing literature, especially the studies by Onofrei et al. (2022) and Alaganthiran and Anaba (2020), which indicated favorable emissions impacts resulting from economic expansion. This study indicates a troubling escalation in the growth-emissions link after 2005, with elasticity rising from 0.17 to 1.04. This temporal pattern was inadequately recorded in prior research and indicates that the swift industrialization of rising G20 economies has established a more carbon-intensive economic trajectory than traditionally noted. The discovery that the effects of economic growth are uniform across income levels (0.88 for low-income, 0.84 for high-income) contradicts the Environmental Kuznets Curve hypothesis, which posits that developed economies inherently attain reduced emissions intensity, thereby reinforcing the more pessimistic evaluations of Aye et al. (2017) concerning the decoupling of growth and emissions.

The energy intensity findings validate the favorable correlation identified by Saidi and Hammami (2015) and Liu et al. (2019), while also offering novel perspectives on temporal dynamics within the G20 framework. The observation that energy intensity impacts have intensified over time (from 0.25 to 0.66 elasticity post-2005) indicates that energy efficiency has increasingly emerged as a significant factor influencing emissions, perhaps attributable to the growth of energy-intensive industries in developing G20 nations. This temporal intensification trend was not significantly highlighted in prior research, which generally concentrated on static correlations. The uniformity of energy intensity impacts across socioeconomic brackets endorses the universal relevance of energy efficiency initiatives proposed by Namahoro et al. (2021).

This study's methodological contributions rectify significant deficiencies in prior research by utilizing CCEMG and AMG estimators that consider cross-sectional dependence and parameter heterogeneity. Much prior research in this field has insufficiently addressed these econometric issues, which may result in skewed estimates and policy suggestions. The investigation of variation across temporal intervals and income strata offers a more refined comprehension of emission factors compared to the aggregate analyses commonly seen in the literature.

CONCLUSION

The purpose of this study is to examine the economic and energy sector factors affecting CO_2 emissions in G20 economies from 2000 to 2021, focusing on renewable energy consumption, trade openness, economic growth, and energy intensity through advanced dynamic panel econometric methods.

The empirical research identifies four principal conclusions that enhance our comprehension of emission determinants within the G20 framework. The usage of renewable energy markedly decreases CO_2 emissions, exhibiting elasticity values ranging from –0.15 to –0.16, with more pronounced benefits noted in low-income nations and in the post-2005 timeframe. Trade openness has no impact on CO_2 emissions among all G20 economies, with statistically insignificant effects irrespective of income level or time frame. The correlation between economic growth and CO_2 emissions is significant, with elasticity values between 0.83 and 0.89. This link has intensified markedly since 2005, while maintaining consistency across various income levels. Energy intensity markedly increases CO_2 emissions, exhibiting elasticity values ranging from 0.69 to 0.82, with impacts intensifying over time and demonstrating stability across various income levels.

These findings yield numerous significant consequences for climate policy and sustainable development. Initially, the adoption of renewable energy constitutes the most efficient strategy for emission reduction within the G20 framework, especially in emerging economies where the capacity for carbon intensity reduction is most significant. Secondly, trade liberalization alone cannot be depended upon to attain environmental enhancements, requiring supplementary policies that amplify the technique effect while alleviating potential pollutant haven consequences. The ongoing and escalating correlation between economic growth and emissions demonstrates that G20 economies have not attained significant decoupling, necessitating the immediate adoption of low-carbon growth strategies. Fourth, enhancements in energy efficiency have significant potential for emission reductions across all G20 nations, becoming increasingly critical as energy-intensive activities proliferate.

Future research should tackle various limitations and investigate new aspects of the growth-emissions nexus. The inclusion of data more recent than 2021, when accessible, would augment the temporal breadth of the study and elucidate post-pandemic trends. The incorporation of institutional quality indices, innovation measures, and environmental policy variables would yield a more thorough comprehension of emission causes. Advanced nonlinear modelling techniques may uncover threshold effects and intricate relationships that linear panel methods fail to capture.

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