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RESEARCH ARTICLE

A link between productivity, globalisation and carbon emissions: evidence from emissions by coal, oil and gas

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Abstract
Although much has been discussed about the link between renewable energy, globalisation and carbon dioxide (CO_2) emissions, yet the impact of total factor productivity (TFP) on CO_2 emissions is less known in the existing literature. Therefore, the present study considers TFP as one of the determinants of CO_2 as it is believed that technological enhancement plays an essential role in improving the environmental quality by raising efficiency in energy use and pollution treatment. In contrast, it may also have unfavourable impacts. In particular, this study analyses how TFP along with renewable energy and globalisation affect the aggregate and source of CO_2 emissions (oil, coal and gas) in the case of top ten carbon emitters from the developing economies over the period 1980–2018. To achieve the above objective, we use the second-generation panel unit root, cointegration and causality tests. We also implement a cross-sectional autoregressive distributed lag model (CS-ARDL) to find the long-run and short-run coefficients. Findings from panel cointegration tests show that there exists a significant long-run relationship between renewable energy, non-renewable energy, globalisation, total factor productivity and CO_2. Moreover, findings show that renewable energy consumption has a negative and significant impact on CO_2 emissions while non-renewable energy consumption significantly increases the CO_2 at aggregate and disaggregated levels. Further, our results confirm that TFP increases the CO_2 emissions whereas globalisation decreases CO_2. From the policy point of view, TFP growth needs to be accelerated to a higher level so that it enables low carbon growth. The slower TFP growth may enhance output which requires more energy and produces more emissions. Thus, there should be a promotion of emissions' reducing technology along with better TFP growth. Also, our findings recommend that CO_2 in sample countries can be reduced through promoting low carbon technology, and globalisation.

Keywords CO_2 emissions · Renewable energy · Fossil fuels · Globalisation · CS-ARDL · Dumiterescu-Hurlin causality test

JEL Classification Q2 · Q3 · F6 · O4

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Introduction

The growth of the economy and the progress of industrialisation are resulting in massive amounts of fossil fuel energy usage. In recent years, various economic and non-economic activities have increasingly grown depending energy inputs that cause problems of energy security and sustainable development (IEA 2017; BP Global 2018). Energy combustion generates a large chunk of the greenhouse gas (GHG) emissions. According to the BP Global (2018) forecast, a surge in global energy demand (GED) has been noted in the upcoming years. Further, it is mentioned that GED will continue to increase by triple times by 2040 under the

Evolving Transition scenario.[1] This depicts that huge energy will be required to continue the current growth pace as compared to the last 25 years, which thereby decays the level of environmental sustainability (BP Global 2018). This problem is more prominent in the fastest-growing economies like China and India and some other developing countries which have a greater share in the GED (BP Global 2018). Moreover, over the decades, a structural shift in energy compositions such as change in fossil fuels mix (coal, oil and natural gas) has been observed. From REN21 (2018), it has been noticed that fossil fuel is the key source of energy which has around 78% share in GED, whereas the share of renewable energy consumption (REC) is noticed around 19%. Particularly, a significant shift from coal to gas is documented in upper-middle-income economies (WEO 2018). Further, followed by renewables and oil consumption, natural gas resource is found to be the largest share in meeting the GED. According to the World Economic Outlook (WEO 2018), natural gas demand could rise even more in the coming years, and can surpass coal and may become an important source of primary energy by 2030. As a result, there would be a significant change in the energy mix, investment and technology, especially in emerging economies. A continuous surge in imbalances between energy demand and energy supply in these countries needs immediate attention. Given these facts, an enormous increase in GED certainly will boost the growth in GHG (greenhouse gas) emissions and it might be doubled by 2050 if serious attention is not paid to reformulate the environmental policies and implement eco-friendly technology (IEA 2013).

While looking at the historical data, it has been observed that the industrialised economies account for a large surge in global GHG emissions. However, in recent years, relatively high growth in GHG emissions is noted in the emerging economies (IEA 2017). In terms of GHG emissions, a vast disparity has been seen across the globe. More specifically, around 80% of world CO_2 is emitted by the top 25 countries, where developing countries have 60% share and it is further projected to increase to 80% of world CO_2 emissions (Huwart and Verdier 2013). Most of the developing countries (or non-Annex I) are exempted from emission reduction obligation under the Kyoto protocol. Nevertheless, these countries are expected to contribute to the fight against climate change and the reduction of GHG emissions. Some of developing countries are making significant efforts to shift their energy mix by creating renewable energy systems (RES), and promoting energy-efficient technology. However, because energy-efficient and pollution-controlling technologies are widely used in developed countries, there is a significant gap between developed and developing countries in terms of energy intensity and CO_2-GDP ratio. In Fig. 1, we have given the energy intensity of our sample countries (top ten developing and six developed countries). The USA has a relatively higher energy intensity among developed countries, while developing countries have higher energy intensity compared to most developed countries.

In Fig. 2, we have plotted the share of emissions from different fossil fuel sources like coal, natural gas and oil for the sample of the top ten carbon emitters among developing countries. From Fig. 2, we visualise that there has been a substantial variation across these countries in terms of energy and emission sources. For example, China, India and South Africa heavily relied on coal consumption, thereby having the largest share of CO_2 emissions.

The above discussion makes it clear that there is a need to identify different sources of emissions and factors, which vary across countries. Ahmad et al. (2016) and Nain et al. (2017) have argued that several related factors which also differ with respect to the sources of emission. For example, renewable energy is a key component for handling the problem associated with fossil fuel like energy security and GHG emissions. In addition, "it tells about non-exhaustive source of energy that should be increased for long-term sustainability (Bhat 2018)". According to the existing studies, the government's initiative in recent years has resulted in the development of renewable energy sources along with a significant decrease in the cost of renewable energy technology, which has evolved in tandem with the increase in energy demand. Despite the fact that renewable energy has a lower share in the energy mix in recent years, policymakers and researchers are nonetheless curious about finding an answer to the question "how does renewable energy lead to economic growth and emissions reduction?" (Shahbaz et al. 2015a, b; Apergis and Payne 2015; among others). Further, it is argued by researchers that the world has accomplished greater command towards the globalisation process with the help of technological progress. Hence, it has built a good connection between economic activity and GED across the world. Moreover, a study by Shahbaz et al. (2016a) gives the different flavours of how globalisation affects GHG emissions. It is believed that globalisation has potential to boost the diffusion of green energy and clean technologies of best practices (Huwart and Verdier 2013). Technological enhancement plays an essential role in economic development and delivers an improved signal to the growth process over time. Recently, few studies have also examined the role of total factor productivity (TFP) in influencing

[1] Assume that social preferences, technology and government policies continue to progress in away and speed seen over the past few years.

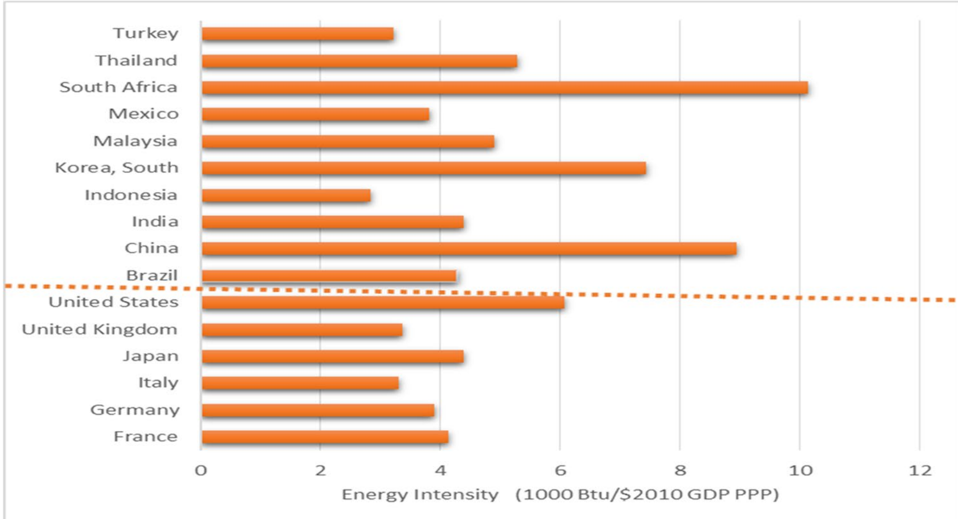

Fig. 1 Energy intensity in developing and developed countries. Source: World Bank (2020)

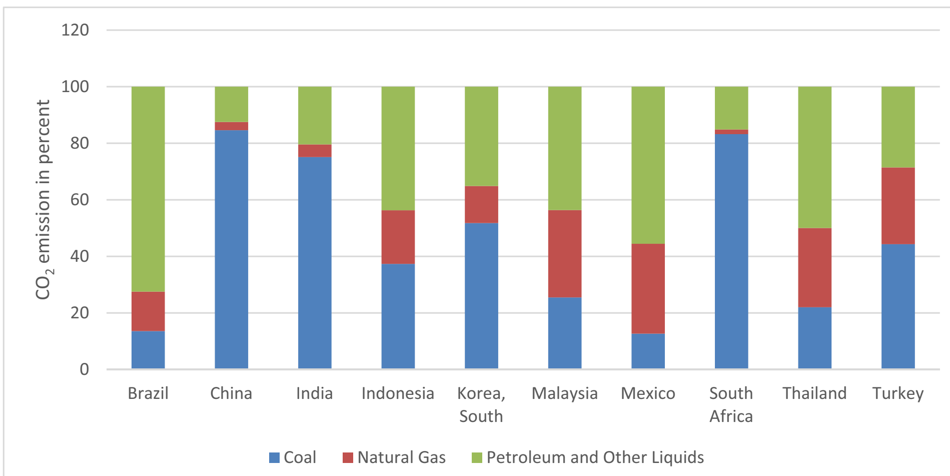

Fig. 2 Sources of CO_2 emission from different energy use. Source: World Bank (2020)

energy consumption and carbon emission reduction (Ladu and Meleddu 2014; Amri et al. 2019; Altinoz et al. 2020). As it is a good proxy for technological progress, it shows the growth of output not attributed to the growth in inputs. Technological advancements have the potential to reduce the carbon emission level by improving the efficiency in energy use, pollution treatment, etc. Thus, this empirical work differs from the earlier studies by considering the TFP as a measure of economic growth. The main reasons for selecting TFP are explained in different ways. Firstly, TFP does reflect not only the technology but also efficiency in the economy. Secondly, it indicates the main and the most important element of growth compared to the factor accumulation (Atesagaoglu et al. 2017). Thirdly, TFP reflects the ability of a country to create technology innovations; therefore, it is considered an indicator of the quality of growth (Cantore et al. 2016). Fourthly, it is a measure of growth instead of GDP (Ladu and Meleddu 2014). However, its effect on the environmental quality is less known; it may also have unfavourable impacts. In this case, TFP is insufficient to protect and improve the environment. This is because lower expenditure on research and development enabled to improve TFP i.e. a measure of technological and innovation change in the economy which may degrade environmental quality (Amri et al. 2019). Hence, a big role can be played by technological progress in reducing GHG emissions. It becomes pertinent to examine the role of TFP on emission control. It will provide crucial policy insight about enhancing technological upgradation and transfer from advanced countries. As the economy grows, the relative importance of productivity becomes more crucial to provide growth stimulus. At the same time, it also enhances input efficiency and hence reduces wastage and additional input demand. Energy has become a crucial input; hence, improving the overall productivity will also step up energy efficiency and hence reduce emissions. Despite the vital role of TFP, studies on the link between CO_2 emission and TFP are scant. Further, the dynamics and drivers of different emission sources differ; there is a requirement to make a disaggregated analysis to reveal deep policy insight on energy policy. Hence, "there is a need for close investigation of the relationship between environment and its influencing macroeconomic factors to design a nuanced energy and environmental policy". Further, given the position of globalisation and technological progress in the existing literature, the current study tries to bridge the research gap by investigating the impact of globalisation, TFP, renewable and non-renewable on the different carbon emission sources (or disaggregated levels). At the global level, we consider the sample of the top ten CO_2 emitting nations which is of prime importance in the international negotiation on climate change. To the best of our knowledge, none of the previous studies has examined the impact of globalisation, TFP, renewable and non-renewable on carbon emission at the disaggregated level (emission from coal, gas and oil) in a panel data framework in the top ten carbon-emitting countries among developing nations. As a result, this study adds to the research on carbon emissions and macroeconomic nexus in the following ways.

To begin with, our work differs from the previous literature (Ahmad et al. 2016; Asafu-Adjaye et al. 2016; Bhat 2018; Sabir and Gorus 2019; Shahbaz et al. 2018a) in that it uses TFP as a proxy for economic growth to evaluate the role of productivity improvement on CO_2 emission reduction. Second, we have explored the long-run relationship using the advanced panel data model, i.e. cross-sectional autoregressive distributed lag (CS-ARDL) model, because ignoring the issue of cross-sectional dependency in the error term leads to biased results. This problem is critical from the perspective of global economic coordination on "climate change and voluntary carbon emission reduction". Third, we have used a unique dataset of emissions from coal, gas and oil related to the top ten CO_2 emitters from the developing countries at disaggregated levels which have the largest potential for reduction in emissions. The role of the influence factors on the CO_2 emissions by sources has not been discussed in the existing literature, particularly for the top ten carbon emitter countries from the developing nations. Examining such a relationship between influencing variables and CO_2 emissions by sources might offer crucial insights on policy makers in designing the environmental protection policies in these countries.

The remaining part is assembled as follows: the "Literature review" section supplies the assessment of relevant studies. The "Data and methodology" part delineates the empirical modelling, data collection and methods of estimation. The "Empirical results" present the results and discussion, and the "Conclusions and policy implications" division summarises the article with the concluding remark and some relevant policy implications.

Literature review

The theoretical foundation of the environmental Kuznets curve (EKC) has been empirically examined in a large number of studies. It has been tested by investigating the causal link between energy consumption and economic growth. This is the widely tested and debated hypothesis in the literature related to environment/energy. However, there is no single consensus in validating the EKC hypothesis (Tiba and Omri 2017). The reason could be that the EKC hypothesis varies with respect to determinants, time duration and techniques employed in the examination. Studies by Tiba and Omri (2017) and Villanthenkodath and Arakkal (2020) make available a wide-ranging literature survey on the EKC hypothesis. Based on the literature survey, these studies recommend further investigation of the EKC hypothesis by augmenting the EKC model with other relevant variables. For more details, kindly refer to Tiba and Omri (2017). Given the role of renewable energy consumption in recent years of a government mission to achieve the full potential production of renewable energy, recent studies have distinctly looked the effect of renewable energy consumption along with non-renewable energy consumption on economic growth and CO_2 emission.

A set of studies have investigated a causal link between consumption of energy and CO_2 emissions—in total at aggregated level empirically (Bhattacharyya et al. 2016; Nain et al. 2017; MK 2020). The paper investigates the relationship between carbon emissions, renewable energy, non-renewable energy, total factor productivity and globalisation that has diverse characteristics.

Furthermore, only a few researchers have looked into the impact of globalisation and TFP on CO_2 emissions and energy consumption, and various proxies of globalisation have been used as indicators of globalisation, i.e. trade openness. There are no clear-cut conclusions (or mixed ones) in terms of the dominance of size or the composition influence of trade. Some researchers looked at a causal association between energy usage, economic progress and trade; however, the evidence was inconclusive (Shahbaz et al. 2013a, b, 2014).

The existing studies have been divided into two portions to maintain the relevancy of the empirical investigations: (i) studies based on a link between CO_2 emission and renewable energy consumption are given in Table 1; (ii) literature on the relationship between globalisation, energy consumption and carbon emission (an indicator of environmental quality) are reported in Table 2. Table 1 shows that no single study has concluded that increasing renewable energy usage reduces CO_2 emissions. Except for Sebri and Ben-Salha (2014) and Apergis and Payne (2014), the majority of literature indicated that increasing renewable

Table 1 Survey literature on the link between CO_2 emissions and renewable energy consumption

Author	Sample-year	Sample-countries	Methdology	Findings
Sadorsky (2009)	1980 to 2005	G7	PC, ECM	Positive impact of CO_2 on REC
Menyah and Wolde-Rufael (2010)	1960–2009	USA	GC	No causality from REC to CO_2
Apergis et al. (2010)	1984 to 2007	19	ECM	REC increases CO_2
Silva et al. (2012)	1960–2004	USA, Denmark, Portugal and Spain	SVAR	Electricity generation has negative impact by RE on CO_2 emission
Shafiei and Salim (2014)	1980–2011	OECD	PC, AMGE	REC reduces CO_2 Existence of EKC (CO_2 and urbanization)
Apergis and Payne (2014)	1980–2011	25 OECD	PC, ECM	FC between REC and CO_2
Zeb et al. (2014)	1975–2010	SAARC	GC	No causal relation between electricity generation by RE and CO_2
Apergis and Payne (2015)	1980 to 2010	11	ECM, GC,	REC enhances CO_2
Shahbaz et al., (2015a)	1972Q1–2011Q4	Pakistan	ARDL	REC increases the economic growth, REC casuses growth and vice-vsresa
Dogan and Seker (2016a)	1980 to 2012	EU-15	DOLS, GC	REC declined CO_2 REC casues CO_2 and vice-versa
Dogan and Seker (2016b)	1985–2011	Top-10 in RE	FMOLS, DOLS	REC has neagtive impact on CO_2 emission REC casues CO_2 and vice-versa
Paramati et al. (2017)	1990–2012	11	FMOLS, GC	Negative impact of REC on CO_2,
Sebri and Ben-Salha (2014)	1971–2010	BRICS	ARDL, VECM	CO_2 emissions boost the REC
Balsalobre-Lorente et al., (2018)	1985–2016	EU-5	DOLS	Natural resource abundance and RE reduces CO_2 emissions
Sinha and Shahbaz (2018)	1971–2015	India	ARDL	REC decrases CO_2 in short-run and long-run
Ansari et al. (2020)	1991–2017	GCC	FMOLS, DOLS	Globalisation increases environmental pollution
Okumus et al. (2021)	1980–2016	G7	CS-ARDL	REC decreases CO_2 emissions

FMOLS fully modified-ordinary-least-squares, *CS/ARDL* cross-sectional/autoregressive distributed lag model, *DOLS* dynamic ordinary least squares, *REC* renewable energy consumption, *VECM* vector error correction mechanism, *AMGE* augmented mean group estimator, *PC* panel cointegration, *ECM* error correction model, *GC* Granger causality, *SVAR* structural vector autoregression

energy use reduced CO_2 emissions (2014). Salahuddin et al. (2019) have examined globalisation-CO_2 emissions nexus for South Africa using time series data. They have not found any causal link between them while globalisation influences CO_2 emissions in the long-run model. On a similar line, Ahmed et al. (2021a) applied asymmetric ARDL in the case of Japan. They found contradictory results that both increase and decrease in globalisation mitigate ecological footprint (EF). It means changes in globalisation in either direction will ultimately improve environmental performance. Wang et al. (2020) have found that higher economic globalisation induces higher CO_2 emissions, while higher agricultural production reduces it in the sample of G7 countries. Figge et al. (2017) analysed the effect of different aspects of globalisation[2] on EF for a sample of 171 countries. They have documented that except for the political dimension of globalisation, other dimensions of globalisation increase FE of consumption, exports and imports. Phong (2019) examined the nexus between globalisation, financial development and environmental degradation for ASEAN-5 countries spanning from 1974 to 2014. He found that globalisation increases CO_2 emissions. Ahmed and Le (2021) found that trade globalisation and ICT reduce CO_2 emissions in the case of ASEAN-6 countries. Further, the causality test suggests unidirectional causality from ICT and trade globalisation to CO_2 emissions. Saud and Chen (2018) found that globalisation has a negative impact on energy demand in the case of China. At the same time, a unidirectional causality has been detected from globalisation to energy demand. Shahbaz et al. (2020) found that the economic aspect of globalisation negatively impacts CO_2 emissions in the case of the UAE. Pata and Caglar (2021) found that globalisation, trade openness and income influence environmental pollution while human capital reduces it in the long term.

Further, renewable energy has no significant effect. Saud et al. (2020) has investigated the link between financial development and globalisation on environmental performance for selected one-belt-one-road initiative countries. They found that globalisation negatively affects EF, carbon footprint and CO_2 emissions. Ahmed et al. (2021b)

[2] They have taken five dimensions of globalisation that are political, economic, social–cultural, technological and ecological.

Table 2 Survey literature on the link between globalisation, energy consumption, TFP and CO2 emission

Study	Period	Countries	Method	Results
Shahbaz, et al. (2018b)	1970–2014	Japan	Asymmetric threshold version of the ARDL	Postive link between Globalisation, growth, EC and CO_2
Shahbaz, et al. (2018a)	1970–2015	BRICS	NARDL	Positive link between globalisation and EC
Shahbaz et al. (2018e)	1975Q1–2014Q4	UAE	Cointegration and Toda-Yamamoto causality	Globalisation declined the CO_2 emissions
Shahbaz, et al. (2018c)	1970–2014	25	PC and AMGE	Globalisation increases the CO_2
Shahbaz, et al. (2018d)	1970Q1–2015Q4	Ireland,Netherlands	ARDL (Quantile)	positive link between globalisation and EC
Shahbaz, et al. (2016a)	1970–2012	China	Bayer-Hanck cointegration and ARDL	Ngetaive link between Globalisation CO_2 emissions
Shahbaz, et al. (2016c)	1971–2012	19 African	ARDL	Mix findings
Shahbaz, et al. (2016b)	1971–2012	India	Bayer-Hanck cointegration test and ARDL	globalisation decreases EC
Shahbaz, et al. (2015b)	1970–2012	India	Bayer-Hanck cointegration test and ARDL	Postive link between Globalisation, EC and CO_2 emissions
Ansari et al. (2021)	1991–2016	Top RE	PMG, FMOLS, and DOLS	Negative link between Globalisation and CO2 emissions
Amri (2018)	1975–2014	Tunisia	ARDL	Positive link between TFP and CO_2 emission
Amri et al. (2019)	1975–2014	Tunisia	ARDL	TFP stimulates carbon emissions
Altinoz et al. (2020)	1995–2014	Top emerging economies	GMM	Negative link between TFP and CO_2 emissions

ARDL autoregressive distributed lag test, *EC* energy consumption, *REC* renewable energy (RE) consumption, *TFP* total factor productivity, *VECM* vector error-correction, *AMG* augmented mean group, *PMG* pooled mean group, *GMM* generalised method of moments have analysed asymmetries in globalisation-CO_2 emissions nexus. They have found that negative changes are more influencing than positive changes in a different dimension of globalisation. Further, the study documented that increased social globalisation reduces EF while increased political globalisation enhances FE. Recently, Usman et al (2021) investigated the effect of natural resource, globalisation, renewable and non-renewable energy on environmental quality in financially rice countries from 1990 to 2018. The results explore that globalisation and renewable energy consumption negatively affect the ecological footprint while natural resource and non-renewable energy increases environmental degradation. Sheraz et al. (2021) explored the relationship between globalisation, renewable energy financial development and CO2 emission and found that both globalisation and renewable energy improve the quality of environment. Using the time series data from 1971 to 2016 for BRIC countries, Pata (2021) analysed the impact of renewable energy and globalisation on carbon emissions. His empirical findings showed that renewable energy consumption reduces environmental degradation while globalisation increases in China and Brazil, respectively. By employing the wavelet statistical tool, Adebayo and Kirikkaleli (2021) studied the connection between economic growth, globalisation, renewable energy and technological innovation and CO_2 emission in Japan. Their empirical outcomes revealed that economic growth technological innovation and globalisation stimulate CO_2 emissions while renewable energy mitigates CO_2 emission during the period 1990Q1–2015Q4. Tahir et al. (2021) use the second-generation econometric tool to examine the linkage between globalisation and financial development on environmental quality spanning the period 1990–2014. The results of FMOLS, DOLS and PMG showed that globalisation reduces the emission while financial development increases them in South Asian economies. Yurtkuran (2021) used the bootstrap ARDL method to examine the association between globalisation and renewable energy on CO_2 emissions. They found that both these variables affect CO_2 emission positively in Turkey.

The studies examining the effect of globalisation on CO_2 emissions have found mixed findings stating that globalisation enhances or reduces CO_2 emissions. The method used, distinct supplementary variables, period and sample size could all be factored in contradicting results (Dogan and Seker 2016a). Most of the panel data studies do not account for potential cross-sectional dependence. Further, most studies have taken aggregate CO_2 emission, which may limit the scope of policy insights at the sectoral level. Hence, we have taken CO_2 emission by sources that are coal, oil and gas which may provide better policy insights to reduce emissions from different sources. There are no clear findings from the existing studies on the impact of TFP on environmental performance, which suggest further investigation in a more coherent manner. There are limited studies that consider the TFP in the determinants of CO_2 emission, as innovation and technological upgradation play a crucial role in reducing emissions. We have extended the literature by conducting a thorough examination of the effect of TFP on CO_2 emissions by source.

Data and methodology

Data and source

This study collects the data of the top ten CO_2 emitters from the developing countries which are vital to examine to implement the policies which can help to reduce the emissions at the global level. They are China, Malaysia, Turkey, South Africa, Indonesia, Mexico, Brazil, India, South Korea and Thailand. By selecting this country group, the objective is to direct the carbon emission mitigation policies of these top ten economies with high CO_2 emissions in the context of globalisation, total factor productivity and carbon emission. Especially, India, China and South Africa are the three countries that emit the most in terms of CO_2 emission according to the World Bank (2020). The top ten CO_2 emitter countries from the developing countries are the highest energy consuming and carbon emitter countries. These economies significantly contribute to world economic output. Hence, it is worth examining the impact of globalisation and TFP on CO_2 emission in these economies. Further, we have employed annual data spanning from 1980 to 2018 and estimated an augmented CO_2 emission function. The selection of the sample period is purely based on the data availability of the variables considered in this study. Following earlier studies (Villanthenkodath and Mahalik 2020), we convert all the variables in the natural log-linear form to minimise the problem related to the distributional properties of estimated coefficients. Further, these studies state that converting variables into log specification overcomes the problem associated with heteroskedasticity and provide direct elasticities. Table 3 shows the name of variables, their symbols, descriptions and the measurement of units as well as the data source used in this study. This study uses the data set from 1980 to 2018 based on the data availability.

Methodology

Before employing panel data estimation techniques, one should check the cross-sectional dependence (CD) in the error term that arises due to economic integration among the countries (Pesaran 2004). This may lead to inefficient estimators and standard errors will be biased. This test guides the researchers on whether to go for the first-generation

Table 3 Data sources and description

Variables	Symbol	Description	Units	Source
Carbon dioxide emissions (CO_2)	lnCO_2	Total carbon dioxide emissions from energy consumption	Million metric tons (MMT)	US-EIA
Renewable energy	lnREC	Sum of hydro, modern and traditional biomass,wind,solar,liquid biofuel, biogas,geothermal,marine and waste resource	Quadrillion Btu (Qd. Btu)	US-EIA
Non-renewable energy	lnNREC	Sum of coal, oil and gas consumption	Qd. Btu	US-EIA
Carbon dioxide emissions (CO_2) from coal	lnCO_2Coal	Carbon dioxide emissions from coal consumption	MMT	US-EIA
Carbon dioxide emissions (CO_2) from oil	lnCO_2Oil	Carbon dioxide emissions from oil consumption	MMT	US-EIA
Carbon dioxide emissions (CO_2) from gas	lnCO_2Gas	Carbon dioxide emissions from gas consumption	MMT	US-EIA
Energy consumption from coal	lnECCoal	Non-renewable energy consumption particularly from coal	Quadrillion Btu (Qd. Btu)	US-EIA
Energy consumption from oil	lnECOil	Non-renewable energy consumption particularly from oil	Qd. Btu	US-EIA
Energy consumption from gas	lnECGas	Non-renewable energy consumption particularly from gas	Qd. Btu	US-EIA
Total factor productivity	lnTFP	measured as constant prices (2011 = 1)	Constant prices 2017	PWT10.0
Globalisation	lnG	measured by (Dreher 2006) as KOF index of globalisation consists of mainly three parameters (economic, political and social)	Index	SEI

US-EIA United States Energy Information Agency, *SEFA/WB* Sustainable Energy for All published by World Bank, *BS* Stats British Petroleum Statistics, *PWT* Penn World Table, *ETH* Ethereum Zurich, *SEI* Swiss Economic Institution

panel data model or second-generation panel data model. Therefore, to account for the CD, this study uses the CD test advanced by Pesaran (2004) for each variable as well as for each model (Eqs. 1–4).

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

where CD stands for cross-sectional dependence; N refers to the cross-sections; T stands for time. $\hat{\rho}_{ij}$ indicates the error pairwise correlation obtained from the augmented Dickey-Fuller (ADF) regression. The null hypothesis is "there is no cross-sectional dependency". This test also works better even in the case of a small panel.

In the next step, we check the stationarity of the variable before assessing the long-run relationship. To do so, this paper implements the second-generation cross-sectional augmented Im–Pesaran–Shin (CIPS) panel unit root test advanced by Pesaran (2007). The CIPS panel unit root test accounts for the cross-sectional dependence and heterogeneity that arises due to the error correlation. Therefore, the CIPS panel unit root test is preferred over the first-generation panel unit root tests (Levin et al., 2002; Im et al. 2003). The following equation can be estimated:

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

where $t_i(N,T)$ refers to the t-statistics.

Next, to investigate the long-run equilibrium relationship between carbon emissions (at aggregate and by source) and selected variables, this study makes use of Westerlund's (2008) panel cointegration test. This test is useful in the case of a mix of unit root $I(0)$ and $I(1)$. This test does not require any prior information about the integration orders of the variables rather it is implemented under very general conditions. Westerlund's (2008) panel cointegration is based on the Durbin-Hausman tests which include two statistics namely panel and group mean. Further, this test provides consistent results in the presence of cross-sectional dependency which is modelled by the factor model in which errors are computed by idiosyncratic innovations and unobservable factors (Auteri & Constantini 2005). The panel (p) and group (g) mean statistics of Durbin-Hausman (DH) are based on the homogeneous and heterogeneous structure of the panel coefficients.

The DH statistics based on group mean can be attained as follows:

$$DH_g = \sum_{i=1}^{n} \widehat{S}_i(\tilde{\phi}_i - \widehat{\phi}_i)^2 \sum_{t=1}^{T} \widehat{e}^2_{it-1} \quad (3)$$

The DH statistics based on the panel mean can be obtained as follows:

$$DH_p = \widehat{S}_i(\tilde{\phi}_i - \widehat{\phi}_i)^2 \sum_{i=1}^{n} \sum_{t=1}^{T} \widehat{e}^2_{it-1} \quad (4)$$

where DH_g shows the group statistic which is formulated by first multiplying the various terms and then adding. DH_p stands for the panel statistic obtained by first adding the n individuals before multiplying them all together. DH_g tests the cointegration in case of heterogeneous cross-sections while DH_p produces the results when cross-sections are homogeneous. $\widehat{\phi}_i$ is the OLS estimators of ϕ_i. The corresponding cross-section and pooled instrumental variable (IV) estimators of ϕ_i is represented by $\phi_i$and ϕ, respectively, which are calculated by instrumenting $\widehat{e}_{it-1}$ and $\widehat{e}_{it}$.

The null and alternative hypotheses for DH_g are given as follows:

$H_0 : \phi_i = 1, \forall i = 1, 2, ..., N$, versus$H_1 : \phi_i < 1$, at least for some i's.

The null and alternative hypotheses for DH_p are given as follows:

$H_0 : \phi_i = \Phi, \forall i = 1, 2, ..., N$, versus $H_1 : \phi_i < 1$, for all i's.

The rejection of the null hypothesis provides the existence of the long-run relationship.

Next, after the confirmation of the long-run relationship between carbon emissions and total factor productivity, globalisation, renewable energy and non-renewable energy consumption, we estimate the long-run and short elasticities by using the cross-sectional autoregressive distributed lag (CS-ARDL). As discussed above, there might be a possibility of the existence of cross-sectional dependency among the sample countries. The test, i.e. CS-ARDL, proposed by Chudik and Pesaran (2016) is very flexible to curb the issue of cross-sectional dependency by including lagged dependent variables. Moreover, this test is most efficient in the case of unobserved common factors. This test also addresses the CD in both the short run and long run. The estimators are unbiased when $N \to \infty$ for both $T \to \infty$ and fixed T. The model can be estimated as follows:

$$\Delta lnY_{it} = \mu_i + \varphi_i\left(lnY_{i,t-1} - \beta' X_{i,t-1} - \varnothing_{1i}\overline{lnY}_{t-1} - \varnothing_{2i}\overline{X}_{t-1}\right) + \sum_{j=1}^{p_i} \lambda_{ij}\Delta lnY_{it-1} + \sum_{j=0}^{q-1} \zeta_{ij}\Delta X_{it-1} + \eta_{1i}\overline{lnY}_{t-1} + \eta_{2i}\Delta\overline{X}_t + \varepsilon_{it} \quad (5)$$

where Y shows the dependent variable. X shows the set of explanatory variables. $\overline{Y}$ and $\overline{X}$ indicates the mean of dependent and explanatory variables, respectively. Δ indicates the short-run relationship. j refers to the cross-section dimension whereas t indicates the time dimension. φ_i, λ_{ij}, η_{1i} and $\varnothing$ are the parameters to be estimated.

To check the robustness of our results, we further apply the fully modified ordinary least squares (FMOLS) which accounts for the endogeneity issue and estimates the long-run elasticities FMOLS is developed by Pedroni (2001). This test can resolve the issues of endogeneity and serial correlation. In addition, it corrects the biases through implementing the demeaning process and the vector of lagged explanatory variables. FMOLS is considered to be one of the better methods because of its outperformance in the case of a small sample, overcoming autocorrelation correlation and endogeneity issues by including lags. The FMOLS can be presented as follows:

$$\widehat{\beta}^*_{\text{FMOLS}} = N^{-1} \sum_{n=1}^{N} \widehat{\beta}^*_{\text{FMOLS},n} \quad (6)$$

where $\widehat{\beta}^*_{\text{FMOLS}}$ represents FMOLS regression parameter applied in n countries.

Finally, in this paper, we use the causality panel test which is implemented by Dumitrescu-Hurlin (2012, D-H, hereafter). This test is superior to panel Granger causality by accounting for the cross-sectional dependency. The model can be written as follows:

$$\text{Y}_{i,t} = \sum_{k=1}^{K} \alpha_i^{(k)} Y_{i,t-k} + \sum_{k=1}^{K} \beta_i^{(k)} X_{i,t-k} + \varepsilon_{i,t} \quad (7)$$

$$\text{X}_{i,t} = \sum_{k=1}^{K} \theta_i^{(k)} X_{i,t-k} + \sum_{k=1}^{K} \gamma_i^{(k)} Y_{i,t-k} + \varepsilon_{i,t} \quad (8)$$

where K refers to the lag length. α, β, θ and γ are the autoregressive parameters that need to be estimated. One can reach to conclusion of causality if the tabulated value is greater than the critical value. In other words, the null of no causality running from one variable to other can be rejected, if the tabulated value is greater than the critical value.

Empirical models

To empirically analyse the effect of renewable, non-renewable energy, total factor productivity and globalisation at

Table 4 Cross-sectional dependence results

Variables	Breusch-Pagan LM		Pesaran CD		Pesaran scaled LM		Bias-corrected scaled LM	
	Stat	Prob	Stat	Prob	Stat	Prob	Stat	Prob
$LnCO_2Agg$	1662.636***	0.000	170.514***	0.000	170.382***	0.000	40.768***	0.000
$LnCO_2Coal$	1553.391***	0.000	158.998***	0.000	158.866***	0.000	39.391***	0.000
$LnCO_2Oil$	1577.350***	0.000	161.524***	0.000	161.392***	0.000	39.689***	0.000
$LnCO_2Gas$	1188.302***	0.000	120.514***	0.000	120.383***	0.000	33.109***	0.000
LnECCoal	1554.127***	0.000	159.076***	0.000	158.944***	0.000	39.402***	0.000
LnECOil	1551.022***	0.000	158.748***	0.000	158.617***	0.000	39.346***	0.000
LnECGas	1188.302***	0.000	120.514***	0.000	120.383***	0.000	33.109***	0.000
LnNREC	1676.038***	0.000	171.926***	0.000	171.795***	0.000	40.933***	0.000
LnREC	1675.406***	0.000	171.859***	0.000	171.728***	0.000	40.925***	0.000
LnTFP	663.336***	0.000	65.1783***	0.000	65.046***	0.000	1.532***	0.000
LnG	1638.69***	0.000	167.989***	0.000	167.858***	0.000	40.470***	0.000
Models	**Model 1**		**Model 2**		**Model 3**		**Model 4**	
CD	−0.469	0.6389	−3.368***	0.000	7.314***	0.000	−1.693*	0.090

***Cross-sectional independence is rejected at 1% level of significance; LM and CD test performs the null hypothesis of cross-sectional independence. *Agg* aggregate

aggregated and disaggregated levels on carbon emissions, we employ the following algebraic form of equations:

$$\ln CO_{2it} = \beta_0 + \beta_1 \ln NREC_{it} + \beta_2 \ln REC_{it} + \beta_3 \ln TFP_{it} + \beta_4 \ln G_{it} + \mu_{it} \tag{9}$$

where $\ln CO_2$ represents the natural log of per capita carbon emissions; lnNREC is the natural log of non-renewable energy consumption; lnREC denotes the natural log of renewable energy consumption; lnTFP is the natural log total factor productivity, and *lnG* is the natural log of per capita globalisation. In addition, β_0 is constant and μ is the unknown error term. A separate function for the consumption of non-renewable energy (coal, oil and gas) at disaggregated analysis is depicted by the following equations.

$$\ln CO_{2it}Coal = \beta_0 + \beta_1 \ln ECCoal_{it} + \beta_2 \ln REC_{it} + \beta_3 \ln TFP_{it} + \beta_4 \ln G_{it} + \mu_{it} \tag{10}$$

$$\ln CO_{2it}Oil = \beta_0 + \beta_1 \ln ECOil_{it} + \beta_2 \ln REC_{it} + \beta_3 \ln TFP_{it} + \beta_4 \ln G_{it} + \mu_{it} \tag{11}$$

$$\ln CO_{2it}Gas = \beta_0 + \beta_1 \ln ECGas_{it} + \beta_2 \ln REC_{it} + \beta_3 \ln TFP_{it} + \beta_4 \ln G_{it} + \mu_{it} \tag{12}$$

Equations 1–4 are used to analyse the effect of non-renewable energy consumption, lnREC, lnTFP and globalisation on carbon emissions.

Empirical results

First, we discuss the results of CD based on Pesaran (2004)'s cross-sectional (CD),[3] Breusch and Pagan (1980)[4]'s Lagrange multiplier approach (LM), Pesaran scaled LM and bias-corrected scaled LM test reported in Table 4 for each variable. Results reported in Table 4 indicate that for each variable, we reject the null no cross-sectional dependency. This suggests that all ten countries are economically integrated for the selected variables. Further, this study applies Pesaran (2004)'s CD test for models 13–16; again, results reported in Table 4 exhibit the evidence of cross-sectional dependency except model 1.

These findings suggest that the first-generation panel unit root can provide biased results. Hence, to tackle this problem, we apply the CIPS unit root test which accounts for both cross-sectional dependency and heterogeneity in the series. The CIPS panel unit root results are presented in Table 5. Results indicate that we do not reject the null of panel unit root for all the variables except lnECOil and lnG at the level. Further, we take the difference of the series

[3] This test is used in both case balance and unbalance panels data where $T < N$.

[4] The test performs well while working with panel countries with $T > N$.

Table 5 Results of CIPS panel unit root test

Variables	CIPS unit root test			
	Level		First difference	
	C	T&C	C	T&C
$lnCO_2Agg$	−1.647	−2.220	−5.144***	−5.190***
$lnCO_2Coal$	−1.763	−2.523	−5.443***	−5.473***
$LnCO_2Oil$	−2.160	3.159	−5.705***	−5.786***
$lnCO_2Gas$	−1.708	−1.552	−4.736***	−5.301***
lnECCoal	−1.755	−2.433	−5.266***	−5.335***
lnECOil	−2.216*	−2.839*	−5.631***	−5.730***
lnECGas	−1.708	−1.552	−4.736***	−5.301***
lnNREC	−2.117	−2.515	−5.141***	−4.916***
lnREC	−2.127	−2.659	−5.084***	−4.881***
lnTFP	−1.435	−2.171	−5.160***	−5.355***
lnG	−2.417	−2.855*	−5.257***	−5.641***

***, **, and * indicate rejection of null hypothesis at 1%, 5%, and 10% level of significance respectively. *C* constant, *T* trend, *Agg* aggregate. Where lnNREC is the logarithm of non-renewable energy consumption; LnREC is the logarithm of renewable energy consumption; lnECCoal is the logarithm of energy consumption particularly from coal; lnECOil is the logarithm of energy consumption particularly from oil; lnECGas is the logarithm of energy consumption particularly from gas; lnTFP is the logarithm of total factor productivity; lnG is the logarithm of globalisation

and run the CIPS panel unit root test. Results exhibit the stationarity for all the variables at first difference.

The findings of CIPS panel unit root test suggest that variables are cointegrated with order one except for lnECOil and lnG, and there might exist a long-run relationship. Further, to examine the long-run relationship, this uses the Westerlund cointegration test for models 9–12.

Table 6 Results of panel cointegration test

Test	Model 1		Model 2	
	Value	Prob	Value	Prob
DH_g	38.469***	0.000	38.719***	0.000
DH_p	75.014***	0.000	75.417***	0.000
	Model 3		**Model 4**	
	Value	**Prob**	Value	**Prob**
DH_g	39.134***	0.000	39.338***	0.000
DH_p	75.570***	0.000	75.846***	0.000

***, ** and * indicate the rejection of the null hypothesis of no cointegration at 1%, 5% and 10% level of significance. Model 1: $LnCO_{2it} = \beta_0 + \beta_1 lnNREC_{it} + \beta_2 lnREC_{it} + \beta_3 lnTFP_{it} + \beta_4 lnG_{it} + \mu_{it}$; Model 2: $LnCO_{2it}Coal = \beta_0 + \beta_1 LnECcoal_{it} + \beta_2 LnREC_{it} + \beta_3 LnTFP_{it} + \beta_4 LnG_{it} + \mu_{it}$; Model 3: $LnCO_{2it}Oil = \beta_0 + \beta_1 lnECOil_{it} + \beta_2 lnREC_{it} + \beta_3 lnTFP_{it} + \beta_4 lnG_{it} + \mu_{it}$; Model 4: $lnCO_{2it}Gas = \beta_0 + \beta_1 lnECGas_{it} + \beta_2 lnREC_{it} + \beta_3 lnTFP_{it} + \beta_4 lnG_{it} + \mu_{it}$. The *p*-values are based on asymptotic normal distribution

The results of the long-run equilibrium test are reported in Table 6. It is clear from Table 6 that the null of no cointegration can be rejected for models 9–12 which state the existence of long-run relationship among carbon emissions, renewable energy, non-renewable energy, total factor productivity and globalisation in the top ten carbon emitters in developing economies.

After examining the long-run relationship, we estimate the long and short-run impacts of lnNREC, lnREC total factor productivity and globalisation on CO_2 emission at the aggregated and disaggregated levels. To do so, we use the bias-corrected CS-ARDL test. The results are illustrated in Table 7 for models 9–12. The results of CS-ARDL for model 1 show that lnNREC has a positive and significant impact on the CO_2. More specifically, a 1% increase in the lnNREC leads to an increase in CO_2 emissions by 0.40% in the long run whereas in the short impact is found to be around 0.74%. Further, it is noted that lnREC has a negative and significant impact on CO_2 emissions. In other words, a 1% improvement in lnREC reduces the CO_2 emission by 1.81% in the long run. The negative impact of lnREC in the short is found to be around 0.81%. Our findings clearly suggest the use of more lnREC and reduction of lnNREC to improve the environmental quality. Moreover, sample countries should find a different source of energy to reduce their environmental impact. One of the possible methods for reducing carbon emissions is to improve energy efficiency. According to Wang et al. (2016), low energy efficiency increases the emissions from CO_2. At the same time, increasing the consumption of renewable energy (environmentally friendly) in overall energy consumption is another possible measure that will reduce carbon emissions in these top CO_2 countries. Although lnREC helps in mitigating environmental degradation in the top carbon-emitting economies, still much more needs to be done for the renewable energy source to meet both the Paris Agreement and the sustainable development goals to increase the percent share of a clean source of energy in these nations; this can be accomplished by (i) increasing energy independence and security, (ii) reducing environmental pollution and providing access to modern energy, (iii) reducing energy demand in all sectors by 2030, (iv) reducing non-renewable energy consumption, particularly oil and coal, while increasing the use of renewable energy sources, and (v) adequate financial instruments, such as incentives, subsidies and the removal of barriers, are required to accelerate investment in the renewable energy sector. Finally, to meet the Paris Agreement's goals, the elimination of subsidies and the implementation of a carbon price scheme are critical. Feed-in tariffs have previously proven to be effective in encouraging the growth of renewable energy (REN21, 2018). This result is crucial for designing climate change policy. Our empirical findings are in the line with Nathaniel and Iheonu (2019) and Okumus et al. (2021) where they mentioned that lnNREC increases the CO_2 emissions level whereas lnREC reduces the CO_2 emission level (Dogan and Seker 2016a; Shafiei and Salim 2014). Further, we augment the CO_2 model by including lnTFP and globalisation as two important determinants of CO_2 emissions. Our results show that a 1% increase in lnTFP leads to an increase in the CO_2 emissions by 0.11% in the long run. Whereas in the short run, it declines the CO_2 emissions. This implies that a higher level of technology leads to high economic growth which required massive energy use. As a result, it degrades the environmental quality especially in developing countries by releasing more emissions in the long run. The increasing relationship between lnTFP and carbon emissions is consistent with Amri (2018) and Amri et al. (2019). Therefore, this finding endorses that production efficiency reduces energy requirement which in turn induces energy consumption and carbon emissions. This phenomenon shows the presence of rebound effects. While looking at the globalisation results, we noted that globalisation does not have any significant impact on CO_2. This is because the top CO_2 emitter countries have not reached a level where it could impact the CO_2 emissions (aggregate level). This relationship is consistent with those of Ahmed et al. (2019) who also found insignificance linkage between globalisation and carbon emissions but opposite to the study suggested by Shahbaz et al. (2015b), Sabir and Gorus (2019) and Jun et al. (2021) which showed the positive impact of globalisation on environmental pollution.

In order to provide more insights, we further disaggregate the CO_2 emissions by a source like CO_2 from coal, CO_2 from oil, and CO_2 from natural gas and examined the impact of lnREC, coal consumption (lnECCoal), lnTFP and globalisation. The results are reported in Table 7. In particular, in model 2, we examine the relationship between energy consumption from coal, lnTFP, globalisation, lnNREC and CO_2 emissions from coal (lnCO_2Coal) is found to be statistically significant and positive. A 1% increase in lnREC decreases carbon emissions from coal by 1.81% in the long run. Similarly, in the short run, it declines by 0.81%. Further, we found that coal consumption (lnECCoal) has a positive and significant impact on CO_2 suggesting that coal consumption is the key source of increasing the CO_2 emissions in top ten emitters. The possible reason could be that coal-burning energy plants are a major source of GHG emissions and air pollution. In addition to heavy metals and carbon monoxide like mercury, the consumption of coal emits sulphur dioxide a harmful substance associated with acid rain. As compared to other sources of energy, coal reserves appear to be the most abundant. However, in particular, due to their high pollution of SO_2 and toxic substances, they contribute to environmental degradation. These findings are consistent with Shahbaz et al. (2015c), Tiwari et al. (2013) and Ahmad et al. (2016). They found that increase in coal consumption leads to environmental degradation. Regarding the impact of total factor productivity, it is observed that lnTFP results to be statistically insignificant but has positive effects on CO_2 emissions whereas lnG is found to be statistically significant

Table 7 CS-ARDL estimation results

	Model 1		Model 2		Model 3		Model 4	
	Coeff	Prob	Coeff	Prob	Coeff	Prob	Coeff	Prob
Long term elasticities								
LnNREC	0.40***	0.00	…	…	…	…	…	…
LnREC	−1.81***	0.00	−1.81***	0.00	−1.21***	0.00	−1.29**	0.02
LnEC coal	…	…	0.25***	0.00	…	…	…	…
LnEC oil	…	…	…	…	0.30***	0.00	…	…
LnEC gas	…	…	…	…	…		0.18***	0.00
LnTFP	0.11***	0.00	0.02	0.96	0.31**	0.05	0.41***	0.00
LnG	−0.13	0.74	−0.08***	0.00	−0.30	0.31	0.22***	0.00
ECT	−0.62***	0.00	−0.54**	0.01	−0.26***	0.00	−0.84***	0.00
Short run elasticities								
Δ(LnNREC)	0.74***	0.00	…	…	…	…	…	…
Δ(LnEC coal)	…	…	0.43***	0.00	…	…	…	…
Δ(LnEC oil)	…	…	…	…	0.34***	0.00	…	…
Δ(LnEC gas)	…	…	…	…			0.35***	0.00
Δ(LnREC)	−0.81***	0.00	−0.81*	0.08	−0.21*	0.06	−0.29	0.59
Δ(LnTFP)	−0.19***	0.00	−0.24	0.59	0.41**	0.04	0.31	0.24
Δ(LnG)	−0.02	0.68	0.01	0.97	−0.12	0.45	−0.86	0.25
Obs	370	…	350	…	380	…	380	…
R-square	0.75	…	0.78	…	0.75	…	0.82	…

***, **, and * indicate rejection of null hypothesis at 1%, 5%, and 10% level of significance respectively

Table 8 Robustness check: FMOLS results

Variables	Model 1		Model 2		Model 3		Model 4	
	Coefficient	Prob	Coefficient	Prob	Coefficient	Prob	Coefficient	Prob
LnNREC	2.05***	0.00	…	…	…	…	…	…
LnREC	−1.10***	0.00	−0.01	0.25	−0.20***	0.00	−2.51	0.13
LnEC coal	…	…	0.98***	0.00	…	…	…	…
LnEC oil	…	…	…	…	0.88**	0.03	…	…
LnEC gas	…	…	…	…	…	…	1.00***	0.00
lnTFP	0.15***	0.00	0.02*	0.07	0.24***	0.01	1.65***	0.00
LnG	−0.05*	0.06	−0.03**	0.05	−0.12	0.17	1.28*	0.08

***, **, and * indicate rejection of null hypothesis at 1%, 5%, and 10% level of significance respectively

and harms carbon emissions. The importance of globalisation is revealed here in reducing the carbon emission from coal consumption. Hence, policy should be designed for the opening of the economy as per the developing countries is concerned. Most of the developing countries have the largest share of coal in the total energy mix, which is also emission-intensive. Therefore, policy for increasing the level of globalisation should be given due importance. This finding is in conformity with many recent studies like Shahbaz et al. (2016b) and Shahbaz et al. (2018b), showing an increase in globalisation reduces CO_2 emissions. Our empirical findings contradict the findings of the recent study done in the case of MENA countries by Gorus and Ali (2021), where they find that globalisation has a statistically significant and positive effect on CO_2 emissions.

Similarly, in model 3, we investigate the long-run relationship between CO_2 emissions from oil and its determinants. The results produced in Table 7 show that oil consumption (lnECOil) has a positive and significant impact on carbon emission from oil (lnCO_2Oil). In particular, a 1% increase in oil consumption leads to an increase in carbon emissions by 0.30%. This suggests that oil consumption is also one of the factors which degrade the environmental quality. This outcome may be due to the low oil prices which lead to more usage of oil consumption. As a result of decrease in oil prices, most producers and consumers introduce inefficient technologies to increase their manufacturing costs. This finding is again consistent with the existing literature by Ahmad et al. (2016) and Alkhathlan and Javid (2013) where they have found that coal, oil and gas consumption simulate the CO_2 emissions in the case of India. Our results show that the coefficient of lnREC is again negative and statistically significant which is similar to model 2. However, the magnitude is different. In particular, a 1% increase in lnREC reduces the CO_2 emissions from oil by 1.21%, whereas lnTFP is found to stimulate carbon emissions.[5] Further, globalisation does not have any significant impact on carbon emissions from oil. Similar relation can be noticed from model 4.

Overall, our findings show that disaggregated energy consumption from coal (lnECCoal) is less polluting than another source of energy in the top ten CO_2 emitters in developing countries. On the contrary, aggregate non-renewable energy consumption (lnNREC) is a top contributor to carbon emissions in these countries. In recent years, there is a greater importance of lnREC as one of the crucial solutions for reducing GHG emissions. This study enhances the understanding of this regard which shows the unambiguous role of lnREC in reducing carbon emission in the existing studies. Further, the results identified the use of a disaggregated dataset to reveal the influence of globalisation on different carbon emission sources. Hence, globalisation should be promoted across developing countries to reduce carbon emissions from different sources of fossil fuel energy consumption. After discussing the short and long run coefficients, we focus on coefficients of error correction term (ECT). The results produced in Table 7 indicates that ECT is found be negative and significant which confirms the long-run equilibrium for all the four models. In particular, for models 1 to 4, the speed of adjustment is −0.62, −0.054, −0.26 and −0.84, respectively. This empirical finding refers to an equilibrium process in the long run.

To check the robustness of our CS-ARDL results, we apply further FMOLS. The results are presented in Table 8 show that findings are consistent with CS-ARDL results. Hence, we can say that our results are robust irrespective use of the methodology.

To perform the panel causality among CO_2 emissions, renewable energy, non-renewable energy, total factor productivity and globalisation in the top ten carbon emitters among the developing countries at the aggregate and disaggregated levels, the Dumitrescu and Hurlin (2012) test is applied. The results of D-H panel causality test are summarised in Table 9. The empirical results show the Granger causality is running from lnNREC and lnREC to lnCO_2

[5] Since we have discussed the environmental effect of lnTFP on carbon emission in model 1, so we do not discuss here.

Table 9 Results of Dumiteterescu-Hurlin panel Granger causality test

	Null hypothesis	Stat	Prob
Model 1	lnNREC $\nRightarrow$ l nCO_2	3.91***	0.01
	lnCO_2 $\nRightarrow$ l nNREC	3.30	0.10
	lnREC $\nRightarrow$ l nCO_2	4.39***	0.00
	lnCO_2 $\nRightarrow$ l nREC	3.30	0.10
	lnG $\nRightarrow$ l nCO_2	3.42*	0.07
	lnCO_2 $\nRightarrow$ l nG	8.57***	0.00
	lnTFP $\nRightarrow$ l nCO_2	1.65	0.50
	lnCO_2 $\nRightarrow$ l nTFP	8.38***	0.00
Model 2	lnECCoal $\nRightarrow$ l nCO_2Coal	2.52***	0.00
	lnCO_2Coal $\nRightarrow$ l nECCoal	2.40***	0.00
	lnREC $\nRightarrow$ l nCO_2Coal	1.69	0.20
	lnCO_2Coal $\nRightarrow$ l nREC	4.08	1.00
	lnG $\nRightarrow$ l nCO_2Coal	3.52	7.00
	lnCO_2Coal $\nRightarrow$ l nG	4.08	1.00
	lnTFP $\nRightarrow$ l nCO_2Coal	1.41	0.47
	lnCO_2Coal $\nRightarrow$ l nTFP	2.97***	0.00
Model 3	lnECOil $\nRightarrow$ l nCO_2Oil	2.52***	0.00
	l nCO_2Oil $\nRightarrow$ l nECOil	2.90***	0.00
	lnREC $\nRightarrow$ l nCO_2Oil	2.39**	0.00
	l nCO_2Oil $\nRightarrow$ l nREC	1.53	0.34
	lnG $\nRightarrow$ l nCO_2Oil	3.45	1.00
	l nCO_2Oil $\nRightarrow$ l nG	7.02***	0.00
	lnTFP $\nRightarrow$ l nCO_2Oil	0.50	0.26
	l nCO_2Oil $\nRightarrow$ l nTFP	2.88***	0.00
Model 4	lnECGas $\nRightarrow$ l nCO_2Gas	1.88	0.13
	l nCO_2Gas $\nRightarrow$ l nECGas	2.42***	0.01
	lnREC $\nRightarrow$ l nCO_2Gas	8.92	4.00
	lnCO_2Gas $\nRightarrow$ l nREC	6.49***	0.00
	lnG does $\nRightarrow$ l nCO_2Gas	8.98	2.00
	lnCO_2Gas $\nRightarrow$ l nG	6.10***	0.00
	lnTFP does $\nRightarrow$ l nCO_2Gas	6.49***	0.00
	lnCO_2Gas $\nRightarrow$ l nTFP	7.62	1.00

***, ** and * indicate rejection of the null hypothesis at 1%, 5% and 10% level of significance. $\nRightarrow$ indicates does not cause

for model 1. We also find that unidirectional causality from lnCO_2 to lnG and lnTFP. For model 2, we noted the bi-directional Granger causality between lnECCoal and lnCO_2Coal. Further, we find that unidirectional causality running from lnCO_2Coal to lnTFP. In the case of model 3, results show the bi-directional causality between lnECOil to lnCO_2 Oil. However, the unidirectional causality is running from lnCO_2Oil to lnG and lnTFP. For model 4, we find unidirectional causality is running from lnCO_2Gas to lnECGas, lnREC and lnG. We also find a unidirectional casualty is running from lnCO_2Gas to lnTFP. Hence, we can conclude that energy consumption at aggregated and disaggregated levels causes environmental pollution, whereas globalisation mitigates while total factor productivity stimulates carbon emissions in developing countries.

Conclusions and policy implications

While the bulk of the studies examined the role of economic growth, trade openness and financial development on CO_2 emissions, studies on the link between renewable and non-renewable energy consumption, total factor productivity and globalisation and CO_2 at aggregate and disaggregated levels are scanty. By using the top ten carbon emitter countries' data for the period 1980–2018, this study adds to the existing literature with new policy insights by investigating the linkage between lnREC, lnNREC, total factor productivity, globalisation and CO_2 and CO_2 from coal, oil and gas. To do so, we first implemented the CIPS panel unit root test to check the stationarity of the variables. Second, we applied a panel cointegration test to find the long-run relationships among the variables. Third, once, we established the long-run relationships among the variables, we identified the short and long-run relationship between renewable energy consumption, non-renewable energy consumption, total factor productivity, globalisation and CO_2 by using the CS-ARDL test. Fourth, we used the Dumitrescu-Hurlin panel causality test to check the causation between the variables.

Empirical findings from the panel unit root tests showed that all variables contain the unit root except lnECOil and lnG. Results derived from panel cointegration tests exhibited the existence of the long-run relationship between CO_2 and renewable energy, non-renewable energy, globalisation and total factor productivity for all the models except model 4. Further, findings obtained from the CS-ARDL test showed that renewable energy consumption has a negative and significant impact on CO_2 emissions while non-renewable energy consumption significantly increases the CO_2 emissions both at aggregate and disaggregated levels. Our findings also showed that total factor productivity is positively linked to CO_2 emissions whereas globalisation decreases CO_2.

From this empirical work some findings and policy implications can be drawn. First, the results of CS-ARDL model indicate that non-renewable energy consumption promotes an increase in CO_2 emissions in the top ten carbon emitter countries among developing nations. This suggests that the policy must be implemented in such a way that it stimulates the use of renewable energy consumption. Further, our findings recommend that less dependency on non-renewable energy consumption can help in reducing CO_2 emissions. This can be done by increasing renewable energy consumption. In particular, off-grid energy solutions allow developing nations to embrace electrification and a low carbon pathway which can be achieved by emphasising more on renewable energy sources.

Secondly, it is evident from the findings that energy consumption from coal and oil is statistically significant and positive on the carbon emission. The top CO_2 emitter country among the developing economy highly depends on the consumption of energy for their fast-rising energy demand to meet their production and sustainable economic development in the country. Thus, from policy point of view, to improve the environmental quality without compromising the country's economic development, policymakers should focus on the disaggregated energy resources that help to identify a strategy for the best combination of sources of energy. Hence, the government of these countries can attain minimum carbon emissions with maximum economic growth by identifying the alternate source of energy such as coal. This is because according to empirical results, coal consumption is less polluting than other forms of energy resources which is favourable in improving environmental quality. For the next 20 years, coal will remain the primary source of energy whereas oil consumption reserves are vanishing at the rate of more than 4 billion tonnes a year (Ahmad et al. 2016). Energy demand needs to bring down by using efficient energy technologies that could significantly contribute to enhance the quality of the environment. Moreover, for the development of efficient and new technology, the policy makers can incentivise the business sector about training workers, managerial skills, new ideas and advanced innovations in domestic firms to further mitigate the carbon emissions and to enhance the economic growth of a country.

Thirdly, the empirical work reveals that total factor productivity increases environmental degradation in the long run. This implies that the TFP level does not permit the improvement in environmental quality. In this regard, government authorities of these countries should increase the technological capacity, and research and development activities in order to improve the efficiency of TFP (Amri et al. 2019). There is an urgent need to import and imitate advanced energy-saving technologies from developed countries. It can be done through technology transfer or foreign direct investment.

Lastly, globalisation in these economies has a negative impact on environmental quality. Globalisation invites international administration or organisation to set up new policies on the environment in order to mitigate GHG emissions and hence CO_2 emissions (Bilgili et al. 2020). One such example of the international organisation is the Kyoto protocol. It increases the technological capacity via technology transfer, competition, trade and foreign direct investment and decreases cross-border restrictions on the movement of labour, investment and trade by providing better management of environmental resources and efficiency in the long run. One might claim to be the technique effect of globalisation which helps in the reduction of CO_2 emissions in the top ten CO_2 emitters among developed economies.

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Declaration

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