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RESEARCH ARTICLE

Post-COP26: can energy consumption, resource dependence, and trade openness promote carbon neutrality? Homogeneous and heterogeneous analyses for G20 countries

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Abstract
The need to halt the pervasive issue of global warming has triggered commitments from policymakers, international organizations, and research pundits with an ambitious goal of neutralizing carbon emissions, forming the core of COP26 in November 2021. Consequently, the carbon neutrality agenda is globally debated in the environment and economic growth literature. Given the preceding narratives, this study examines the tripartite effects of energy consumption, resource dependence, and trade openness on carbon neutrality in G20 economies from 2001 to 2019. The empirical evidence relies on homogenous and heterogeneous dynamic models based on a system generalized method of moments (GMM), fully modified ordinary least squares (FM-OLS), and quantile regression estimators. The following results are evident from the empirical analyses. Among the heterogeneous indicators, nonrenewable energy, oil rents, coal rents, and imports contribute to the surge in carbon emissions, while renewable energy, gas rents, and exports moderate carbon emissions. The homogenous impacts show that total energy consumption, total natural resource rents, and trade openness promote significant carbon emissions. Further, the long-run results from FM-OLS and the disintegrated mean effects from quantile regression are robust for the main short-run results based on the two-step system GMM. Based on the empirical fallout, investing in renewable energy and diversifying from natural resource exploration are among the emanating policy that can enhance the sustainability of the G20 environment.

Keywords Energy consumption · Resource abundance · Trade openness · G20

Introduction

Global warming has proven to be one of the most contending issues in the last few decades due to the adverse effects it has on human peaceful coexistence and sustainability of the present and future ecosystem. To sustain the environment for the current generation without compromising the stake of the future, human activities that are believed to be the prime culprit of global warming must be checked and moderated to promote carbon neutrality in both developed countries and developing economies. To this end, keeping global warming lower than 2 °C and maintaining a limit of 1.5 °C below the pre-industrial era have been globally adopted (Oke et al. 2021). The climate target metamorphosed from global climate conferences held by international organizations, the most recent being the United Nations Climate Change Conference 2021 (COP26), held in November 2021, hosted by the UK in Glasgow. COP26 is the most recent climate conference with attendance spanning nearly 200 countries, emphasizing the need for holistic decarbonization of the environment by 2050. Policymakers and research pundits at COP26 believe that any further addition to the current global warming is undesirable and must be fought against because, according to Prime Minister Mia Mottley at the COP26 Climate Summit, entering a 2 °C global warming is a death sentence (COP26 2021).

Among many other environmental sustainability plans, COP26 set up new dimensions for reaching net-zero global warming by 2050 while halving it by 2030. For instance, the conference recorded commitments to cover nearly 85% of global GDP within the net-zero agreement. More so, not less than 153 economies buy into the idea of taking practical actions on the Nationally Determined

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Contributions (NDCs), which account for approximately 80% of the world's greenhouse gas (GHG) emissions, with plans to strategize toward cutting off GHG emissions of around 5 billion by 2030 (COP26 2021). To achieve the new or modified commitments, the Glasgow Climate Pact (COP26) emphasized massively reducing coal power, putting a great end to deforestation, fast-tracking the transition to electric vehicles, and phasing down methane emissions. In addition, COP26 advocates for the indispensable need to bring down fossil fuel subsidies (estimated at around $5.9 trillion in 2020), contributing not less than 89% to global carbon emissions. The role of natural resources on the global greenhouse gas emissions surge has been extensively debated, with diverging views advancing that natural resources reduce carbon emissions. At the same time, others submit it compounds the global warming challenges. With this in mind, the choice between exploring the rents from natural resources and diversifying into other sectors of the economy leaves much to be desired. Hence, moving forwards from COP26 resolutions, policymakers are in the dilemma of how best to explore the natural resources without jeopardizing the sustainability of humanity and the immediate ecosystem.

It is equally instructive to note that the achievement of the various resolutions entrenched in the Glasgow pact hinges on the practical steps national and regional governments take to achieve the set targets (Gudde et al. 2021). To this end, intergovernmental organizations such as the Group of Seven (G7), the Group of Twenty (G20), the Emerging Seven (E7), and the Next Eleven (N-11) economies have roles to play in ensuring total commitment to the Glasgow pact. In other words, climate policies from these leading economies could set a good pace for others to follow. Given the preceding arguments, critically examining carbon neutrality's driving (enhancing) and dragging (deterring) factors becomes a top-notch policy target for the developed and developing economies the former nations must lead. The successful conduct of empirical verification of the two sets of factors will allow policymakers to decide on factors to suppress and elements to support from the policy angles in reaching zero emissions by the target period. The preceding narratives underscore the need for empirical studies that will explicitly highlight the determinants of carbon neutrality for logical inferences and policy deductions. Although copious research studies have been conducted on carbon neutrality, most are country specific. The existing panel studies focus mainly on the Next-Eleven countries (Shao et al. 2021); EU-5 countries (Caglar et al. 2021); Group of Seven (G7) economies (Khan et al. 2022a, b, c); BRIC countries (Zhang 2021); Emerging seven economies (E7) (Tao et al. 2021); and ASEAN-5 countries (Tan et al. 2021). We are unaware of any study on carbon neutrality for the G20 countries, especially since the post-COP26 conference was concluded in 2021. This cavity is prominent and cannot be neglected, considering the notable roles of the G20 in today's global economy.

Empirical research objective

The primary objective of the present study is to investigate how energy consumption, resource dependence, and trade openness can enhance or deter the pursuance of carbon neutrality targets in G20 economies. By extension, the study aims to estimate the homogenous (aggregated) and heterogeneous (disaggregated) effects of the drivers on carbon neutrality (carbon emissions per capita). The consideration of carbon neutrality determinants in this study will cover income variables energy consumption (renewable, renewable energies, and total energy), resource dependence (total natural resources rents, oil rents, coal rents, and natural gas rents), and trade openness (imports, exports, and share of trade in GDP). Other exogenous indicators include population growth, technology, structural change, and regulatory quality. To unravel the effects of the determinants on carbon neutrality, the study employs the two-step generalized method of moments and fully modified ordinary least squares (FM-OLS).

Research contribution

The contributions of this study to the carbon neutrality literature are fivefold. First, the resolutions at COP26 open the floor for exploring the drives of carbon neutrality. Thus, the recency of the concept following the just-concluded climate change conference opens the door for contributions on the ways toward achieving the targets. The present study will thus be among the early contributors to carbon neutrality. Second, as much as studies are emanating massively on the concept of carbon neutrality, the scopes of research have not catered for the G20 economies. This study will represent the first empirical effort to evaluate the determinants of carbon neutrality for the G20 countries. Third, the consideration of homogenous and heterogeneous effects of the drivers of carbon neutrality is yet another new approach that this study brings to the fore. To the best of our knowledge, no study has considered investigating the drivers of carbon neutrality from disaggregated and aggregated angles for the G20.

Besides the introductory section, a comprehensive review of the extant literature is assessed in Sect. 2, method and estimation procedures are presented in Sect. 3, and Sect. 4 presents and discuss empirical outcomes. Section 5 concludes and provides insightful suggestions.

Literature review

Even though it is undeniable that the speedy pace in economic advancement and interconnectedness of countries are among the remarkable achievements of the present time, this breakthrough poses stunning challenges to the continued human and environmental existence. While many measures have been suggested toward salvaging the present and future stakes of human and ecological peaceful coexistence, the need to reduce carbon emissions believed to be the primary perpetrator of global warming has topped the priority list of governments, research pundits, and international organizations alike. As the present study equally seeks to contribute to the ongoing carbon neutrality debates, an in-depth understanding of the extant studies is sorted in the following reviews.

Starting on the recent note, Yu et al. (2022a) evaluate the impacts of renewable energy consumption, energy poverty, trade freedom, natural gas, GDP, and square of GDP on carbon emissions in developing economies based on annual data from 2001 to 2019 estimated through the panel quantile regression. Findings from the study provide an empirically supported argument that eliminating poverty should remain the utmost target toward decreasing carbon emissions and achieving SDG7. The empirical findings in Ibrahim and Ajide (2022) uncover that trade procedures mitigate the surge in carbon emissions for a panel of selected 48 Sub-Saharan African countries from 2005 to 2014. Dong et al. (2022) examine the nonlinear association between renewable energy and carbon emission efficiency in 33 advanced economies on the drive to attain carbon neutrality. The empirical evidence relies on annual data from 2000 to 2018 estimated using the latest panel threshold model with interactive fixed effects. Empirical fallout from the study reveals that renewable energy development holds great potential to drive carbon emissions efficiency. Sarwat et al. (2022) find empirical evidence that supports the EKC hypothesis amidst natural resources, globalization, and renewable energy in BRICS. Besides, Yu et al. (2022b) establish the empirical regularity of oil export, renewable energy, and transport infrastructure for the Chinese and Indian economies. Yuan et al. (2022) explore the novel rolling-window Granger causality test to investigate the impact of renewable energy in moderating carbon emissions. The study's feedback shows an inverse relationship between renewable energy and carbon emissions. Zhao et al. (2022) provide an empirically based comparative analysis of China, the European Union, and the USA using annual data on carbon neutrality and international trade. Empirical findings from the study reveal positive nexus between energy consumption and carbon emissions. The share of fossil fuels in the Chinese energy mix remains very high. These results are more apparent in China than in the EU, the US, or other nations.

Some empirical investigations focus on policy implications stemming from the G7 economies. For instance, the role of a composite index, innovations, and environmental regulations in pursuing the carbon neutrality goal constitutes the core of research interest in Qin et al. (2021) for the G7 economies from 1990 to 2019. Findings from the analyses uncovered support for EKC validity in the G7 countries. Besides, indicators like green innovation, environmental policy, and composite risk index significantly reduce carbon emissions, implying a drive toward carbon neutrality for the group. However, GDP deters the strides to achieve carbon neutrality through its substantial contributions to the stock of carbon emissions. Still, within the G7 economies, Safi et al. (2021) evaluate how the joint interplay of research and development (R&D) and environmental taxes enhance or deter the achievement of carbon neutrality using data from 1990 to 2019. Empirical results expose that R&D, environmental taxes, and exports moderate carbon emissions while GDP promotes carbon emissions. Considering this line of argument, Gyamfi et al. (2021) evaluate the drivers of carbon environmental quality measured by carbon emissions in G7. The authors consider the extent to which income level, energy consumption, and natural resource rent drive or drag carbon emissions in G7 countries. The study's empirical analysis relies on augmented mean group (AMG), dynamic OLS (DOLS), and quantile regression (QR) on annual data with the stochastic impacts by regression on population, affluence, and technology (STIRPAT) framework. The outcomes reveal that natural resource rent promotes carbon emissions in all the estimated quantile besides the 0.05 quantile. More so, renewable energy reduces carbon emissions while fossil fuel promotes it. Ajide and Ibrahim (2021) find capital investment harmful to the environment in a panel of G20 economies.

Within the framework of carbon neutrality debates, BRICS economies have attracted many empirical studies. Razzaq et al. (2021) probe the functional nexus between technology innovation and carbon emissions in BRICS economies using monthly datasets from 1990 to 2017 estimated using quantile on quantile framework. The empirical outcomes reveal the practical impacts of green innovation significantly reduce carbon emissions in all seven countries. Rahman et al. (2021) examine the factors influencing the surge in carbon emissions for the BRIC economies from 1989 to 2019. Economic growth, energy consumption, and globalization are evaluated on carbon emissions using FM-OLS and DOLS techniques in estimating the specified models. The findings reveal the existence of long-run nexus between the regressors. Besides, energy consumption is a positive predictor of carbon emissions, while globalization negatively predicts carbon emissions in the group of economies. In addition, verifying the anticipated direct and indirect effects of economic growth on carbon emissions is not validated for the BRICS. Zhang (2021) probes the functional nexuses among economic growth, technological innovation, and carbon emissions in the BRICS using annual data spanning 1990 to 2019 based on the STIRPAT framework. The empirical findings reveal that technological innovation enhances the transition toward carbon neutrality by effectively decreasing the stock of carbon emissions. Considering the impacts of economic growth, GDP deters the pathway to carbon neutrality by contributing to carbon emissions. More so, a unidirectional causality is evident in the specified mode.

Currently, the dual G7 and BRICS economies have received the highest frequency of empirical investigations in panel studies on carbon neutrality. Other available panel studies are appraised thus. Focusing on emerging seven (E7) countries, Tao et al. (2021) investigate the dynamic impacts of environmental taxes and eco-innovation on carbon neutrality based on annual data straddling 1995 to 2018. Verifying the EKC hypothesis also constitutes an additional crucial objective of the study. The empirical evidence based on second-generation estimation techniques, including cross-sectional autoregressive distributed lag (CS-ARDL), common correlated effect mean group (CCEMG) and augmented mean group (AMG), provides sturdy backings for enhancing the roles of environmental taxes and eco-innovation in promoting carbon neutrality through a significant reduction in carbon emissions. The verification exercise conducted on the EKC hypothesis confirms such in the E7 economies. The European Union has come under scrutiny in investigating target neutrality targets. Within this research scope, Salvia et al. (2021) conducted an empirical study on the roadmap toward carbon neutrality target among 327 towns in the EU region. The analysis primarily focuses on assessing the nature of town size, geographical location, and climate network membership cover more than 25% of the EU population. The key findings from the study reveal the commitment of 78% of towns to GHG emissions mitigation. The study concludes that the EU cities are on track to delivering their 47% average emissions target.

The next eleven (N-11) economies are among the research scope of the recent empirical investigations on carbon neutrality. For instance, Shao et al. (2021) evaluate the effects of renewable energy and technology innovation on carbon emissions in N-11 countries based on yearly data spanning 1980 to 2018. The study's methodology covers econometric issues relating to cross-sectional dependence, unit root, slope homogeneity, and structural break that distort the reliability and validity of parameter estimates. The CS-ARDL estimation technique is adopted. The results reveal that technological innovation and renewable energy significantly curb the surge in carbon, thereby setting the stage for carbon neutrality. Besides, other estimators such as AMG and CCEMG provide empirical evidence affirming the robustness of the CS-ARDL results. Examining the carbon neutrality target in the Association of Southeast Asian Nations (ASEAN) countries constitutes the primary research for Tan et al. (2021). They evaluate the asymmetric impacts of income inequality on renewable energy consumption from 1990 to 2015. The empirical results emanating from the ARDL estimator show that inequality propels renewable energy consumption.

Research gaps

The assessment of the existing studies uncovers some gaps the present research fills. For instance, the evolving panel studies on carbon neutrality have neglected the scope of G20 economies despite the group's composition with the most developed economies in the world. Besides, the empirical investigations have been primarily engrossed by homogeneous effects testing, while the heterogeneous effects remain a less explored area. This is despite the high possibilities of divergence in the impact of different explanatory variables on carbon neutrality measures. Hence, it becomes highly intuitional to conduct both homogenous and heterogeneous effects of selected carbon neutrality measures to verify whether similar or divergent impacts will be evident.

Method

This section is divided into two subsections: Sect. 3.1 illustrates the theoretical framework underpinning the relationship under investigation and the specification of the empirical model to be estimated. Section 3.2 is devoted to explaining the expected intuitions guiding the direction of the determinants of carbon neutrality on the outcome variable (carbon emissions per capita).

Theoretical underpinning and empirical modeling

The nexuses among the outcomes and explanatory variables in the current study rely on the stochastic impacts by regression on population, affluence, and technology (STIRPAT). Conventionally, three variables such P for population, while A and T denote affluence and technology, respectively. The nexus between these variables and environmental measures can be stated thus:

$$Env = \theta P_i^{\tau 1} \times A_i^{\tau 2} \times T_i^{\tau 3} \times \sigma_i. \tag{1}$$

Equation (1) ϑ denotes the constant that scales the model. Further, the parameters ρ_1, ρ_2, ρ_3 represent the exponential functions for population (P), affluence (A), and technology (T). The linear form of Eq. (1) states thus

$$\ln Env_{it} = \theta_0 + \tau_1 P_{it} + \tau_2 A_{it} + \tau_3 T_{it} \times \sigma_i. \quad (2)$$

Drawing from Zhu et al. (2022) with alterations based on the focus of the current research, *Env* is assumed to represent carbon neutrality proxy by carbon emissions per capita (CO2pc), while P, A, and T denote population, economic growth, and technology. The framework is expanded to include other carbon neutrality determinants: energy consumption, resource dependence, and trade openness. An extended version of the model is presented in the dynamic form.

$$CO2PC_{it} = \theta_0 + \tau_1 CO2PC_{it-1} + \tau_2 ENC_{it} + \tau_3 RA_{it} + \tau_4 TOP_{it} + \tau_5 X_{it} + \sigma_{it} \quad (3)$$

Equation (3) $CO2PC_{it}$ represents carbon neutrality captured by carbon emissions (CO2). $CO2PC_{it-1}$ is the initial state of the environment moving toward or away from carbon neutrality. ENC_{it} (energy consumption) is a vector for three indicators: renewable energy consumption (*REN*), nonrenewable energy consumption (NEC), and total energy consumption (TENC). NRA_{it} denotes resource dependence entailing four components thus: coal rents (COALR), natural gas rents (GASR), oil rents (OILR), and the aggregate indicated which is total natural resource rents (TNRR). TOP_{it} represents trade openness comprising three indicators imports, exports, and the aggregate. X_{it} signifies a vector for the control variables vectoring technology (TECH), regulatory quality (RQ), and structural change (STC), population growth (POPG). σ_{it} is the error term, while $\tau_{1\ldots13}$ comprises the parameters to be estimated. Further, *i* and *t* denote the cross section of the 19 countries in the G20 (excluding the European Union) and the study period, which spans 2001 to 2019. It is worth emphasizing that the exclusion of the European Union from the study is due to the non-availability of institutions' data for the group.

A priori *expectations*

The explanatory and explained variables' economic intuitions guiding the functional nexuses are explicated with adequate reference to the extant literature. Firstly, it is essential to explain the meaning of carbon neutrality and the interpretation of the behavior of its proxy to the selected determinants. The word carbon neutrality implies offsetting the carbon content of the various drivers of economic growth. Hence, it means achieving more growth with fewer carbon emissions in a relationship depicted as economic growth at a decreasing carbon emission rate. The goal of carbon neutrality is broadly directed toward reducing carbon emissions and its equivalents toward the zero point (net-zero emissions) by 2050 as adopted by United Nations and other international organizations. The reason for neutralizing carbon emissions among different environmental pollution variants is that the adversities posed by carbon emissions to the environment and human existence are more than what others contribute. Consequently, carbon neutrality enhances a variable if it reduces, mitigates, moderates, or deters carbon emissions. A variable that supports, contributes, or induces any percentage increase in carbon emissions hinders carbon neutrality. So, a negatively signed variable to carbon emissions enhances carbon neutrality through the decline it will cause, while a positively signed variable will impact otherwise.

Beginning with population, it is empirically hypothesized as a hindering factor for carbon neutrality because it induces carbon emissions. Empirically, a significant population increase will result in a corresponding rise in carbon emissions (Wang and Zhang 2021), making the relation positive $\tau_2 = \left(\frac{\partial CO2PC}{\partial POPG} > 0\right)$. Technology enhances the utilization of low-carbon equipment in the production processes and equally efficient production. The transition toward clean energy can be high through technological advancement. The prior studies opined that technology is crucial in decreasing carbon emissions, anticipating a negative nexus (Ibrahim et al. 2022) $\tau_4 = \left(\frac{\partial CO2PC}{\partial TECH} < 0\right)$. The nexus between economic growth and carbon emissions has been debated extensively among scholars, with some alluding to the hindering impacts of the former on the latter (Gyamfi et al. 2021). Following this argument, a positive nexus is hypothesized thus $\tau_4 = \left(\frac{\partial CO2PC}{\partial GDPG} > 0\right)$. Energy consumption affects carbon emissions depending on the source of energy. In the case of renewable energy, a negative nexus has been primarily advanced in the literature (Zhang et al. 2021) $\tau_6 = \left(\frac{\partial CO2PC}{\partial REN} < 0\right)$. In contrast, nonrenewable energy promotes the surge in carbon emissions, thereby positively related to it Ajide and Ibrahim (2021), leading to positive nexus $\tau_6 = \left(\frac{\partial CO2PC}{\partial NRE} > 0\right)$. Natural resource rents are recently attracting attention in the environmental quality debates. The preponderance of the extant studies alludes that natural resource rents trigger consistent depletion of the natural resources with ensuing effects increasing the stock of carbon emissions. In line with this argument, the extant studies posit natural resource rents promote carbon emissions (Iqbal et al. 2022; Ibrahim and Ajide 2021b) $\tau_8 = \left(\frac{\partial CO2PC}{\partial NRR} > 0\right)$.

Furthermore, opening countries to the global marketplace has some significant environmental implications. Some studies argue that trade openness enhances the quality of the environment by reducing the stock of carbon emissions through the transfer of technology and knowledge diffusion (Ibrahim et al. 2022). Following this argument, trade openness would enhance the achievement of carbon neutrality by mitigating its impacts on carbon emissions $\tau_9 = \left(\frac{\partial CO2PC}{\partial TOP} < 0\right)$. Contra-wise, the inverse association of trade openness on the environment through carbon emissions promotion has been established (Ibrahim and Ajide 2020) $\tau_9 = \left(\frac{\partial CO2PC}{\partial TOP} > 0\right)$.

Estimation technique

The estimation methods adopted in this study are three. The first is the system generalized method of moment is employed to estimate the empirical model's short-run effects. At the same time, the second estimator involves using fully modified ordinary least square (FM-OLS) to evaluate the long-run impacts of carbon neutrality determinants. The third estimator, quantile regression (QR), is employed to address nonlinearity in the nexuses among the indicators. Besides, QR is considered to decompose the mean effects of the regressors to different quantiles such as lower quantiles (0, 10, 0.20, 0.30, and 0.40), middle quantiles (0.50 and 0.60), and upper quantiles (0.70, 0.80, and 0.90).

Dynamic system generalized method of moments (SYS-GMM)

The estimation of Eq. (1) is usually encountered with the issue of endogeneity that tends to restrict the unbiased and reliability of the estimated parameters. This problem occurs because of the bidirectional nexus between the regressors and outcome variables. For instance, economic growth can improve or deteriorate the environment. Alternatively, environmental pollution caused by increased carbon emissions can adversely affect economic growth. Similar two-way effects are applied in the case of population growth and carbon emissions. The persistent rise in population leads to continuous depletion of natural resources, increasing carbon emissions, and other pollutants. Conversely, increased pollutions endanger the environment and threaten human existence, leading to a decrease in population. Based on the preceding exposited nexuses, the potential issue of endogenous becomes apparent. Besides, the lagged value of the outcome variable on the right-hand side of the model creates an estimation challenge in arriving at unbiased parameter estimates. A model characterized by large N and small T will most likely suffer from unobserved country-specific variables associated with the error term. In a typical model of this nature, the OLS estimator cannot provide consistent and unbiased estimates of which generalized method of moment (GMM) can handle. This estimator is augmented to the level of system GMM becoming (SYS-GMM) which are credited to scholars such as Arellano and Bover (1995), Blundell and Bond (1998), and Roodman (2009). The standard model of the SYS-GMM method can be stated as follow.

$$\begin{aligned} CO2PC_{it} &= \theta_0 + \tau_1(CO2PC_{it-1} - CO2PC_{it-1}) \\ &+\tau_2(ENC_{it} - ENC_{it-1}) + \tau_3(RA_{it} - RA_{it-1}) \\ &+\tau_4(TOP_{it} - TOP_{it-1}) + \tau_5(X_{it} - X_{it-1}) + \sigma_{it} \end{aligned} \quad (4)$$

Fully modified ordinary least square

The initial work on fully modified least squares (FM-OLS) regression was credited to Phillip and Hansen (1990), which focused on providing optimal parameter estimates for the long-run regression model. The FM-OLS estimator amends OLS to address the twin issues of endogeneity and serial correlation due to long-run nexus in a model. Following Pedroni (1996), the model illustrating the FM-OLS method is given thus:

$$\hat{\beta}^*_{NT} - \beta = \left(\sum_{i=1}^{N} L_{22i}^{-2} \sum_{t=1}^{T} \left(x_{it} - \bar{x}_i\right)^2\right)^{-1} \sum_{i=1}^{N} \hat{L}_{11i}^{-1}\hat{L}_{22i}^{-1}\left(\sum_{t=1}^{T} \left(x_{it} - \bar{x}_i\right)\mu^*_{it} - T\hat{\gamma}_i\right). \quad (5)$$

Equation (5) $\hat{L}_i$ denotes the subordinate triangular disintegration of the idiosyncratic asymptotic covariance matrix, which is consistent with the following $\Omega_i = \Omega_i^0 + \Gamma_i + \Gamma_i'$ wherein $\hat{L}_i$ is normalized. Further, $\hat{L}_i = \hat{\Omega}_{i22}^{-1/2}$ and where μ^*_{it} is given by $\mu^*_{it} = \mu_{it} - \frac{\hat{L}_{21i}}{\hat{L}_{22i}}\Delta x_{it}$ and the serial correlation adjustment parameter $\hat{\gamma}_i = \hat{\Gamma}_{21i} + \hat{\Omega}^0_{21i} - \frac{\hat{L}_{21i}}{\hat{L}_{22i}}\left(\hat{\Gamma}_{22i} + \hat{\Omega}^0_{22i}\right)$.

Quantile regression results

The current research employs the novel quantile regression (QR) estimator to extend the knowledge frontier on the longevity debate in Africa. The justification for adopting quantile regression is based on the ground that it provides robust analyses of the decomposed impacts of the regressors on the outcome variable in different median points (quantiles). Moreover, the effects of each explanatory variable are evaluated through low, middle, and upper quantiles.

Data source and variable description

This study employs a panel dataset to analyze the determinants of carbon neutrality in G20 economies from 2001 to 2019. The choice of data coverage is due to the non-availability of critical variables in the years preceding 2001 and years after 2019 for all the cross-sectional units. Two categories of data are utilized in line with the study's objectives. The first category, which involves data on heterogeneous impacts, focuses on assessing the individual effects of the determinants. For instance, natural resource rents are decomposed into three indicators: oil rents, coal rents, and natural gas rents. A similar situation applies to other explanatory variables. The second data category entails examining the individual indicators' aggregate effects. In the case of resource dependence, total natural resource rents are employed to evaluate the homogenous (aggregate) effects. The datasets are sourced from World Bank's World Development Indicators (2021), available at https://databank.worldbank.org/source/world-development-indicators.

The descriptive statistics of the dataset are presented in Table 1. The mean value of the carbon emissions per capita for the G20 stands at 7.79%, with the minimum and maximum values standing at 0.89% and 20.18%. Oil rents constitute the highest within the group of natural resource rents with 3.39%, implying that the countries in the group are averagely oil-dependent. Next to oil rents are coal rents, which stand at an average of 0.50%, and gas rents, which average 0.48%. Furthermore, we could also infer from the performance of the various indicators of natural resource rents that natural gas is yet to be fully explored among the peers of other resources.

Considering energy consumption, the average consumption of 80.28% for nonrenewable energy surpassed that of renewable energy at 14.55%. This discrepancy further accentuates the view that the G20 economies still depend more on nonrenewable energy for their productive economic and non-economic activities. The average values of exports (27.41%) and imports (25.57%) show that the G20 countries are net exporters of goods and services.

Presentation and discussion of empirical results

The results of the estimated model are presented twofold. First, the main results comprise estimates from the two-stage system generalized method of moments (SYS-GMM). Furthermore, the SYS-GMM results include the heterogeneous effects and the homogenous effects. It should, however, be noted that the SYS-GMM is a short-term estimator implying the short-run nexus between the indicators is assessed. Going by the preceding observation, the second category involves the robustness checks, which is the fully modified OLS (FM-OLS) in estimating the long-run impacts of the determinants of carbon neutrality. The robustness checks also involve heterogeneous and homogeneous effects.

Main results based on SYS-GMM estimator

Prior to analyzing the nexuses among the indicators, the post-estimation tests are first examined to check the validity and reliability of the parameter estimates. As evident in Table 2, AR(2), Sargan, and Hansen tests generally justify the absence of autocorrelation in the residuals. This is equally sufficient to advance the efficiency of the instruments employed in the SGMM estimations.

The main results are presented in Table 2 for heterogeneous and homogenous drivers of carbon neutrality in G20 economies. Going by the outcome of the components of natural resource rents in Model 1, it is apparent that the heterogeneous impacts of resource abundance based on oil rents and coal rents positively influence the rise in carbon emissions while gas rents mitigate it. Hence, it could be inferred that rents from oil and coal have short-term effects on carbon emissions such that an increase in these resources leads to a corresponding rise in carbon emissions. The homogenous effects based on total natural resources (ttnr) are significantly positive, suggesting a rise in the total natural resources compounds the menace of environmental pollution in the G20

Table 1 Descriptive statistics

Variables	Names and measurements	Mean	Median	Maximum	Minimum	Std. dev
CO2PC	CO2 emissions (metric tons per capita)	7.79	7.51	20.18	0.89	4.89
COALR	Coal rents (% of GDP)	0.50	0.04	8.05	0.00	1.02
OILR	Oil rents (% of GDP)	3.39	0.68	54.50	0.00	9.11
GASR	Natural gas rents (% of GDP)	0.48	0.06	8.67	0.00	1.09
TTNR	Total natural resources rents (% of GDP)	4.96	2.20	55.52	0.01	9.57
REN	Renewable energy consumption (% of total final energy consumption)	14.55	10.19	51.86	0.01	13.78
NEC	Fossil fuel energy consumption (% of total)	80.28	84.24	100.00	46.23	12.69
TENC	Total energy use (kg of oil equivalent) per $1000 GDP (constant 2017 PPP)	126.91	104.62	278.86	60.52	54.36
IMPORTS	Imports of goods and services (% of GDP)	25.57	26.38	52.23	9.48	8.03
EXPORTS	Exports of goods and services (% of GDP)	27.41	26.94	62.11	9.03	10.62
TOP	Trade openness (% of GDP)	52.98	53.43	105.57	19.56	17.86
STC	structural change (services, value-added % of gdp)	3.81	3.14	16.07	-9.72	3.44
RQ	Rule of law (estimate)	0.57	0.47	2.05	-1.07	0.79
TECH	Technology (ICT goods exports % of total goods exports)	8300.00	2240.00	7480.00	8100.00	1250.00
POPG	Population growth (annual %)	0.87	0.89	3.09	-1.85	0.68

S.D. implies standard deviation. Max means maximum. Min denotes minimum

Table 2 Short-run heterogeneous and homogeneous estimates based on system GMM

Variables	Outcome variable: carbon emissions per capita (co2pc)		
	Model 1	Model 2	Model 3
l.co2pc	.962***	1.052***	.983***
	(.015)	(.045)	(.009)
oilr	.034***		
	(.009)		
coalr	.033**		
	(.015)		
gasr	−.143*		
	(.070)		
ttnr	.089**		
	(.027)		
ren		−.039	
		(.036)	
nec		.079***	
		(.017)	
tenc		.006***	
		(.001)	
imports			.011*
			(.006)
exports			−.006***
			(.002)
top			.025***
			(.005)
stc	−.042***	−.101**	−.064**
	(.008)	(.039)	(.023)
tech	−.038**	−.064***	−.032**
	(.014)	(.012)	(.013)
rq	−.026	.123	.077
	(.067)	(.296)	(.037)
popg	.703***	.535**	.154***
	(.186)	(.187)	(.037)
_cons	.748***	4.877	−.056
	(.225)	(4.943)	(.243)
AR(1)	.014	.012	.007
AR(2)	.712	.780	.692
Sargan OIR	.015	.278	.000
Hansen OIR	.277	.377	.358
Fisher	29.97***	41.31***	51.20***
Instruments	16	16	16
Country	20	20	20
Observations	284	240	284

Standard errors are in parentheses *** $p<.01$, ** $p<.05$, * $p<.1$

economies. Furthermore, it is pertinent to note that prior studies like Ling et al. (2022), Chopra et al. (2022), Ibrahim and Ajide (2021c), and Zhang et al. (2021) find similar evidence that advances the contributing role of resource rents on carbon emissions. In Model 2, renewable energy is not substantial enough to moderate the surge in carbon emissions, while nonrenewable energy induces it. This suggests that the level of renewable energy among the G20 is far from offsetting the inducing effects of nonrenewable energy on carbon emissions. This is not surprising because fossil fuels in general still constitute the bulk of energy sources for most developed and developing economies. The homogenous impacts of energy consumption measured by total energy (tenc) are positive and significant on carbon emission. By implication, the carbon-inducing effects of nonrenewable energy relegate the expected mitigating impacts of renewable energy.

Consequently, the G20 economies remain fossil-fuel dependent on the average. This result agrees with what is obtained in the extant studies such as Ibrahim and Ajide (2021a) for G7 economies and Zhang et al. (2021) for Sub-Saharan African countries. For the trade-led carbon neutrality hypothesis, the fallout from Table 2 lent credence to the inducing effects of imports on carbon emissions which is plausible due to the carbon-embedded goods that are imported from other countries. Besides, some imported goods do not sometimes meet up with the required standard and end up as waste in the country of destinations, which eventually adds to the volume of environmental pollution. In contrast, exports moderate carbon emissions, suggesting that a percentage rise in exports would significantly reduce carbon emissions. This is plausible on the ground that asides from the use of environmentally friendly production methods, the level of technology in the advanced countries promotes eco-friendly production and consumption of goods and services. Overall, the aggregated impacts of trade are carbon emission inducing implying trade contributes more to emissions than mitigating them. This result supports previous studies such as Ali and Kirikaleli (2022), and Ibrahim and Ajide (2020).

Regarding the covariates, the impacts of structural change are negative on carbon emissions across the three models implying that the service-led growth is not carbon intensive; rather, it moderates carbon emissions. This suggests why most advanced and emerging countries are moving toward service-led growth. Previous studies like Adebayo et al. (2022) and Hou et al. (2021) show that structural change led by the service sector moderates the surge in carbon emissions. The impacts of technology negatively interact with carbon emissions. The adverse effects imply that technology reduces the volume of carbon emissions significantly and enhances the drive toward a green environment. This is plausible going by the fact that technology improves the efficiency of production processes and promotes the utilization of clean energy. The mitigating effects of technology are in line with prior studies such as Ibrahim et al. (2022), Zhao et al. (2022), and Zhang et al.(2021).

The effects of regulatory quality (rq) are not significant to curb the surge in carbon emissions in the short run. This is intuitional, given that the implementation of laws requires some stages on the one hand, and the time interval for the people to fully abide by the laws requires some time lapses. Alluding to this fact, Sakyi et al. (2017) opine that institutions alone are not sufficient to drive. The impacts of population growth are positively significant on carbon emissions, implying that a rise in population will result in a corresponding increase in carbon emissions. The empirical results from Wang and Zhang (2021) support the inducing role of population in the rising volume of GHG emissions.

Robustness checks results based on FM-OLS estimator

As a robustness check to the main results presented above, Table 3 shows the long-run impacts of the various determinants of carbon neutrality. The aim is to check if the long-run results support the earlier reported short-run results. Based on the results presented in Table 3, it is evident that the long-run FM-OLS outcomes empirically support the short-run results based on the system GMM. Specifically, the deterring impacts of resource dependence based on oil rents, coal rents, and total resource rents are empirically confirmed. Besides, gas rents, nuclear power, and renewable energy reduce the volume of carbon emissions. All these findings confirm the empirical regulatory of the system GMM outcomes.

Robustness checks results based on quantile regression

To enhance robustness of the preceding empirical results on the drivers of carbon neutrality in G20 economies, this study employs quantile regression estimator. Three categories of effects are highlighted thus: lower quantiles (0.10 to 0.40), middle quantiles (0.50 to 0.60), and upper quantiles (0.60 to 0.90). Based on the quantile results presented in Table 4, the impacts of rents from oil and coal are positive and significant on carbon emissions across the three levels. By implication, every portion of oil and coal consumption substantially contributes to the stock of carbon emissions. Contra-wise, gas rents negatively impact carbon emissions, suggesting carbon neutrality is enhanced. However, the overall aggregate impacts from total natural resource rents positively affect carbon emissions. This result supports the previous results from system GMM and FM-OLS.

Across all the quantiles, renewable energy mitigates carbon emissions, while nonrenewable energy and the aggregated impacts denoted by ttnr induce significant rise in carbon emissions. On the trade-carbon emission nexus, the inducing effects of imports on carbon emissions are significant in the middle and upper quantiles. The effects in the lower quantile are not substantial enough to drive the increase in carbon emissions. However, the impacts of exports are reportedly negative on carbon emissions across the three categories, while the homogenous impacts captured by trade openness (top) deter the drive toward carbon neutrality due to its increasing effects on carbon emissions.

Table 3 Long-run heterogeneous and homogeneous estimates FM-OLS

Variables	Outcome variable: carbon emissions per capita (co2pc)		
	Model 1	Model 2	Model 3
oilr	.211***		
	(.025)		
coalr	.708***		
	(.213)		
gasr	−.445***		
	(.211)		
ttnr	.044***		
	(.004)		
ren		−.086***	
		(.022)	
nec		.069***	
		(.021)	
tenc		.039***	
		(.004)	
imports			.396**
			(.055)
exports			−.335***
			(.041)
top			.097**
			(.035)
stc	−.165***	−.126**	−.038
	(.060)	(.065)	(.0073)
tech	−.012***	−.019	−.087***
	(.004)	(.015)	(.016)
rq	−.433***	−.358***	−.447***
	(.027)	(.029)	(.035)
popg	.022	1.299***	.078*
	(.343)	(.288)	(.339)
Observations	256	256	323

Standard errors are in parentheses *** $p<.01$, ** $p<.05$, * $p<.1$

Conclusion

This study examines the tripartite effects of energy consumption, resource abundance, and trade openness from heterogeneous and homogeneous angles on the achievement

Table 4 Quantile regression

	Lower quantiles				Middle quantiles		Upper quantiles		
	Q.10	Q.20	Q.30	Q.40	Q.50	Q.60	Q.70	Q.80	Q.90
oilr	.615***	.572*	.766**	1.239***	1.206***	2.122***	2.276***	1.537**	.223
	(.169)	(.314)	(.373)	(.351)	(.344)	(.607)	(.788)	(.659)	(.303)
coalr	1.004***	1.269**	2.014***	3.063***	2.982***	4.753***	5.047***	4.569***	1.669***
	(.31)	(.575)	(.684)	(.642)	(.629)	(1.111)	(1.444)	(1.207)	(.555)
gasr	−.717***	−.79*	−1.239**	−1.773***	−1.835***	−3.149***	−3.764***	−3.37***	−.758*
	(.234)	(.433)	(.516)	(.484)	(.474)	(.837)	(1.088)	(.91)	(.418)
ttnr	***.855****	***.761****	***.939****	***1.362****	***1.244****	***2.198****	***2.282****	***1.631****	***.337***
	(.169)	**(.313)**	**(.372)**	**(.35)**	**(.342)**	**(.605)**	**(.786)**	**(.657)**	**(.302)**
ren	−.208***	−.184***	−.177***	−.185***	−.17***	−.185***	−.159***	−.134***	−.115***
	(.012)	(.023)	(.027)	(.025)	(.025)	(.044)	(.057)	(.048)	(.022)
nec	.068***	.021***	.045**	.037***	.059**	.075*	.099*	.149***	.209***
	(.013)	(.003)	(.018)	(.006)	(.025)	(.045)	(.058)	(.049)	(.022)
tenc	***.017****	***.020****	***.029****	***.025****	***.026****	***.039****	***.067****	***.099****	***.078****
	(.003)	**(.005)**	**(.006)**	**(.006)**	**(.006)**	**(.010)**	**(.013)**	**(.011)**	**(.005)**
imports	.079	.170	.081	.093	.202**	.306**	.373**	.398**	.399***
	(.048)	(.095)	(.083)	(.078)	(.077)	(.136)	(.176)	(.147)	(.068)
exports	−.127***	−.104*	−.081**	−.083***	−.148**	−.149***	.214*	−.224*	−.374***
	(.034)	(.062)	(.034)	(.017)	(.068)	(.012)	(.107)	(.131)	(.060)
top	**.045*****	**.067*****	**.068****	**.077****	**.102****	**.236*****	**.273*****	**.286****	**.324*****
	(.015)	**(.017)**	**(.023)**	**(.028)**	**(.037)**	**(.036)**	**(.076)**	**(.113)**	**(.078)**
_cons	10.605***	4.579**	5.342*	2.898	1.694	−.215	−6.314	−11.529**	−11.186***
	(1.234)	(2.286)	(2.72)	(2.554)	(2.503)	(4.419)	(5.743)	(4.8)	(2.206)
Observ	277	277	277	277	277	277	277	277	277

Standard errors are in parentheses *** $p < .01$, ** $p < .05$, * $p < .1$. Bolded indicators and values denote homogenous outcomes

of carbon neutrality targets in G20 economies from 2001 to 2019. The heterogeneous impacts of energy consumption cover renewable and nonrenewable energy consumption; resource dependence comprises oil rents, coal rents, and gas rents; and trade openness entails imports and exports. For the homogenous effects, total energy consumption, total natural resource rents, and trade openness are considered. The empirical evidence relies on the novel dynamic system generalized method of moments, fully modified OLS (FM-OLS), and quantile regression. Major findings from the study show that among the nonrenewable energy components, renewable energy and total energy consumption drive the surge in carbon emissions.

On the other hand, renewable energy promotes carbon neutrality by reducing carbon emissions. For the resource dependence outcomes, oil and coal rents contribute to carbon emissions, while gas has moderating impacts on carbon emissions. Moreover, imports and trade openness promote carbon emissions, while exports reduce carbon emissions. The main findings from system GMM are robust and consistent with the results from fully modified OLS and quantile regressions. The following policies are recommended following the empirical outcomes. First, massive investment in renewable energy is inevitable to raise the level of renewable energy resources to match up with abundant fossil fuels. Hence, an unconditional transition to renewable energy as advanced by COP26 resolutions becomes an essential policy suggestion to achieve carbon neutrality in G20 economies. The government should encourage green energy consumption in the service sector through tax waivers for companies that adopt renewable energy while imposing a heavy tax on fossil fuel energy consumption. Besides, governments of the G20 countries should follow the advocacy in COP26 regarding reducing subsidies on fossil fuels. Second, the government should prioritize diversifying away from the exploration of natural resources. In the meantime, efforts should be made to increase the consumption of gas rents, which moderates carbon emissions. Third, stricter regulations should checkmate the importation of goods and services, focusing on carbon-embedded products. Fourth, regulatory quality should be strengthened to exert immediate effects in regulating the consumption of environmental pollutants goods and services.

Author contribution RLI writes the manuscript.

Data availability The datasets generated during and/or analyzed during the current study are available in: World Bank Development Indicators (WDI): https://databank.worldbank.org/source/world-development-indicators.

Declarations

Ethics approval and consent to participate This article does not contain any studies with human participants performed by any of the authors.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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