Disaggregated environmental impacts of non-renewable energy and trade openness in selected G-20 countries: the conditioning role of technological innovation

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Abstract

This study examines the disaggregated impacts of non-renewable energy (NRE) indicators comprising coal, gas, and fuel, and trade openness (TO) entailing imports and exports on environmental quality proxied by (carbon emission per capita, $co2pc$) in selected G-20 countries with the conditioning role of technological innovation ($ecoi$) from 1990 to 2018. The empirical analyses are evaluated using a battery of estimation techniques comprising augmented mean group (AMG), common correlated effect mean group (CCEMG), and mean group (MG), respectively. The following major results are evident from the analyses. First, coal, gas, fuel, and imports increase $co2pc$ while exports reduce it. Second, the unconditional and conditional effects of technological innovation ($ECOI$) significantly reduce $co2pc$. These results are consistent with the robustness checks based on CCEMG and MG estimators. On the policy front, promoting technological innovation remains a veritable option to curtailing the devastating impacts of $co2pc$.

Keywords Non-renewable energy · Trade openness · Carbon emission · G-20

Introduction

The quest to attaining economic development without surpassing the cycle of global warming limit of less than 2 °C and to pursue efforts aimed for a 1.5 °C limit (IPCC 2014) has necessitated the need to explore more sustainable ways of living on the human planet. This has equally placed sustainable development agenda high on the priority list of many international, regional, and national governments (Sathaye et al. 2007, Omisore 2018). Sustainable development (SD) has been viewed as a pattern of development that avails an economy of the basic economic, social, and environmental needs without endangering the natural, built, and social systems (Bugaje 2006). Hence, the call to resolve the growth and environment conflicts threatening both the present and future

atmospheric ecosystem has made the SD agenda an urgent global imperative (Manteaw 2012). Consequent to the foregoing, various international commitments have come up with a common and ambitious goal of protecting the environment. Prominent among such agreements are the Kyoto Protocol of 1997; the 21st edition of conference of the parties (COP21) in 2015; and the Sustainable Development Goals (SDGs) of 2015, respectively. With the latter goals having as one of its central focuses reduction in carbon emissions, which has maintained a rise at the rate of 1.5% annually with a record high at 37.5 GtCO₂ per year (UNEP 2019; Pedersen 2018; He et al. 2017; UNFCCC 2016). The growing attention on environmental quality can be attributed to three compelling concerns. First, researchers have come to realize that the sustenance of nearly billions of lives is strongly connected to environmental sustainability (Diffenbaugh 2020; Destek and Sarkodie 2019). This is particularly important as the surge in greenhouse gas emissions poses severe threats to human life on the planet (NASA 2020). The second concern relates to global warming which has resulted in series of environmental disasters such as heavy rainfalls, floods, heatwaves, and droughts in the last few decades (Khan et al. 2020a; Atasoy 2017). Third, aside from the decision dilemma between seeking for more growth or less in the growth-environment

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tradeoff, the devastating effects of environmental pollution are receiving a huge percentage in the annual budgets of countries across the globe (Ali et al. 2019). Alluding to this view, Gu and Wang (2018) opine that corporate organizations and national governments are promoting investment in research and development through budgetary allocation channel towards ensuring environmental sustainability.

Among the various factors which have been advanced in the literature as major determinants of environmental quality, and particularly in regard to the rise in carbon emissions, the roles of both the non-renewable energy consumption (NRE), and trade openness (TO) are no less significant. Empirically, a strong relationship has been established between NRE and surge in carbon emissions (Awodumi and Adewuyi 2020; Pata 2018; Bildirici and Gökmenoğlu 2017). Further, the impact of trade on the quality of environment has been extensively advanced both from theoretical perspectives (see environmental Kuznets curve, pollution haven hypothesis, and factor endowment hypothesis) and empirical standpoints (see Brandi et al. 2020; Ibrahim and Ajide 2020; Zhang 2020; Kolcava et al. 2019; Cherniwchan 2017; Copeland 2013). While NRE contributes to the increase in carbon emissions through fossil fuel (gas, fuel, and coal), the environmental impact of trade was initially studied by Grossman and Krueger 1991 and Shafik, 1994, and advanced by later studies via different channels. These channels include scale effects, trans-border movement of pollution embodied goods and services as well as the international trade agreements such as the preferential trade agreements among others (Umar et al. 2020; Ibrahim and Ajide 2020; Kolcava et al. 2019).

Recently, the mitigating effect of technological innovation has been empirically supported as a reliable option for curtailing the surge in greenhouse gas (GHG) emissions (Ahmad et al. 2020a; Khan et al. 2020b; Ahmad et al. 2019). Technology can enhance effective transition from fossil fuels to emission-free energy sources, thus enabling development without concomitant increase in carbon emissions as postulated by the technique effect (Copeland and Taylor 2004). The argument in favor of technology-environment nexus is that progress in technology can stimulate efficiency in the way natural resources, energy, and production of goods and services are utilized (Churchill et al. 2019). This is grounded on the fact that, technological innovation has been accorded great importance and identified as a catalyst, contributing significantly to all spheres of human life (Ibrahim et al. 2021; Ridwan-Lanre et al. 2019). The emerging research interest in the technology-environment nexus motivates the present inquiry.

Consequent upon the above expositions, the central objective of this study is to investigate the disaggregated effects of non-renewable energy (NRE), and trade openness (TO) while controlling for the modulating influence of technological innovation (TECH) on environmental quality in selected G-20

countries (USA, Canada, Australia, Saudi Arabia, Russia, and Germany).

The choice of the G-20 economies is motivated by at least four reasons. First, environmentally, G-20 contributes about 78% of the global greenhouse gas (Ajide and Ibrahim 2021; Crippa et al. 2019). The energy mix in the group of countries is predominantly fossil fuels with coal, accounting for 44% of electricity generation, and fuel taking 39% with significant contribution from natural gas with no significant change in last three decades (International Energy Agency, IEA 2018). Second, with consumption-based emissions attracting the centerpiece of academic debate on the trade-emission nexus through territorial emissions for export (production) and import (consumption) (Crippa et al. 2019), global performers in world trade must take cautious action in evaluating the channel of trade (consumption or production) that contributes most to the stock of carbon emissions. Hence, evaluating the impacts of trade on carbon emissions in G-20, which accounts for 75% of global trade (IEA, 2018) becomes highly significant for policy decisions in abating the associated risks in the unresolved global warming. Third, the issue of global warming has become one of the severe challenges affecting humanity (Umar et al. 2020) of which G-20 constitutes two-third of the population globally (IEA, 2018). Fourth, since the economic composition and political strength of G-20 have accorded them the trio roles as a corrector of global market failure, promoter of green economy, and prominent investor in innovation, they mostly influence the trends in global emissions and the extent to which the 2030 target of closing emission gap can be achieved. Among the group of 20, the present study considers six (USA, Canada, Australia, Saudi Arabia, Russia, and Germany) for three reasons. First, the six countries are the top emitters of carbon emission per capita (see Fig. 1), accounting for nearly 58% of the aggregate emissions in the group. Second, availability of data on the variables of interest constitutes another key motivating reason for the choice of the selected countries. Third, it is believed that with the percentage contribution of the six countries of G-20,

Fig. 1 Average CO2 emission per capita in G-20 from 1970 to 2018. Source: Author's computation based on EDGAR, (2019) (EDGAR denotes The Emissions Database for Global Atmospheric Research (EDGAR))

policy suggestions that will emanate from the study can be extrapolated to other countries within the group and beyond. Consequently, the main objective of the present study is to examine the heterogeneous environmental impacts of non-renewable energy and trade openness in selected G-20 countries with conditioning role of technological innovation.

The present study contributes to the extant literature in the following ways. First, the majority of the existing literature that have assessed the factors influencing the quality of environment hardly considers the disaggregated effects of both NRE and trade openness at a time. For policy direction, investigating the channels through which NRE (fuel, coal, and gas) and trade openness (imports and exports) impact the environment seem pertinent in this present era of global warming. By decomposing trade effects into imports (consumption) and exports (production), we can account for both consumption-based and production-based effects of trade openness on the environment. This avails the present study the opportunity to embark on an all-inclusive trade-environmental analysis. Second, the various ambiguities surrounding the debates on the environment have made hard to come to concrete conclusions on the practical way of resolving the surge in environmental pollution. Thus, prompting the need for a piece of fresh evidence to resolve the inconclusiveness on a global scale and particularly without assuming homogenous effects of both NRE and TO on the environment.

Third, while the role of technology in abating global warming is gradually gaining momentum in both theoretical and empirical literature, an investigation into the causal linkages among the advanced G-20 economies can be best described as emerging. Fourth, this study constitutes the first strand elucidating the twin impacts of non-renewable energy and trade openness at the disaggregated levels for the G-20 countries. Fifth, the use of technological innovation in this study seems novel in two major ways. In the first place, the study employs environment-related technology (eco-innovation, hereafter) which is an emerging indicator of technology that is directly related to carbon abatement. Similarly, the tech-innovation data is employed directly on the environment (unconditional effect) and later interacted with the indicators of NRE and TO (conditional or interactive effect). This approach is largely missing in recent studies that have assessed the effects of technological innovation on the environment (Ahmad et al. 2020b; Hao et al. 2020; Hu 2021; Hussain et al. 2020; Khan et al. 2020a; Su et al. 2020a; Villanthenkodath and Mahalik 2020; Wang et al. 2020). A very few strand of the extant literature have only addressed this concern¹. The justification for eco-innovation lies in the fact that it caters for efficient utilization of natural resources together with reduction in the relative environmental costs (Khan et al. 2020a). More so, the present study argues that

while transition to clean energy requires the inevitable role of technology, achieving technique effect in the trade-environment nexus is never without the role of technology. This makes the consideration for the role of technological innovation in resolving the non-renewable energy-trade-environment conflicts highly fundamental. Sixth, the study employs series of pre-test comprising first- and second-generation panel unit root tests, cross-section dependence test, slope homogeneity test, and the recent dynamic heterogeneous estimators comprising augmented pooled mean group (AMG), common correlated effect mean group (CCEMG), and mean group (MG) in estimating the functional nexuses with data spanning 1970 to 2018.

Literature review

The pervasive adverse effects of environmental degradation on human life and other living and non-living organisms have attracted quite commendable empirical efforts in the literature. Among the enormous scholarly contributions, this section reviews recent studies focusing on environmental impacts of energy consumption, trade, technological innovation, and other relevant variables. Consequently, the review is organized in the following: energy-environment, trade-environment, and technology-environment nexuses.

Energy-environment nexus

Mahalik et al. (2021) investigate the effects of renewable and non-renewable consumption, education (primary and secondary), economic globalization, urbanization, and economic growth, on per capita CO₂ emission in selected BRICS economies for the period spanning 1990 to 2015. Based on the analyses from random effects and system GMM estimators, findings show that non-renewable energy consumption, primary education, total energy consumption, economic globalization, and economic growth increase the volume of carbon emissions. Contrarily, renewable energy consumption, urbanization, and secondary education reduce carbon emissions. The reducing impacts of renewable energy on carbon emissions are equally confirmed by Oke et al. (2021) in a study conducted for a panel of 51 African countries from 1990 to 2015. This outcome is consistent with the study conducted by Adedoyin et al. (2021a) in 26 EU member countries from 1995 to 2018. The study reveals that tourism, real GDP per capita, and energy consumption increase the stock of carbon emissions. A crucial contribution to the energy-environment nexus is evident in Adedoyin et al. (2021b). The authors examine the direct and mediating role of economic policy uncertainty in the energy-growth-emission nexuses for a panel of 32 Sub-Saharan African countries for the period straddling 1996 to 2014. The empirical analyses based on one-

¹ See literature review for details

step system generalized method of moment (GMM) reveal that economic policy uncertainty, real GDP, and non-renewable energy production intensify CO₂ emissions. However, when economic policy uncertainty is interacted with renewable and non-renewable energy production, the level of carbon emissions is reduced. These findings are equally corroborated by Su et al. (2021) for the BRICS economies.

Sarkodie and Ozturk (2020) employ an autoregressive distributed lag technique (ARDL) bound testing to cointegration and U-test in examining whether there is evidence for or against the environmental Kuznets curve hypothesis in Kenya from 1971. Empirical evidence from the study provides strong support for EKC. Specifically, it was evident from the study that, there exists a positive and statistically significant relationship between energy consumption and carbon emissions in the long run. Besides, a negatively significant nexus between electricity from renewable energy sources and carbon dioxide emission is confirmed. The results are supported by Sarkodie et al. (2020) who find fossil fuel consumption as a positive predictor of carbon emissions thus increasing the volume while renewable energy consumption reduces it. The empirical outcomes from the study conducted by Ulak and Ozcan (2020) equally accentuate the non-renewable energy increases carbon emissions and carbon footprint while renewable energy reduces both in the case of the Organization for Economic Co-operation and Development (OECD) economies from 1980 to 2016. Zafar et al. (2020) examine the environmental impacts of renewable energy consumption in the Organization for Economic Co-operation and Development countries from 1990 to 2015 by employing second-generation estimation approach. Empirical fallouts from the study reveal that renewable energy consumption is a significant predictor in determining quality of the environment. Among other covariates, education reduces carbon emissions while both natural resource abundance and foreign direct investment increase it. Further, country-specific analyses conducted show renewable energy enhances economic growth. The study concludes on raising the bar of investment in renewable energy and education on the one hand, and strategizing for research and development in renewable energy as preconditions for the attainment of environmental sustainability. Besides, the rising attention on energy consumption in the environmental literature both from political front and from global market forces are highlighted by Su et al. (2020b) in the case of US oil production. In an extended version of this argument, Su et al. (2019) further establish the fundamental nexuses among geopolitical risk (GPR), oil prices (OPs), and financial liquidity from the monetary point of view in the case of Saudi Arabia.

Destek and Sarkodie (2019), investigate the extent to which the nexuses among disaggregated renewable energy (hydroelectricity, wind, solar, and biomass) consumption, and economic growth impact environmental pollution from

1991 to 2014 in G-7 countries based on the augmented mean group method and panel bootstrap causality approach. Major findings from study reveal that biomass energy consumption significantly reduces carbon emissions in four countries (France, Germany, Japan, and the USA). Hydroelectricity consumption lessens the volume of carbon emissions in Italy and the UK, wind energy use is found to effectively abate carbon emissions in Canada, while solar energy consumption is noted to be efficient enough in subsiding emission in France and Italy. In the panel analyses, similar abating effects are upheld for hydroelectricity, biomass, and wind energy consumption on carbon emissions. Of the group of renewable energy indicators, consumption of hydroelectricity turns out to be the most efficient in reducing environmental pollution for the panel of G-7 countries. Destek and Sarkodie (2019) examine the connection between biomass energy consumption, natural resource depletion, economic growth, and carbon dioxide emissions in G-20 economies from 1992 to 2013. The study employs a battery of estimation techniques such as panel unit root tests, the panel cointegration test, the panel fully modified OLS (FMOLS) method, and the panel VECM Granger causality approach. The following results are confirmed in the study. First, the existence of cointegration is reported for biomass energy consumption, CO₂ emissions, natural resource depletion, and economic growth. Second, biomass energy consumption positively and negatively impacts economic growth and carbon emissions respectively. Third, the energy-growth hypothesis is confirmed from the unidirectional causality running from biomass energy consumption to GDP growth. Fourth, the causality running from biomass to carbon emission is bidirectional.

The empirical results from the analyses conducted by Inglesi-Lotz and Dogan (2018) on the impacts of renewable (RE) and nonrenewable energy (NRE) consumption on carbon emissions in sub-Saharan African countries from 1980 to 2011 reveal RE reduces CO₂ while NRE increases it. This finding is inconsonant with Ajide and Ridwan (2018) who established fundamental nexuses among energy consumption, carbon emissions, and economic growth in G8 economies. Katircioglu (2014) evaluates the long-run nexuses among tourism, energy consumption, and environmental degradation measured by carbon dioxide (CO₂) emissions in Turkey using the autoregressive distributed lag (ARDL) bound testing to cointegration. Empirical findings from the study indicate that tourism, energy consumption, and CO₂ emission cointegrate in the long run. Specifically, the study finds that tourism development in Turkey positively impacts both energy consumption and climate change.

Trade-environment nexus

Literature expositing the drivers of environmental quality often focus on validating or refuting the theory of

Environmental Kuznets Curve (EKC). In line with this assertion, Khan and Ozturk (2021) examine the direct and indirect impacts of financial development on environmental pollution in 88 developing economies from 2000 to 2014. The empirical evidence is based on both difference and system generalized method of moments. Due consideration are equally given to the environmental effects of trade openness and FDI. Findings from the study reveal that the direct effects of financial development reduce environmental pollution. Besides, while income, trade openness, and FDI increase carbon emissions, the indirect effects of financial development mitigate their impacts. Ibrahim and Ajide (2021a) probe the extent to which trade facilitation (TF) hinders or promotes environmental quality in 48 Sub-Saharan African countries for the period spanning 20005–2014 by employing the pooled ordinary least squares (POLS) and two-step system generalized method of moments (Sys-GMM) method. The study considers six indicators of TF comprising costs, documents, and time required to import and export on vis-à-vis the environmental quality (captured by carbon emissions (CO₂), and nitrous oxides (N₂O)). Empirical findings that emanate from the study reveal that, TF reduces environmental pollution thus promoting environmental quality in the region. In a similar study with consideration for the institutions, Ibrahim and Ajide (2020) investigate the conditioning roles of institutions in the trade facilitation-sustainable environment nexus in 41 Sub-Saharan African countries from 2005 to 2014 using the system generalized method of moments estimator. The study finds trade facilitation as a hindrance to environmental sustainability (ES). The impacts of institutions are found to exert dampening effect on ES. Further, interactive impacts of both trade facilitation and institutions indicate severe impacts on environmental problems eroding the region. Khan et al. (2020a) assess the impact of international trade and consumption-based emission on carbon emissions in G7 economies from 1990 to 2017 by employing second-generation panel cointegration approaches comprising Pesaran and Yamagata slope heterogeneity test, Pesaran's cross-sectional dependence test with estimation technique anchored on augmented mean group (AMG) and common correlated effect mean group (CCEMG). Findings from the study provide evidence for the existence of cross-sectional dependence among the panel series, while slope heterogeneity is equally established. Also, the results establish the presence of cointegration among CO₂ emissions, income, trade, renewable energy, and environmental innovation. The study finds evidence for the enhancing role of imports and income on consumption-based carbon emissions, while environmental innovation, exports, and renewable energy consumption significantly reduce it. The results are equally robust for augmented mean group (AMG) and common correlated effect mean group (CCEMG) methods. Kolcava et al. (2019) evaluate the medium through which trade liberalization augments

the transition of environmentally embedded goods in 183 developed and developing countries by considering import and export from 1987 to 2013. Results from the panel OLS fixed effects estimator reveal evidence for partial trade induced environmental burden shifting. Also, it notes the existence of significant association between increase in footprint exports and trade liberalization in low-income countries and insignificant for high-income countries. Wang and Ang (2018) examine the impacts of international trade on the volume of global/national carbon emissions. The study reveals that rise in exports increases total emissions. More so, the impacts of imports on the environment are significant for developed countries that rely on imports to meet up with local demands. Liddle (2018a) examines the influence of international trade, energy prices, fossil fuel usage, and industry share of GDP in conducting analyses on both territory and consumption-based carbon emissions for 102 countries over the period spanning 1990–2013. Empirical results from the study reveal that import reduces and increases carbon emissions for territorial-based emission and consumption-based emission respectively. GDP is found to be emission enhancing from both ends (territorial and consumption-based emission). The impacts of fossil fuel consumption and industry share of GDP are found to escalate emission while energy prices reduce it from both ends. These findings are consistent with the study conducted by Liddle (2018) for the Asian countries from 1990 to 2013. The empirical analyses from the work of Shahbaz et al. (2019) find support for the negative effects of trade openness on environmental quality for the global, high income, middle- and low-income panels. The empirical results from the study conducted by Al-mulali and Sheau-Ting (2014) from 1990 to 2011 show that imports and exports are carbon emissions inducing for 6 regions comprising 189 countries on the aggregate.

Technology-environment nexus

In recent environmental literature, the role of technological innovation is becoming increasingly popular as an effective medium of addressing the incessant rise in carbon emissions and other related environmental pollutants. Searching through the available studies in this line of argument, Ma et al. (2021) examines the extent to which technological innovation, emission taxes, tertiary sector development, investments in the energy sector, and expenditure on research and development (R&D) influence Chinese provincial carbon dioxide emission for a period of 24 years (1995–2019). Empirical results from the study identify increased investments in energy, renewable energy consumption, technological innovation, R&D, carbon emission taxes as negative predictors of carbon emissions (pollution-abating). Contrawise, provincial growth and tertiary sector development turn out to be positive predictors (pollution-enhancing). Ibrahim and Ajide (2021b) examine the

nexus among non-renewable energy (NRE), renewable energy (RE), trade openness (TO), technology, and environmental quality (CO₂ emission) in G-7 economies from 1990 to 2019. The study employs second-generation estimation techniques comprising cross-sectional dependence test, second-generation panel unit root test, and Westerlund cointegration test. The empirical study confirms the mediating roles of technology in directly reducing carbon emissions and equally moderating the contribution of non-renewable energy and trade to rise in carbon emissions.

Villanthenkodath and Mahalik (2020) investigate the nexus between technological innovation and environmental quality in India from 1980 to 2018 by employing the autoregressive distributed lag (ARDL) bounds testing cointegration approach. The additional role of economic growth and inward remittances are considered as key factors in CO₂ emissions determinants. Feedbacks from the empirical analyses reveal the presence of long-run cointegration among the series. Major findings from the study indicate technological innovation and economic growth as deterrents to environmental quality captured by CO₂. The study also finds evidence for the existence of U-shaped nexus between carbon emissions and inward remittances. Khan et al. (2020d) explore the impact of public-private partnership investment in energy and technological innovation on consumption-based carbon emissions for China based on quarterly data from 1990 to 2017. To examine the stationary status of the series, the study utilizes the generalized least square (GLS) unit root test while cointegration test is based on Maki cointegration test. The fully modified ordinary least square (FMOLS), dynamic ordinary least square (DOLS), and canonical cointegration regression (CCR) are employed for the long run estimation. The following findings are established from the empirical analyses. First, the existence of cointegrating is confirmed among the series comprising public-private partnership investment in energy, imports, exports, renewable energy consumption, technological innovation, and consumption-based carbon emissions. Second, renewable energy consumption, exports, and technological innovation are significant enough in reducing consumption-based carbon emissions. Third, imports, GDP, and public-private partnership investment in energy escalate the surge in consumption-based carbon emissions. Fourth, causality running from technological innovation and public-private partnership investment to consumption-based carbon emissions in China is confirmed in the long run. The research work by Ahmad et al. (2020b) was motivated by the need to evaluate the effect of the nexuses among natural resources, technological innovations, economic growth, and the environment proxied by ecological footprint from 1984 to 2016 in emerging economies. Feedbacks from the empirical analyses indicate the existence of long-run cointegration between the ecological footprint, economic growth, technological innovations, and natural resources. The long run result

indicates that natural resources and economic growth amplify ecological footprint, whereas technological innovations reduce it. Hussain et al. (2020) examine the role of environmental-related technology in carbon emission abatement of seven developing economies from 1990 to 2016. Second-generation methodologies comprising cross-sectional dependence test, CIPS unit root test, and Westerlund co-integration are employed for the preliminary analyses. The empirical estimation is anchored on cross-sectional augmented autoregressive distributive lag (CS-ARDL) method. Findings from the study provide strong evidence for the abating role of environment-related technologies together with renewable energy on carbon emissions. Conversely, GDP growth turns out to exacerbate degradation of the environment. While the effective role of technological innovation in reducing the level of carbon emission is well established, studies often shy away from the technological impacts of energy consumption (renewable and non-renewable) which are equally major players in the environmental quality debates. Few of the recent study, which considers this nexus, are Khan et al. (2020c). They investigate the heterogeneous impact of eco-innovation and human capital on different indicators of energy resources (total energy consumption, non-renewable energy consumption, and renewable energy consumption) in G-7 for the period spanning 1995–2017. The study was able to empirically confirm the reducing impacts of eco-innovation together with human capital, research and development expenditures (R&D), and energy price on non-renewable energy consumption and total energy consumption while their effects are found to increase renewable energy consumption. This suggests that technological innovation is a crucial channel through which the negative effects of non-renewable energy on the environment can be mitigated while the positive effects of renewable energy are enhanced.

Yin et al. (2015) also affirms the mitigating role of technological progress on carbon emissions in a study conducted for Chinese regions. The authors find that technical progress facilitates the reduction of carbon emissions in the long run. On the other hand, regulations enacted to protect the environment serve as push factors for pollution-intensive industries to the environment with little or no restrictions. Mensah et al. (2018) examine the technological-environment nexus in 28 OECD countries from 1990 to 2014. Results reveal that technological innovation hinders the surge in carbon emissions. However, the medium of carbon abatement differs for country-specific level in the group. Besides, the findings fail to provide strong support for the existence of environmental Kuznets curve (EKC) in the selected economies. The role of innovation is examined through the channel of energy together with foreign direct investment (FDI) and financial development in a study conducted by Shahbaz et al. (2018) for France from 1955 to 2016. Findings from the study reveal that innovation in energy

and financial development is efficient in reducing carbon emissions, whereas FDI amplifies it. Similar results by Álvarez-Herránz et al. (2017) for 28 OECD also lent empirical credence, especially in regard to energy innovation. The results indicate that innovation moderates energy consumption in reducing carbon emissions.

The review of literature in the preceding paragraphs indicates the growing efforts from scholars towards unraveling the probable determinants of environmental degradation to date. That notwithstanding, some gaps are still apparent in the extant literature. First, at least, the preponderance of available studies to a large extent agree that non-renewable energy (NRE) deters the environment (Mahalik et al. 2021; Inglesi-Lotz and Dogan, 2018) by assuming homogeneous effects of NRE. While this might seem plausible, it is pertinent to point that NRE is a composition of fossil fuels comprising gas, coal, and fuels with each exerting effects on the environment. Thus, examining the heterogeneous effects of NRE will allow for robust and pragmatic policy suggestions in the NRE-environment conflicts. Second, the trade-induced emission has, doubtlessly, been advanced from both empirical and theoretical perspectives. Notwithstanding the prominence regarding environmental degrading induced effects of trade, little or no efforts have been accorded to the consumption and production-based trade effects. Third, the joint consideration of the disaggregated effects of NRE and TO is still clearly missing in the literature to date thus making this present study the first of its kind. Fourth, the consideration for the role of technological innovation has been limitedly considered as either a main or control variable while the interactive effects are still largely neglected in the environmental degradation literature. These are gaps that the present study seeks to fill in addition to the arguments advanced in the introductory section.

Method

Model specification and estimation techniques

To examine the conditioning role of technological innovation on the environmental impact of disaggregated non-renewable energy consumption (coal, gas, and fuel) and trade openness (import and export) in selected G-20 economies (comprising USA, Canada, Australia, Saudi Arabia, Russia, and Germany), the present study relies on the research work of Grossman and Krueger (1995). The study lays emphasis on the reducing impacts of technology on environmental quality (carbon emissions per capita, $co2pc$). Besides, sustainable path to growth has been advanced as a check on the surge in carbon emissions with technological advancement playing prominent roles (Aghion et al. 2016). Leveraging on Hussain et al. (2020), Khan et al. (2020), Inglesi-Lotz and

Dogan (2018), and Katircioglu (2014), the empirical model for this study is thus specified.

$$\begin{aligned} co2pc_{it} = & \varphi_1 coal_{it} + \varphi_2 gas_{it} + \varphi_3 fuel_{it} + \varphi_4 impgd_{it} \\ & + \varphi_5 expgd_{it} + \varphi_6 ecoi_{it} + \varphi_7 (ecoi \times W)_{it} \\ & + \mu_{it} \end{aligned} \quad (1)$$

Where $co2pc$ denotes carbon emission per capita as a proxy for environmental quality, $coal$ represents coal consumption per capita, gas is natural gas consumption per capita, $fuel$ denotes petroleum consumption per capita, $impgd$ represents imports of goods and services, $expgd$ denotes exports of goods and services, $ecoi$ represents eco-innovation, $(ecoi \times W)$ represents the interaction of technological innovation with the different structures consisting the indicators of non-renewable energy and trade openness (“coal $\times$ ecoi”; “gas $\times$ ecoi”; “fuel $\times$ ecoi”; “impgd $\times$ ecoi” and “expgd $\times$ ecoi”), t represents time period comprising 1990 to 2018, i denotes the countries such as the selected top six emitters, $\phi_1, \phi_2, \phi_3, \phi_4, \phi_5, \phi_6$, and ϕ_7 are the parameters to be estimated and μ is the disturbance term.

For the a priori signs of the variables coefficients, non-renewable energy (NRE) indicators (coal, gas and fuel) are expected to increase $co2pc$. Recent empirical studies have advanced significant impacts of NRE on carbon emissions (see Ibrahim and Ajide, 2021c; Mahalik et al. 2021; Hanif et al. 2019; Shahbaz et al. 2019; Wang et al. 2020; Zaidi et al. 2018). Hence, NRE indicators are expected to exert positive effect on $co2pc$ $\varphi_{1...3} = \left(\frac{\partial co2pc}{\partial NRE} > 0 \right)$. Besides, import of goods and services are hypothesized to escalate the volume of $co2pc$. This is particularly applicable to G-20 economies where the imports are concentrated in energy-intensive products (Khan et al. 2020a; Bhattacharya et al. 2020). Hence, a positive impact is anticipated $\varphi_4 = \left(\frac{\partial co2pc}{\partial impgd} > 0 \right)$. Contrarily, export of goods and services constitutes one of the driving forces for adopting technology that mitigate carbon emissions (Liddle, 2018). As such, exports are assumed to be negative predictors of $co2pc$ by exerting declining effects on it $\varphi_5 = \left(\frac{\partial co2pc}{\partial expgd} < 0 \right)$. The post Paris Climate Agreement (PCA, 2016) era has seen remarkable progress and increasing attention directed towards investment in eco-friendly technologies which are anticipated as effective tool to reducing carbon emissions (Mensah et al. 2019; Zhang et al. 2017; Lee and Min 2015). Hence, technological innovation has the capacity to abate carbon emissions thereby enhancing the attainment of green growth and sustainable environment (Ulucak et al. 2020). Consequently, negative effect is envisaged $\varphi_6 = \left(\frac{\partial co2pc}{\partial ecoi} < 0 \right)$. Further, the present study estimates conditional effects of NRE and TO on $co2pc$ subject to technological innovation as a partial derivative of $co2pc$ with respect to NRE and TO thus $\frac{\partial co2pc}{\partial NRE_{it}} = \sigma_{1,2,3} + \sigma_6 * ecoi_{it} \frac{\partial co2pc}{\partial TO_{it}} = \sigma_{4,5} + \sigma_6 * ecoi_{it}$. Empirical

studies have advanced the useful role of technological innovation in the transition to clean energy (Khan et al. 2020b). In such situation, a negative impact is envisaged $\varphi_7 = \left(\frac{\partial co2pc}{\partial ecoi \times W} < 0\right)$

Data and descriptive statistics

This study assesses the disaggregated effects of non-renewable energy (NRE) and trade openness (TO) on environmental sustainability of the some selected G-20 economies between 1990 and 2018 using data from three sources comprising World Development Indicators (WDI 2020), International Energy Agency (IEA 2020) and Organization for Economic Cooperation and Development (OECD 2020). The time coverage is influenced by data availability consideration for the variables of interest in a balanced form. The dependent variable is environmental sustainability captured by carbon emission per capita (co2pc), the explanatory variables are NRE (natural gas, coal, and fuel) and TO (import and export of goods and services % of GDP).

Table 1 presents the descriptive statistics and normality tests for the data employed in the present study. The minimum, maximum, and mean values are presented for all the indicators together with the median and standard deviation values. Among the group of NRE indicators, natural gas has the highest mean value (77.6%) followed by fuel (49.7%) and coal (28.7%). The emergence of gas with the highest mean implies more of it is consumed than others going by the fact that it holds the potentials to enhance transition to cleaner energy, air, and decarbonization. According to International Energy Administration report on World Energy Outlook (IEA 2019) besides the fact natural gas is fast gaining prominence as one of the sources of global energy, evidence has shown it is becoming a perfect alternative to fuels. The report also holds that natural gas leads to improved air quality and reduces the surge in carbon emissions. Available statistics indicate that, since 2010, transiting from coal to gas delivered nearly 500

million tons of CO₂ (IEA 2019). The normality test employs the skewness, kurtosis, and JB values in determining the normality state of the data employed. The skewness measures whether the data is asymmetric or not, kurtosis focuses on sharpness and JB assesses the goodness-of-fit between the skewness and kurtosis determining a normal distribution (Amin et al. 2020). The standard criteria in the normality test require that skewness and kurtosis should stand close to zero mean and mesokurtic. Besides, the rule of thumb guiding the skewness is that values between -0.5 and 0.5 imply firmly asymmetrical; -1 and -0.5 or 0.5 and 1 denotes moderately asymmetrical and -1 or more than 1 implies high skewed. In the case of our dataset, majority of the values fall in the range of > 1 implying they are highly skewed. Similarly, both the kurtosis and JB further corroborate the results of skewness indicating the data employed are not normally distributed. These results are plausible going by the heterogeneous and dynamic nature of the data employed in the panel model of the present study.

Cross-sectional dependence and slope heterogeneity tests

The consideration for cross-sectional dependence in a panel study can be argued from the viewpoint that unpredictable shocks, evolving interconnection among national, regional, and international economies exhibit reasonable level of dependence and homogeneity (Khan et al. 2020a; De Hoyos and Sarafidis 2006). This makes conducting cross-sectional dependence (CSD) test a necessary step to help determine the most suitable estimation method in a panel study. The Pesaran (2021) can be stated as

$$CSD = \sqrt{\frac{2T}{N(N-1)N}} \cdot \sum_{i=1}^{N-1} \sum_{j=i+1}^N Corr_{i,j} \quad (2)$$

Table 1 Descriptive statistics and normality tests

Variables	Name/measurements	Obs#	Min	Max	Mean	Median	S.D.	Skew	Kurt	J.B.
CO2PC	Carbon emission per capita	158	9.5	20.98	15.19	16.31	3.56	− 0.12	1.52	14.81
GAS	Natural gas consumption per capita (cubic feet)	158	58.4	274.44	77.60	31.47	82.97	1.02	2.45	29.50
COAL	Coal consumption per capita (cubic feet)	158	0	112.80	28.71	15.57	34.05	1.47	3.75	61.01
FUEL	Petroleum consumption per capita	158	72.1	208.20	49.67	24.35	64.49	1.72	4.08	85.59
IMPGD	Imports of goods and services (% of GDP)	158	10.13	40.21	26.72	28.69	8.30	− 0.29	1.93	9.73
EXPGD	Exports of goods and services (% of GDP)	158	9.04	62.11	29.57	30.80	12.86	0.15	2.30	3.80
ECOI	Eco-innovation % of total technology	158	1.83	42.40	75.79	13.65	11.45	1.60	4.42	80.80

Note: *Obs.* implies observations, *Min* denotes minimum, *Max* denotes maximum, and *S.D.* is standard deviation, *Skew.* is skewness, *Kurt.* denotes kurtosis, and *J.B.* denotes Jarque-Bera

Where *Corr* represents the pairwise correlation computed with the ordinary least square (OLS). The null hypothesis of the CSD assumes the non-existence of cross-sectional unit in the panel model. As robustness to the Pesaran (2021) CSD, the latest version based on Pesaran (2015) is instantaneously tested and reported with the correlation coefficients. Besides the issue of cross-sectional interdependence which is tested using CSD, the divergence in demographic units and socio-economic structures among the cross-sections make it important to examine the chances of heterogeneity in the slope parameters. Hence, this study adopts the Pesaran and Yamagata (2008) slope heterogeneity test which is originally credited to Swamy (1970)². This is specified as

$$\tilde{\Delta}_{SH} = (N)^{\frac{1}{2}}(2k)^{-\frac{1}{2}}\left(\frac{1}{N}\tilde{S}-k\right) \quad (3)$$

$$\tilde{\Delta}_{ASH} = (N)^{\frac{1}{2}}\left(\frac{2k(t-K-1)}{T+1}\right)^{-\frac{1}{2}}\left(\frac{1}{N}\tilde{S}-2k\right) \quad (4)$$

From Eq. (4), *SH* and *ASH* are symbols representing delta and adjusted delta tildes, which hypothesized that slope coefficients are homogenous with the alternative assuming heterogeneous slope coefficients.

The results of cross-section dependence tests, correlation coefficients, and slope heterogeneity coefficients are presented in Table 2. The cross-sectional dependence test fails to accept the null hypothesis of independence among cross-sectional units but does for the alternative hypothesis. This implies that there is existence of interdependence among cross-section units. It is pertinent to point out that the significance levels of the probability values of the results imply there are highly significant. Besides, evidence of cross-sectional dependence among the series is plausible going by the increasing level of economic integration among selected G-20 countries concerning economic policies, trade, and agreements among the regional blocs. Besides, the correlation coefficient results are consistent with the CSD test results which are evident from the high level of correlation among the series ranging from 0.77 to 0.99. Furthermore, considering the result from Pesaran and Yamagata (2008) test which has a statistical significance of 1%, the notion of homogenous slope coefficients proposed by the null hypothesis is strongly rejected. This implies the acceptance of the alternative hypothesis which suggests the case of heterogeneity in the slope coefficients among the cross-section units. It is worthy of note that the existence of dependence among the series couple with slope heterogeneity of the coefficients theoretically implies first-generation unit root tests cannot be employed as it is

observed to be inefficient and provide low power in such a situation (Khan et al. 2020).

Panel unit roots and cointegration test

Conducting checks for unit root in a panel regression are required to evade spurious empirical analyses that may misinform policy suggestions emanating from empirical studies. To achieve this purpose, this study employs both first-generation and second-generation unit root tests comprising Im, Pesaran, and Shin (Im et al. 2003) and Cross-Sectionally Augmented IPS (CIPS) in that order. Among the highlighted unit root tests, the Cross-Sectionally Augmented IPS (CIPS) test is more reliable and persistent because it accounts for the heterogeneous nature in panel models and the cross-sectional dependency attributable to a single common factor (Khan et al. 2020a). The IPS unit root test which relies on Augmented Dickey-fuller (ADF) test can be specified as

$$\Delta g_{it} = \delta_{ir}\mu_{tr} + \phi_i g_{i,t-1} + \sum_{j=1}^{p_i} \chi_{ij} \Delta g_{i,t-j} + \psi_{it}, \quad (5)$$

Such that $i = 0, 1, 2, 3, \dots, N$; $r = 0, 1, 2$. Besides, $\mu_{r0} = 0$ or $\mu_{r1} = 1$, $\mu_{r2} = (1, t)^3$ proposes the null hypothesis that $H_0: \phi = 0$ vs. $H_1: \phi < 0$.

At the other end, the CIPS's equation can be specified as follows:

$$\begin{aligned} \Delta Q_{it} = & \mu_i + \mu_i R_{i,t-1} + \mu_i \bar{Q}_{t-1} + \sum_{m=0}^{\rho} \mu_{il} \Delta \bar{Q}_{t-1} \\ & + \sum_{m=0}^{\rho} \mu_{il} \Delta \bar{Q}_{t-1} \end{aligned} \quad (7)$$

Such that $\bar{R}$ is the cross-section means which can be specified as

$$\begin{aligned} Q_{i,t} = & \mu^1 \overline{coal}^{i,t} + \mu^2 \overline{gas}^{i,t} + \mu^3 \overline{fuel}^{i,t} + \mu^4 \overline{impgd}^{i,t} \\ & + \mu^5 \overline{expgd}^{i,t} + \mu^6 \overline{ecoi}^{i,t} + \mu^7 (\overline{ecoi} \times W)^{i,t} \end{aligned} \quad (8)$$

Hence, the CIPS statistical test can thus be stated as

$$\overline{CIPS} = \frac{1}{N} \sum_{i=1}^n CADF \quad (9)$$

Both the first- and second-generation unit root results are presented in Table 3. Summarily, the outcome shows that all the variables are not stationary at levels except after taking the

² See the original works of Swamy, (1970) and Pesaran and Yamagata (2008) for further details.

³ It should be noted that the possibility of variation is considered in the estimation of the deterministic term and as well as for wide-ranging lag lengths for each series. The conventional standard for each p_i can be estimated by employing a general-to-specific approach centered on available information in regards to either AIC or the Schwartz criterion, or on successively estimating the last coefficient of the $\Delta q_{i,t-j}$.

Table 2 Cross-sectional dependence test, correlation analyses, and slope heterogeneity

	CO2PC	GAS	COAL	FUEL	IMPGDS	EXPGDS	ECOI
CSD (2004)	37.93***	46.79***	47.77***	47.58***	48.56***	48.12***	45.79***
CSD (2015)	48.8***	48.21***	48.19***	47.74***	40.36***	40.54***	45.76***
Correlation	0.77	0.99	0.99	0.99	0.82	0.82	0.99
Heterogeneity	$-\Delta$						$-2.191***$
	$-\Delta$ Adjusted						$-3.795***$

***implies significant level at 1%. CSD implies Pesaran cross-sectional dependence test under the null hypothesis of no cross-section (correlation) among the series

first difference. Once the test for CSD conducted and stationarity level confirmed, the next step is to conduct a cointegration test to examine the long run nexus among the model variables. The present study uses the Westerlund cointegration and results are given in the lower part of Table 3. As evident in the table, both the group and panel statistics are statistically significant at 5% and 1% respectively, thus implying failure to accept the null hypothesis of no long-term cointegration. Intuitively, it can thus be inferred that all the variables are co-integrated in the long-run.

Augmented mean group (AMG)

Having confirmed the presence of long-run relationship among these series, we proceed to model estimation by employing the augmented mean group (AMG) advanced by Eberhardt, (2012). Two major reasons motivate the adoption of the estimator among many others. First, the method has been adjudged to be very relevant and consistent in a situation where non-stationarity is reported (Hu 2021). Second, it accounts for the issues of endogeneity, cross-sectional dependence, and heterogeneous slope coefficient in panel regression model (Hu

2021; Khan et al. 2020a). Thus, the augmented mean group (AMG) equation form is provided as

$$\Delta Y_{i,t} = \varphi_{1,t} + \varphi_{2,t}X_{i,t} + \varphi_{3,t}V_i + \sigma_{i,t} \quad (8)$$

In the above-stated Eq. (8), $Y_{i,t}$ represent the explained variable, $X_{i,t}$ denotes a vector of explanatory variables, and $\varphi_{1,t}$ denotes the constant term which accounts for the heterogeneous time-invariant impacts. Besides, the unobservable common factor in the model is represented by V_i , while $\varphi_{3,t}$ denotes factors loading which are particularly inherent in the heterogeneous terms. Considering $\varphi_{2,t}$ the overall form of the AMG model can thus be obtained:

$$AMG_{Estimator} = \frac{1}{N} \sum_{i=1}^N \tilde{\varphi}_{2i} \quad (9)$$

Presentation and discussion of empirical results

Main results: augmented mean group (AMG)

Table 4 presents the main results for the disaggregated effects of non-renewable energy and trade openness on environmental quality of the selected G-20 economies. Five models are estimated with specific focus on the disaggregated indicators comprising coal (model 1), gas (model 2), fuel (model 3), imports (model 4), and exports (model 5). Among the highlighted five indicators, four (coal, gas, fuel, and imports) are statistically significant and positively signed. This implies that a percentage increase in the consumption of coal, gas, and fuel leads to an increase in the rate of carbon emission per capita by 0.001%, 0.061%, and 0.074%. Such an increase is further compounded by the consumption of goods and services that are imported into the economies. Consequently, we can infer that a certain percentage of environmental pollution in the selected G-20 economies can be attributed to imported goods and services. The insignificant nature of the exports implies the rate of emissions accounted for by exported goods are either less than that of imported goods or

Table 3 First and second-generation unit root tests

Variables	CIPS		Im, Pesaran and Shin (IPS, 2003)	
	Level, trend	First, trend	Level, trend	First, trend
CO2PC	− 2.41	− 4.88***	− 0.92	− 1.34***
GAS	− 2.58	− 4.90***	− 0.35	− 5.38***
Coal	− 2.92	− 3.81**	− 1.19	− 4.47***
FUEL	− 2.73	− 4.83***	− 0.59	− 4.79***
IMPGD	− 2.122	− 4.59***	− 1.86	− 4.71***
EXPGD	− 2.18	− 3.35***	− 1.54	− 4.38***
ECOI	− 1.58	− 4.14*	− 1.60	− 3.99***
Westerlund cointegration results				
DH-group				− 3.12**
DH-panel				− 3.18***

***, **, and * imply significant level at 1%, 5% and 10%

Table 4 Augmented mean group estimation of non-renewable energy, trade openness, and environmental quality nexuses

Variables	Dependent variable: CO2PC				
	Model 1	Model 2	Model 3	Model 4	Model 5
coal	0.001*** (0.000)				
gas		0.061* (0.023)			
fuel			0.074*** (0.002)		
impgd				0.211* (0.105)	
expgd					– 0.029 (0.069)
ecoi	– 0.001*** (0.000)	– 0.057** (0.028)	0.013 (0.001)	0.029 (0.019)	– 0.003* (0.001)
interaction	– 0.034*** (0.011)	– 0.041** (0.019)	– 0.012** (0.005)	– 0.017* (0.001)	– 0.007 (0.005)
_cons	15.846*** (0.756)	18.592*** (1.212)	18.770*** (0.539)	13.8247* (8.123)	12.713*** (3.886)
Observations	174	174	174	174	174
Wald test	13.86***	73.13***	23.17***	4.62**	3.36***

Standard errors are in parentheses

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

significantly low to degrade the environment. Recently, the Emission Gap Report (2019) submits that the rate of emissions imported in developed countries (such as the G-20) surpasses what is exported while the contrary applies in less developed countries (Crippa et al. 2019). Besides, the corresponding increase in co2pc from both NRE (coal, gas, and fuel) and imports can further be explained on the ground that developed countries (like the G-20) import energy-intensive products which increase the rate of energy consumption and subsequently lead to higher emissions (Khan et al. 2020a). This is consistent with previous studies like Hussain et al. (2020), Khan et al. (2020a), and Sadorsky (2012).

Other interesting insights from the results in Table 4 involve the effects of technological innovation (ECOI) both at the unconditional (single effect) and conditional (interactive effect) levels. As evident from the results, technological innovation (ECOI) negatively correlates with co2pc implying the former reduces the latter. The interaction of ECOI with each of the indicators shows that the marginal effects of innovation go a long way to subduing the effects of both TO and NRE in polluting the environment. The impact of technological innovation in reducing carbon emissions can be explained on the ground that innovation is highly instrumental in achieving a more sustainable energy source and subsequently increases the country's environmental performance index (Khan et al. 2020a). These results corroborate the findings of Ahmad et al.

(2020b), Hussain et al. (2020), Khan et al. (2020), Villanthenkodath and Mahalik (2020), and Zhang et al. (2017).

Robustness checks: common correlated effect mean group (CCEMG) and mean group (MG) results

To check how robust the model is and particularly how reliable the empirical results based on the augmented mean group (AMG) are, this study employs both common correlated effect mean group (CCEMG) and mean group (MG) estimators in Table 5. The results are consistent with the empirical outcomes based on the AMG in Table 4. Additionally, the impact of exports becomes significant with negative signs, suggesting exports that demand for environmentally friendly products is of high priority considering the income level of the economies. Moreover, since these economies are major advocates of green economy and transition to clean energy, efforts are geared towards achieving this in order to serve as a model for other countries to emulate.

Conclusion and policy recommendations

G-20 economies constitute leading economies in global trade volumes, thus being high-energy consumers, and

Table 5 Robustness analyses on non-renewable energy, trade openness, and environmental quality nexuses

Variables	Dependent variable: CO2PC				
	Model 1	Model 2	Model 3	Model 4	Model 5
Common correlated effect mean group (CCEMG)					
coal	0.015*** (0.007)				
gas		0.004*** (0.003)			
fuel			0.003*** (0.003)		
impgd				0.256*** (0.021)	
expgd					− 0.118*** (0.021)
ecoi	− 0.005*** (0.001)	− 0.007*** (0.001)	− 0.006*** (0.001)	− 0.005*** (0.002)	− 0.003*** (0.001)
interaction	− 0.012*** (0.001)	− 0.045 (0.011)	− 0.012*** (0.001)	− 0.016 (0.005)	− 0.025*** (0.012)
_cons	17.12*** (0.329)	17.809*** (0.359)	20.645*** (0.622)	22.739*** (0.687)	19.271*** (0.571)
Observations	174	174	174	174	174
Wald test	14.82***	28.78***	20.85***	58.38***	99.60***
Mean group (MG)					
coal	0.025*** (0.005)				
gas		0.091*** (0.006)			
fuel			0.034*** (0.015)		
impgd				0.033	
expgd				(0.025)	− 0.016* (0.008)
ecoi	− 0.002* (0.000)	0.002 (0.002)	− 0.009*** (0.004)	− 0.003*** (0.001)	− 0.001 (0.000)
interaction	− 0.011* (0.002)	− 0.031** (0.006)	− 0.041** (0.009)	− 0.010 (0.004)	− 0.071** (0.031)
_cons	14.499*** (.578)	17.9619*** (.3092)	14.496*** (.4303)	18.015*** (.6059)	17.397*** (0.648)
Observations	174	174	174	174	174
Wald test	13.86***	73.13***	40.23***	28.09***	32.82***

Standard errors are in parentheses

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

consequently remained, at the high echelon of the world carbon emitters. Interestingly, these countries are the leading advocates in carbon emissions reduction and climate change mitigation. The preceding is so advocated via the investment in sustainable technological infrastructures. Despite these efforts, global temperature is not reducing as expected even

among the well-acclaimed developed and developing G economies. The foregoing among other reasons, motivate this inquiry in examining the impacts of disaggregated nonrenewable energy (NRE) and trade openness (TO) on environmental quality of selected G-20 countries with special consideration for the conditioning role of technology from 1990 to 2018.

The empirical analyses are anchored on a set of pre-estimation tests entailing descriptive analyses and normality test, cross-sectional dependence (CSD) tests based on Pesaran (2021) and (2015) for strong and weak assumption of CSD respectively, first-generation and second-generation panel unit test based on Im, Pesaran and Shin (Im et al. 2003), and Cross-Sectionally Augmented IPS (CIPS), respectively, Pesaran and Yamagata (P&Y, 2008) slope heterogeneity test and Westerlund (2007) panel cointegration test. The empirical analyses are evaluated using a battery of estimation techniques comprising augmented mean group (AMG), common correlated effect mean group (CCEMG), and mean group (MG) estimators. The following major results are evident from the analyses. First, results of the CSD and P&Y indicate the existence of cross-sectional dependence and heterogeneity across the countries. These prompted the need to rely on second-generation estimation techniques. Additionally, the panel unit roots test show that all variables are stationary at first difference and are equally integrated in the long run. Second, based on the AMG estimator, the indicators of NRE indicators like coal, gas, and fuel increase $co2pc$ in the selected G-20 countries. Similarly, imports turn out to be significant and positive predictors of $co2pc$ while exports are negative but insignificant. Third, the unconditional and conditional effects of technological innovation (ECOI) are significantly negative on $co2pc$. This suggests the effectiveness of ECOI in abating environmental degradation and enhancing transition from dirty to clean energy sources. Fourth, the validity and reliability of the AMG results are reaffirmed following empirical outcomes from the CCEMG and MG estimators. More so, the effect of exports becomes apparently significant and negative on $co2pc$.

Based on these various empirical outcomes, this study has some relevant policy messages. First, G-20 economies have always remained the main advocators for the need to end global warming and other climatic change conditions. Unfortunately, their pledges can be best described as “empty promises” as they kept funding production of fossil fuels thereby creating ‘lose-lose’ scenario. This is more evident particularly during the coronavirus pandemic. Stimulus spending is being used to support industries and companies that rely on planet-warming fossil fuels. The recent data from the Energy Policy Tracker show that G-20 nations have committed more than \$230 billion in COVID-19 recovery funds towards environment polluting energies thus far. Consequently, reports from the International Institute for Sustainable Development (IISD), Oversea Development Institute (ODI), and advocacy group Oil Change International, then submitted that the G-20 recovery stimulus spending would most likely undo the little progress they have made between 2014 and 2019. Further, G-20 economies have also been alleged as allocating \$170 billion in public money commitments to fossil-fuel intensive sectors in responses to the COVID pandemic between 1 January and 12 August 2020. In light of the foregoing, G-20 should be committed to their pledges in both words and actions. This can be achieved via effective

monitoring mechanisms and uncompromising sanctions. In addition, green conditions should be attached to financing any public money commitments by the G-20 economies. Second, sustainable technological and investment infrastructures should be promoted. This seems salient as technological innovation turns out to be an effective tool to abating the devastating impacts of carbon emissions. Third, since importations constitute a significant medium supporting the surge in carbon emissions, increasing tax rates on imported goods, scaling up border measures, and reinforcing environmental regulations are sacrosanct to addressing this concern. Lastly, since exports offer a supportive platform for mitigating carbon spread and the concomitant energy carbon issues, sustainable green infrastructure should continue to be supported by the export manufacturers and exporting countries as the case may be.

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World Bank Development Indicators (WDI): <https://databank.worldbank.org/source/world-development-indicators>.

Energy information administration
<https://www.eia.gov/petroleum/data.php>

Declarations

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

Competing interests The authors declare that they have no competing interests.

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