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Research paper

The consumption-based carbon emissions effects of renewable energy and total factor productivity: The evidence from natural gas exporters

Fakhri J. Hasanov [a,b,c], Rashid Sbia [d,e], Dimitrios Papadas [f,*], Ioannis Kostakis [g]

[a] *Energy Macro and Microeconomics Department, King Abdullah Petroleum Studies and Research Center, P.O. Box 88550, Riyadh 11672, Saudi Arabia*
[b] *Research Program on Forecasting, Economics Department, The George Washington University, 2115 G Street, NW, Washington, DC 20052, USA*
[c] *Modeling Socio-economic Processes, Institute of Control Systems, 9 Bakhtiyar Vahabzadeh, Baku 1141, Azerbaijan*
[d] *International Monetary Fund, Kuwait*
[e] *Aix-Marseille University, AMSE, Marseille, France*
[f] *Department of Food, Land and Agribusiness Management, Harper Adams University, UK*
[g] *Department of Economics and Sustainable Development, School of Environment, Geography and Applied Economics, Harokopio University of Athens, Greece*

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ABSTRACT

This study first time explores the impact of total factor productivity, renewable energy, exports, imports, and income on carbon emissions in the Gas Exporting Countries Forum (GECF) nations. To ensure that the results are sound and policy insights are well-grounded, three main issues of panel data – cross-sectional dependency, heterogeneity, and nonstationarity – are addressed using cutting-edge methods. Moreover, a theoretically justified framework is employed, offering advantages such as considering a broad set of factors, which are actionable from a climate policy perspective, with dual benefits of emissions reduction and supporting clean growth. We find that total factor productivity, renewable energy, and exports reduce carbon emissions, while income and imports have an increasing effect. Policymakers in GECF countries may consider implementing measures to support technological advancements, efficiency improvements, increased use of renewable energy, expanded exports, and lowered imports. They can reduce emissions while promoting sustainable economic growth.

1. Introduction

Air pollution stands as the foremost contributor to environmental degradation and is a significant driver of global warming, presenting unparalleled challenges to humanity. The primary culprit behind air pollution is carbon dioxide (CO2), a major greenhouse gas emission.[1] Consequently, countries worldwide have instituted international and national initiatives to mitigate these emissions, including the Kyoto Protocol, the Paris Agreement, and the United Nations Sustainable Development Goals for 2030. A critical aspect of this endeavor involves identifying the link between air pollution and sustainability. These initiatives strive to foster a more sustainable future where economic growth is harmoniously balanced with ecological well-being.

As emission is a globally crucial topic, its investigation in each nation is important. This would provide a better understanding of its main drivers, which would help design adequate climate mitigation and adaptation policies. In this regard, natural gas-producing/exporting countries are no exception. The following points could further motivate examining CO2 emissions in these countries. *First*, these nations have considerable contributions to CO2 emissions. For example, only nine counties of the Gas Exporting Countries Forum (GECF), Bolivia, Egypt, Iran, Malaysia, Mozambique, Nigeria, Peru, Qatar, and Russia, hold about 10 % of the global CO2 emissions during 1990–2020, according to the World Bank data (WDI, 2023). This share has expanded since 2017. *Second*, emissions of the mentioned nations increase over time. CO2 emissions have continuously increased since 1999, although declines were recorded pre-1998. Numerically, they increased from 2148 million CO2 in 1998–2962 million CO2 in 2020 (WDI, 2023). *Third*, fossil fuel prices are considerably lower than the global average due to abundant fossil fuel resources, such as natural gas, in these nations. This can lead to three serious issues contributing to a further increase in emissions: inefficient use of fossil fuels, demotivation for using

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* Correspondence to: Harper Adams University, Newport, Shropshire, TF10 8NB, UK.
E-mail address: dpaparas@harper-adams.ac.uk (D. Papadas).

[1] We use CO2 emissions, emissions, and CO2 interchangeably throughout the paper.

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alternative sources of energy such as renewables because of the cost-effectiveness and demotivation for the adoption of energy-efficient technologies (Al-Iriani, 2006; Bianchini et al., 2023; Hasanov et al., 2023 inter alia). *Fourth*, projected growth in energy demand is mainly driven by expanding population and income/economic activity globally, especially in the developing world, where these GECF nations are included. For example, the International Energy Agency projects an average annual growth rate of 0.7 % to 2030 in total energy demand in the stated policies scenario and continuity in increase through to 2050 (IEA, 2023). It is also projected that the share of renewables in total final energy consumption will reach around 10 % only by 2050 in this scenario, meaning that large shares will still be occupied by fossil fuels – major sources of emissions.

Given the backdrop above, this work aims to examine the impacts on CO2 emissions of their main drivers in natural gas-exporting countries. We applied panel time series methods to the data of nine GECF countries over 1990–2020 in the theoretically grounded framework.

The main novelty of this study is that it is the first time the effects on CO2 emissions of their drivers have been investigated for the group of GECF countries, as we are unaware of any previous CO2 emissions studies conducted for these countries to our knowledge. Therefore, this study contributes to the CO2 emissions literature through its findings and policy insights for the GECF countries. Another novelty is that the theoretical framework we employed links consumption-based CO2 emissions to total factor productivity (TFP) and renewable energy (RE) in addition to income, exports, and imports. Hence, the framework offers four advantages over traditional frameworks, such as the Environmental Kuznets Curve (EKC): (i) it includes a broader set of factors in a theoretically grounded way; (ii) most factors are actionable from a climate policy implementation standpoint; (iii) an increase in TFP, RE, and exports have dual benefits for nations – emissions reduction and clean growth enhancing; (iv) it considers consumption-based CO2 emissions. It has been demonstrated that using territory-based CO2 as a measure of emissions could be misleading in assessing international trade-related mitigation efforts. In this regard, consumption-based CO2 is superior to territory-based CO2, as it accounts for global trade, i.e., exports and imports (Mózner, 2013; Knight and Schor, 2014; Liddle, 2018; Hasanov et al., 2018; Jiborn et al., 2018; Bhattacharya et al., 2020). The third novelty of the study is that it explores the group of GECF countries not only in a pooled way, like many studies did, but also, more importantly, in a country-specific manner. To this end, it provides an understanding of how the abovementioned factors impact CO2 emissions in each country, enabling us to propose country-specific recommendations. In addition, we employ state-of-the-art panel time series methods that allow us to address three main issues of the panel data - cross-sectional dependency, heterogeneity, and nonstationarity. It is essential to discover whether (i) there are common factors for the GECF countries, (ii) the relationship between CO2 emissions differs from country to country, and (iii) the relationship holds in the long run.

The rest of the paper is organized as follows. Section 2 briefly surveys relevant studies. Section 3 discusses the theoretical framework. Section 4 details the data, and Section 5 describes the econometrics techniques. Section 6 presents the results of the empirical study, while Section 7 discusses the empirical results. Finally, Section 8 concludes the research with some policy insights.

1.1. Literature review

It is important to note that, to the best of our knowledge, no previous CO2 studies have been conducted with a dedicated focus on the group of GECF economies. Hence, this section reviews the most recent studies on the impacts of renewable energy (RE), total factor productivity (TFP), international trade (TO), and income (GDP) on CO2 emissions at the international scale.

Several studies have investigated the CO2 emissions effects of RE (Namahoro et al., 2021; Olabi and Abdelkareem, 2022; Kostakis et al., 2023; Quang et al., 2023; Wang et al., 2023a), TFP (Altinoz et al., 2021; Lahouel et al., 2021; Hasanov et al., 2023; Yu and Du, 2023), often referred to as technological progress (Cheng et al., 2021), international trade (Liddle, 2018; Hasanov et al., 2018; Wang et al., 2024e), and economic growth (Debone et al., 2021; Li et al., 2022; Naveed et al., 2022) across different countries.

Most studies have confirmed a negative relationship between RE consumption and carbon emissions (e.g., Padhan and Bhat, 2023). In particular, numerous studies have demonstrated that adopting and utilizing RE technologies can substantially reduce CO2 emissions (Al-Mulali et al., 2015; Kim and Park, 2016; Khan et al., 2020; Dauda et al., 2021; Namahoro et al., 2021; Kostakis et al., 2023´Sadiq et al., 2023; Quang et al., 2023). Some studies have found a negative but statistically insignificant impact of RE consumption on air pollution (e.g. Hasanov et al., 2023). Although empirically, the impact of the former on the latter can be found statistically significant or insignificant depending upon countries, the period under study, and the methods considered, theoretically, Hasanov et al. (2021), among other studies, derive a negative effect. Similarly, Wang et al. (2023a) found that renewable energy consumption has a negative but heterogeneous effect on air pollution before and after EKC turning points.

Concerning TFP, previous empirical literature has explored the intricate relationship between TFP and CO2 emissions. Several studies have sought to unveil whether improvements in TFP, often indicative of technological progress and efficiency gains, reduce CO2 emissions (Álvarez-Herránz et al., 2017; Li et al., 2017; Mensah et al., 2018; Shahbaz et al., 2020; Altinoz et al., 2021; Cheng et al., 2021; Shi et al., 2023; Bianchini et al., 2023; Hasanov et al., 2019, 2023). These studies emphasize the potential of technological advancements to decouple economic growth from environmental harm, highlighting the crucial role of innovation and sustainable practices in addressing the global climate challenge. In the modern world, Artificial Intelligence (AI) plays an important role in developing nations. In this regard, AI can be considered a representation of TFP since it can improve technological progress and boost efficiency gains. Several recent studies investigated the impact of AI on carbon emissions and found that it can reduce emissions (Liu et al., 2022; Zhang et al., 2022; Ding et al., 2023; Dong et al., 2023; Zhong et al., 2024; Wang et al., 2023b; 2024a, 2024b, 2024c, 2024d). It is worth noting that the influence of TFP on CO2 emissions can vary depending on several factors, such as the level of economic development or the production structure of a country's economy.

The relationship between international trade and CO2 emissions has been explored in previous empirical literature (Al-Mulali and Sheau-Ting, 2014; Dogan and Turkekul, 2016; Liddle, 2018; Afesorgbor, and Demena, 2022; Li and Yanase, 2022; Hübler et al., 2022; Wang et al., 2024e). Numerous studies have researched this relationship from diverse perspectives, resulting in mixed or conflicting findings, confirming either the pollution paradise or the pollution halo hypotheses (Wang et al., 2023a). For instance, some research suggests that increased trade can lead to higher environmental degradation (Farhani et al., 2014; Mi et al., 2019; Ekwueme and Zoaka, 2020; Dauda et al., 2021; Azam et al., 2022; Kongkuah et al., 2022; Li and Haneklaus, 2022) due to the intensified transportation of goods and production in more carbon-intensive industries. On the contrary, others suggest that trade can also boost the adoption of cleaner and greener technologies and production processes, reducing emissions (Al-Mulali et al., 2015; Saud et al., 2019; Kostakis et al., 2023). Others find mixed or inconclusive results (Heil et al., 2001; Le et al., 2016; Udeagha and Breitenbach, 2023). Also, the disaggregation of the trade openness variable can provide valuable results (Jiborn et al., 2018; Khan et al., 2020; Shahbaz et al., 2020; Hasanov et al., 2018, 2019, 2023), as imports and exports might have a differentiated effect on air pollution. Overall, the literature highlights the complexity of this relationship and underlines the importance of considering multiple factors when analyzing the environmental consequences of international trade.

Finally, there are numerous studies examining the impact of income/economic growth and CO2 emissions in the literature (Li et al., 2024), emphasizing a positive correlation, indicating that as economies grew, so did their carbon emissions significantly in developing countries (Al-Mulali et al., 2015; Boukhelkhal, 2022; Sharif et al., 2023). Most of the research has investigated the idea of the EKC (Stern et al., 1996; Tamazian and Rao, 2010). Many researchers suggest decoupling economic growth and CO2 emissions is possible, mainly in advanced economies adopting cleaner technologies and more sustainable practices (Sarkodie and Strezov, 2019; Shahbaz et al., 2020; Naveed et al., 2022). Other studies (Al-Mulali et al., 2016) have found mixed results, while others support that the relationship between economic growth and CO2 emissions varies across countries (Azevedo et al., 2018). However, the previous scientific literature generally demonstrates a growing awareness of the need for sustainable economic development that minimizes ecological degradation, pointing toward a future where economic growth and environmental quality coexist.

In conclusion, many previous studies have neglected the joint effects on CO2 emissions of RE, TFP, international trade, and income. This work considers these joint effects as it may provide both scholars and policymakers with more accurate insights. In addition, some studies have explored the impact of many factors, including the ones mentioned above, on air pollution, but they have been conducted ad hoc and suffer from a lack of a theoretical framework.

1.2. Theoretical framework

This section introduces the theoretical framework we use in this study. The framework details, including theoretical derivations, are described in Hasanov et al. (2021). Therefore, we do not discuss them here for brevity purposes. Note that other researchers have used the framework to form their studies' theoretical or empirical models/specifications. Examples include Adebayo and Rjoub (2021), Dou et al. (2021), Wang and Li (2021), Ojekemi et al. (2022), Hassan et al. (2022), Gu (2022); Adebayo and Ağa (2022); JinRu and Qamruzzaman (2022), Mukhtarov et al. (2022), Durani et al. (2023), Balcilar et al. (2023), Hussain et al. (2023), Hasanov et al. (2023, 2024a), Jiang et al. (2023), Mukhtarov (2024), Shouwu et al. (2023), Liu et al. (2023). It links consumption-based CO2 emissions to Total Factor Productivity (TFP), Renewable Energy (RE), income, and international trade. In the panel data context and econometrically estimable form, it can be written as follows:

$$cco2_{it} = \alpha_0 + \alpha_1 m_{it} + \alpha_2 x_{it} + \alpha_3 re_{it} + \alpha_4 y_{it} + \alpha_5 tfp_{it} + u_{it} \tag{1}$$

Here, $cco2$ is the natural logarithmic expression of consumption-based CO2 emissions; m, x, re, y, tfp are the natural logarithmic transformation of import size, export size, renewable energy consumption, income, total factor productivity (TFP), respectively. u is the error term. $\alpha_1 - \alpha_5$ represent the elasticities of consumption-based CO2 emissions with respect to import size (M), export size (X), renewable energy consumption (RE), income (Y), and TFP, respectively. α_0 is the intercept, i.e., constant. t is the time dimension, taking $1, 2, 3, \ldots T$, i.e., the number of time series observations. i is the section dimension, taking $1, 2, 3, \ldots N$, i.e., number of panel members.

It is theoretically expected that $\alpha_1 > 0, \alpha_2 < 0, \alpha_3 < 0, \alpha_4 > 0, \alpha_5 < 0$. That is, consumption-based CO2 emissions are negatively influenced by the share of exports in GDP, renewable energy consumption, and total factor productivity (TFP). In contrast, income and the share of imports in GDP are expected to have a positive impact.

We added the appendix section to the paper to conserve space in the main text. Appendix A elaborates on the key factors, particularly TFP and RE of the framework above, and provides a graphical illustration of their structure and potential impact on CO2 emissions. Appendix B briefly introduces recently developed theoretical frameworks and models for CO2 emissions alongside the traditional EKC. It also compares the theoretical framework used in this study with those frameworks, highlighting its advantages and limitations.

1.3. Data

The data set used in this study is a balanced panel of the natural gas exporting economies, which includes the following nine countries: Bolivia, Egypt, Iran, Nigeria, Qatar, Russia, Malaysia, Mozambique, and Peru. The annual data were collected for the selected countries from 1990 to 2020. The availability of data dictates both the countries and time span. Table 1 records the variables' notation, definitions, measurement, and sources.

Carbon dioxide as a metric for carbon emissions offers several advantages. Firstly, it considers emissions from final consumption and purchases abroad (Wiebe and Yamano, 2016). This metric is adjusted to accommodate international trade, making it a convenient tool for identifying carbon emissions originating in one country but being consumed in another one (Peters et al., 2012). Our theoretical framework enables us to analyze the impact of international trade on CO2 separately, distinguishing between exports and imports, in contrast to previous studies that have combined them. Exports produced in the home country but consumed abroad are expected to affect consumption-based CO2 negatively.

Conversely, imports made in other countries but consumed domestically are expected to impact consumption-based CO2 positively (Knight and Schor, 2014; Hasanov et al., 2018; Liddle, 2018). Furthermore, renewable energy consumption is anticipated to reduce consumption-based CO2. GDP is recognized as a significant contributor to CO2 emissions, especially in developing economies, including the GECF countries, as a measure of income. Lastly, TFP (Total Factor Productivity), a measure of technological progress and innovation, can reduce CO2 emissions by promoting more efficient production methods and less energy-intensive technologies, as discussed in Appendix A.

Table 2 presents the descriptive statistics of the variables of interest for each country.

Fig. 1 illustrates how consumption-based CO2 emissions, renewable energy, and TFP variables evolve over the period under consideration in each country.

In brief, overall observations from the figure are that (i) consumption-based CO2 emissions demonstrate upward trends in all countries led by Russia and Iran; (ii) the shares of renewables in total energy consumption either stay relatively constant or decline with quite high shares in Mozambique, Nigeria followed by Peru and Bolivia; (iii) TFP exhibits either upward or downward, or relatively stable pattern depending on country under consideration with high levels in Qatar, followed by Egypt, Iran and Malaysia. In our empirical analysis of estimations and testing, we adhere to the specification provided in Eq. (1), and thus, all the variables mentioned above are expressed in their natural logarithm forms. We notate this with lowercase letters, for example, $cco2 = \ln(CCO2)$.

Table 1
Variables and their features.

Variable	Definition	Measurement	Sources
CCO2	CO2 emissions, consumption-based	Million tonnes	Global Carbon Atlas (2023)
TFP	Total factor productivity index	2017=100	Penn World Table (PWT, Feenstra et al., 2021)
RE	Renewable energy consumption	Percentage of the total energy consumption	WDI (2021)
X	Exports of goods and services	Percentage of GDP	WDI (2021)
M	Imports of goods and services	Percentage of GDP	WDI (2021)
Y	GDP per capita	Measured in Constant 2011 US Dollars	WDI (2021)

Table 2
Descriptive statistics of the variables.

Country	*RE*			*TFP*			*CCO2*		
	Mean	**Max**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**	**Min**
Bolivia	22.51	38.28	7.27	0.96	1.02	0.89	13.87	23.71	8.44
Egypt	6.99	9.83	5.10	1.13	1.37	0.98	164.11	259.99	78.31
Iran	0.98	1.53	0.44	1.04	1.22	0.86	410.98	658.45	202.39
Malaysia	5.32	11.98	1.96	0.99	1.08	0.89	153.82	250.16	65.53
Mozambique	88.41	94.30	77.12	0.93	1.21	0.58	7.92	18.53	1.92
Nigeria	84.90	88.68	79.94	0.85	1.10	0.63	77.27	132.80	33.84
Peru	33.55	41.23	24.15	0.98	1.05	0.89	42.56	66.95	23.64
Qatar	0.05	0.15	0.00	1.68	2.31	0.84	37.89	73.93	10.73
Russia	3.52	4.04	3.13	0.87	1.03	0.61	1290.99	2078.36	778.83
Panel	27.36	94.30	0.00	1.05	2.31	0.58	244.38	2078.36	1.92

Notes: Max and Min denote maximum and minimum values; each country has 31 annual times series observations, 1990–2020, for each variable.

1.4. *Econometric methodology*

The empirical analysis approach is driven mainly by the characteristics of the panel time series data, particularly cross-sectional dependence (CSD) and non-stationarity. Panel data often exhibit CSD effect, and failure to account for it can lead to significant estimation problems, such as inefficiency, inconsistency, and bias in estimates, as highlighted by Pesaran (2015a), Chapter 29, Baltagi, (2021), Sarafidis and Wansbeek, (2012); Sarafidis et al., (2009). Fig. 2 below illustrates a strategy for considering correct panel methods in the empirical analysis.

The flowchart guides the selection of first- or second-generation methods based on whether the data exhibit CSD, to test for unit roots and cointegration, followed by estimating long- and short-run relationships. It also shows that the pathways are selected depending on whether the variables are stationary, non-stationary, and cointegrated. The goal is to ensure that the chosen methods align with the data properties to avoid erroneous estimates.

1.5. *Cross-section dependence (CSD) tests*

The first step includes inspecting cross-sectional dependence (CSD) among the variables of interest, allowing us to employ the appropriate unit root tests, cointegration tests, and the necessary panel data estimators. It is anticipated that CSD will be found among gas-exporting countries due to their similar production structures and regulatory characteristics. The study utilizes advanced CSD tests to address this econometric issue. Pesaran (2015a) shows that assuming that the correlation between panel members is zero would be quite bold. Instead, allowing for some correlation between the members is more reasonable. This is especially true if we work with actual life data and do empirical research with policy insights rather than theoretical or methodological studies. Therefore, he advanced his Pesaran (2006) SCD test to Pesaran (2015a) SCD test, where now the null hypothesis is weak CSD instead of no SCD. Since Pesaran (2015a), his test has been modified in several directions. The examples include the developments by Juodis and Reese (2022), which made the SCD test more powerful in small samples and robust to heterogeneous errors, by Fan et al. (2015), allowing the test to identify strong dependencies more effectively and being adaptive to different forms of dependency, by Pesaran and Xie (2021) focusing on bias-correction, finite-sample performance improvement and being robust to structural breaks. To obtain more robust results and to be able to provide sound policy insights, we employ all the mentioned CSD tests, namely, Pesaran (2015a), Juodis and Reese (2022), Fan et al. (2015), Pesaran and Xie (2021), as they address characteristics of the panel data and account for various econometric issues discussed above.

1.6. *Panel unit root (PUR) tests*

The following step in the econometric analysis involves carrying out unit root tests to assess the stationarity of the variables. According to the literature, panel unit root tests are broadly classified into two generations (Pesaran, 2015b; Baltagi, 2021). First-generation tests assume cross-sectional independence across units, whereas second-generation tests relax this assumption. Fig. 1 illustrates that the second-generation PUR test should be used if the data under consideration demonstrate a strong SCD effect. Otherwise, the first-generation PUR tests can be employed. The present study utilizes both types of tests. The reason is that in the next section, we find evidence of both strong and weak CSD effects, although it is mainly about the former. As the second generation test, we employ the Pesaran (2007) cross-sectionally augmented Im-Pesaran-Shin (CIPS) test, which addresses the issue of cross-section dependence, and we use the Maddala and Wu (1999) test from the first generation.

1.7. *Panel cointegration tests*

After conducting panel unit root tests, the next step is to perform cointegration tests to determine whether the variables exhibit a long-term cointegrated relationship. Again, as we find evidence of strong and weak CSD effects in our data, distinct cointegration tests are utilized. The initial two tests, Pedroni (1999), (2004) and Kao (1999), apply to a panel, assuming no cross-section dependence. The third test, proposed by Westerlund (2007), employs four statistics: two for mean group analysis (Gt and Gα) and two for panel statistics (Pt and Pa) to assess cointegration and accounts for CSD if performed with bootstrapping or robust standard errors.

1.8. *Estimation methods*

Once a long-run equilibrium relationship between the variables is recognized, the econometric analysis applies various panel data estimation models. Our study utilizes first- and second-generation models, as we find strong and weak CSD effects in our data. The Fixed-effects and Between-effects methods from the first-generation estimators are the initial step followed by the Mean Group (MG) estimators developed by Pesaran and Smith (1995). Common Correlated Effect Mean Group (CCE-MG), and Augmented Mean Group (AUG-MG) are employed as the second-generation methods. The main advantage of the MG method over the Fixed-effects and Between-effects methods is that it estimates section-specific regressions for individual countries and averages the estimated coefficients to derive panel coefficients. The CCE-MG estimator developed by Pesaran (2006) considers the presence of unobserved common factors by including cross-sectional averages of the dependent and independent variables in the regression. It demonstrates robustness to non-stationarity, cointegration, breaks, and serial correlation. The AUG-MG approach, enhanced by Eberhardt and Teal (2010), serves as an alternative to the CCEMG method. However, this approach treats the unobservable common factors as a nuisance and sets accordingly.

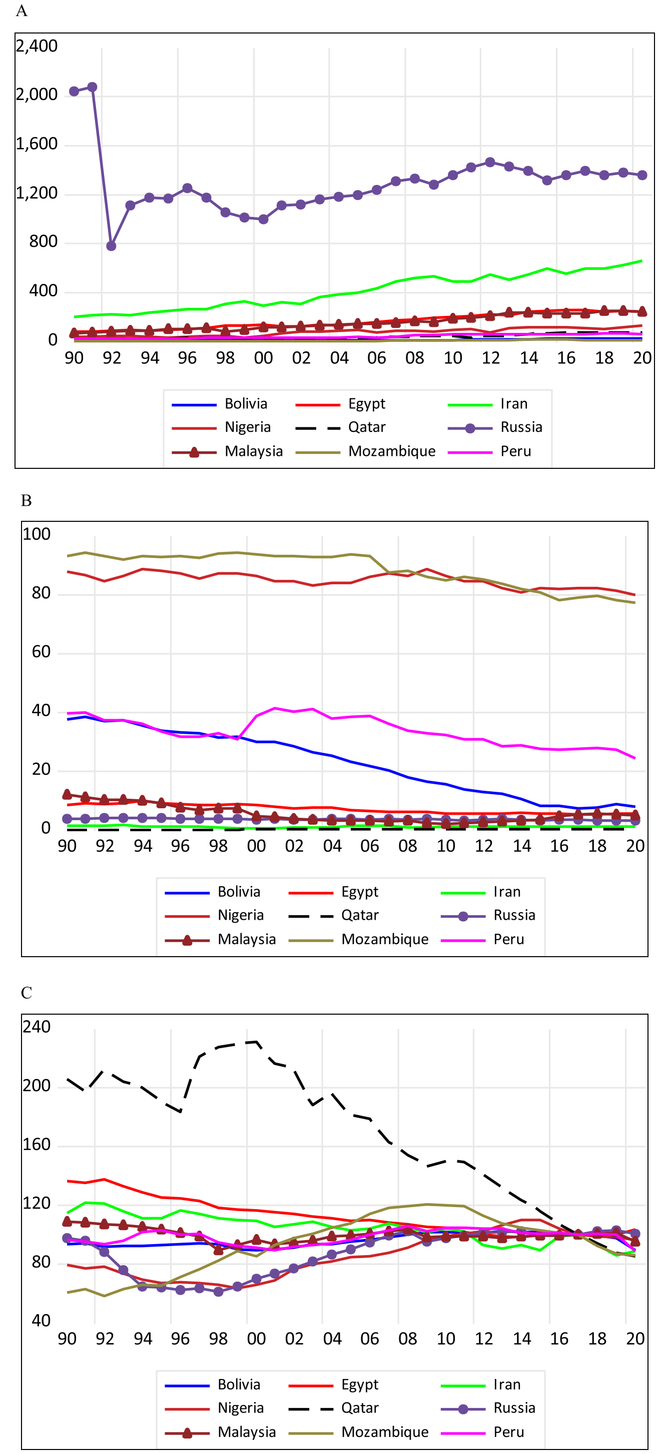

Fig. 1. Time trajectories of the variables Graph A. CO2 emissions, consumption-based, million tonnes Graph B. Renewable share in total energy consumption, % Graph C. Total factor productivity, 2017=100.

2. Empirical results

This section provides the results of the econometric testing and estimations. The first part covers the results of cross-section dependence, unit root tests, and cointegration tests, while the second part discusses the results of long-run estimations. Table 3 records results obtained from four recently developed cross-sectional dependence (CD) tests, namely, Pesaran (2015), Juodis and Reese (2022), Fan et al. (2015), and Pesaran and Xie (2021).

For *cco2*, *re*, *y*, and *e,* three out of four tests performed reject the null hypothesis of weak CD, favoring the alternative hypothesis of strong CD. For *tfp* and *m* only Fan et al. (2015) test rejects the null hypothesis. To this end, the key message from the table is that for unit root and cointegration tests of the variables and estimation of the *cco2* equation, methods accounting for the CD effect should be used to be on the safe side. At the same time, methods assuming cross-sectional independence can also be employed. Table 4 documents the results of the panel unit root tests developed by Pesaran (2007) and Maddala and Wu (1999).

Cross-sectionally augmented Im-Pesaran-Shin (CIPS) test by Pesaran (2007) decisively suggests the unit root process for all the variables. The null hypothesis cannot be rejected because none of the sample test values in the table is greater than the critical values in absolute terms. The same suggestion also comes from the Maddala and Wu (1999) test assuming cross-sectional independence if 1 % significance level is considered.[2] The results are satisfactory enough to conclude that the log level of the variables, i.e., *cco2*, *re*, *tfp*, *y*, *m*, and *e* are unit root processes. Regarding the first difference of the log levels of the variables, both tests profoundly reject the null hypothesis of unit root in favor of the alternative hypothesis of level stationary at the 1 % significance level. Thus, we can conclude that *cco2*, *re*, *tfp*, *y*, *m*, and *e* are integrated of order one, I(1) processes, meaning that they are unit root processes and their first differences are stationary.

The conclusion from the unit root testing supports whether the variables establish a long-run (cointegrating) relation among them. For this, we used the Westerlund (2007) cointegration test accounting for the CD effect as well as Pedroni (2004) and Kao (1999) tests assuming cross-sectional independence. Table 5 documents the results.

The sample values of the three statistics of the Pedroni test reject the null hypothesis of no cointegration in favor of cointegration at the 5 % significance level or even higher. This is the case for the five statistics of the Kao test as well. The Gt and Pt statistics of the Westerlund (2007) tests with and without bootstrapping also confirm cointegration among the variables. However, the other two statistics cannot reject the null hypothesis. It is well-known that Westerlund (2007) test statistics under-reject the null hypothesis if the data span is small, like our case here, as he discusses it in Westerlund (2007). In conclusion, it is reasonable to accept that the variables under consideration, i.e., *cco2*, *re*, *tfp*, *y*, *e*, and *m* are cointegrated.

Finding a cointegrating relation among the variables gives ground to estimate the *co2* equation, providing us with the long-run elasticities. Table 6 presents long-run estimation results from 1st and 2nd generation estimation methods. Including the results of the first-generation methods provides a comparison with those of the second-generation techniques. Also, more importantly, it shows how big or small the magnitudes of the coefficients are for the gas exporters if the CD effect is not accounted for in the period under consideration.

The table shows that regardless of whether the methods account for the CD effect, all yield theoretically expected signs for the variables (except for *tfp* from FE). In addition, the estimated coefficients are statistically significant in most cases.

We also provide long-run estimation results for each country in our sample in Table 7. As discussed in the Introduction section, it is essential to understand how and at what magnitudes consumption-based CO2 emissions are affected by their drivers in each country under consideration.

3. Discussion of the results

This section provides a discussion of the estimation and test results. According to Table 3, the variables under consideration are correlated

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[2] If the 5 % or 10 % significance level is considered, the test still suggests the unit root process for all the variables, except for exp, which seems to be a trend-stationary variable, which is another type of non-stationarity.

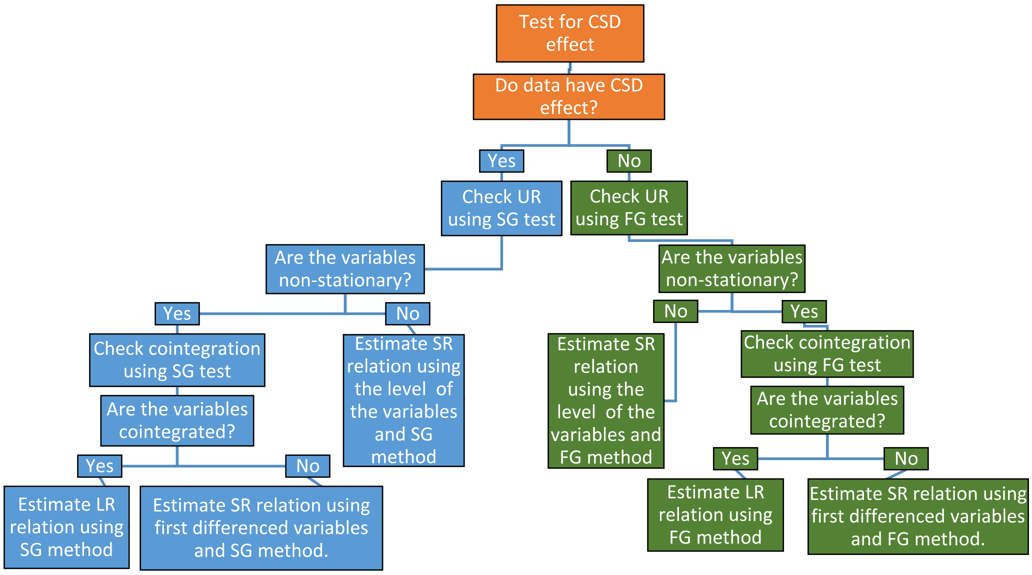

Fig. 2. Empirical Analysis Strategy. *Note:* CSD=cross sectional dependence; UR=unit root; SG=second generation; FG=first generation; LR=long-run; SR=short-run. Source: Re-produced from Hasanov et al. (2024a).

Table 3
The results of the CD tests.

Variables	Pesaran (2015)	Juodis and Reese (2021)	Fan et al. (2015)	Pesaran and Xie (2021)
cco2	24.52***	4.16***	151.25***	0.55
re	10.46***	9.65***	108.08***	2.88***
tfp	0.58	−0.52	110.53***	0.44
y	31.47***	6.55***	195.38***	−1.90*
x	8.50***	0.15	63.09***	1.92*
m	−0.75	−1.26	42.25***	1.42

Notes: *, **, and *** indicate rejection of the null hypothesis of weak CD in favor of the alternative hypothesis of strong CD at the 1 %, 5 %, and 10 % significance levels, respectively.

Table 4
The results of the 1st and 2nd generation panel unit root tests.

	Level		First difference	
Variables	CIPS	MW	CIPS	MW
cco2	−1.264	9.254	−7.954***	250.386***
re	1.897	14.124	−5.994***	126.929***
tfp	−0.094	16.880	−3.025***	71.739***
y	0.949	15.826	−3.241***	51.267***
e	−1.054	30.176**	−6.208***	182.175***
m	0.450	11.209	−6.295***	108.679***

Notes: *, **, and *** indicate rejection of the null hypothesis of unit root in favor of the alternative hypothesis of (trend) stationarity at the 1 %, 5 %, and 10 % significance levels, respectively. Maddala and Wu (1999) test, denoted by MW assumes cross-section independence. Pesaran (2007) test denoted by CIPS assumes cross-section dependence in the form of a single unobserved common factor. The equations of both the tests include intercept and time trend in testing the log level of the variables, while they include intercept only for testing the first difference of the log levels. This is based on the statistical significance of the mentioned determinist regressors. The lag order of two is selected in both tests to remove serial correlation issues in the residuals of the test equations.

across the natural gas exporters in our sample. In addition, the correlation is more substantial for income, renewable energy, consumption-based CO2 emissions, and exports than TFP and imports. Such cross-country dependence on a given variable can happen due to the existence of observable and unobservable factors that are common for these gas exporters. Examples of such factors include but are not limited to the following: globalization of the national economies, spillover effect of technologies and efficiency measures as developing economies try to catch up with advanced economies, international economic linkages including trade, capital and investment flows, commodity and particular energy prices at the global markets, shocks and recessions in large economies that have global impact, being a member of unions or groups, where members follow the same decisions and act together, such as G20, OECD, OPEC (see discussions in Pesaran,2015b, chapter 29; Baltagi and Pesaran, 2007; Baltagi, 2021).

In particular for the natural gas exporters, such common factors include the international price of natural gas, global demand for natural gas and its supply, available technologies for extracting natural gas, climate policies, and transition to green energy, including renewables. For example, the cross-country correlation of CO2, i.e., the dependent variable of our study, is evident, most probably due to the latter two factors mentioned above. Regarding renewable energy and TFP, the two main variables of interest are the following: the former demonstrates a strong correlation across the countries, while the latter does not. This might imply that global calls by the United Nations or other international agencies for climate mitigation policies and green energy transition are considerably influential for our sample countries. For example, all our sample countries are developing nations; hence, they all follow or adopt renewable and emission-reduction technologies and policies from advanced economies. However, it is not a strong case for the TFP in our sample countries. This might imply that mostly country-specific factors have influenced the TFP evolvements of our sample countries. In other words, local factors dominate technological progress and efficiency gains – the two main components of TFP in these sample economies. A stronger correlation for exports but not imports might imply that common factors are more critical for the former but not so much for the latter. This interpretation seems reasonable given that, at least for natural gas exports, these countries collaborate by following the GECF strategy.

Note also that the common factors listed at the beginning of this section are observable. Still, there may also be unobservable or latent factors causing dependence on a given variable across the natural gas exporters. In this regard, another common factor, and perhaps directly unobservable, for our sample countries is the impact of the union they established called Gas Exporting Countries Forum-GECF (https://www.gecf.org). The union, i.e., the forum, is for a course of collective actions for common interests, among other duties.

Table 5
The results of the 1st and 2nd-panel cointegration tests.

Pedroni (1999, 2004) **with constant and trend**					
Statistics	Modified PP t	PP t	Augmented DF t		
Sample value	1.923**	−2.950***	−2.240**		
p-values	0.027	0.002	0.013		
Kao (1999) **with constant**					
Statistics	Modified DF t	DF t	Augmented DF t	Unadjusted modified DF t	Unadjusted DF t
Sample value	−3.201***	−3.408***	−2.424***	−5.893***	−4.328***
p-values	0.001	0.000	0.008	0.000	0.000
Westerlund (2007) **without bootstrap**					
Statistics	Gt	Ga	Pt	Pa	
Sample value	−3.365**	−8.880	−9.387**	−11.325	
p-values	0.012	0.987	0.018	0.498	
Westerlund (2007) **with bootstrap**					
Statistics	Gt	Ga	Pt	Pa	
Sample value	−3.365**	−8.880	−2.098*	−0.004	
p-values	0.050	0.200	0.100	0.200	

Notes: *, **, and *** indicate rejection of the null hypothesis of unit root in favor of the alternative hypothesis of (trend) stationarity at the 1 %, 5 %, and 10 % significance levels, respectively. Pedroni (1999), (2004) and Westerlund (2007) cointegration tests were performed with intercept and trend and with intercept, respectively. This was dictated by the statistical significance of the deterministic components in the test equations; Kao (1999) test was done with constant as it cannot accommodate trend. DF=Dickey-Fuller; PP=Phillips-Perron.

Table 6
Long-run estimations from the 1st and 2nd generation methods.

Regressor	*re*	*tfp*	*y*	*e*	*m*	*DC*
FE	−0.198**	21.513	0.698***	−0.256*	0.424*	*c*
	(0.080)	(13.977)	(0.086)	(0.126)	(0.222)	
BE	−0.301	−58.651	0.884**	−0.326	0.412	*c*
	(0.164)	(116.179)	(0.184)	(0.515)	(0.576)	
MG	−1.354**	−90.070*	1.414***	−0.262**	0.242**	*t*
	(0.657)	(52.216)	(0.420)	(0.128)	(0.121)	
CCE-MG	−1.194*	−14.272	0.702***	−0.429***	0.257*	*c*
	(0.731)	(31.581)	(0.270)	(0.147)	(0.136)	
AUG-MG	−1.134**	−113.879**	1.457***	−0.323**	0.201*	*t*
	(0.581)	(49.223)	(0.396)	(0.145)	(0.113)	

Notes: The dependent variable is *cco2*. *, **, and *** indicate rejection of the null hypothesis of no statistical significance at the 1 %, 5 %, and 10 % significance levels, respectively. FE, BE, and MG denote Fixed-effects, Between-effects, and Mean Group, respectively. CCE and AUG mean Common Correlated Effect and Augmented, respectively. DC stands for deterministic components, i.e., constant (c) and constant and time trend (t). The inclusion of the time trend in the estimations was based on its statistical significance. We did not exclude constant if it is statistically insignificant because it is hard to assume that CCO2 initial level is zero during the period under consideration. Number of observations = 31 (Time series observations) x 9 (Number of countries) = 279.

Table 7
Country-specific long-run estimates from the AUG-MG method.

	re	*tfp*	*y*	*e*	*m*
Bolivia	**−0.73**	**−189.00**	**1.97**	**−0.12**	**0.21**
	[0.00]	[0.17]	[0.04]	[0.48]	[0.43]
Egypt	**−0.11**	**−86.80**	**0.94**	**−0.29**	**0.25**
	[0.63]	[0.01]	[0.04]	[0.00]	[0.06]
Iran	**−0.02**	**−96.89**	**1.44**	**−0.09**	**−0.13**
	[0.72]	[0.03]	[0.00]	[0.13]	[0.04]
Malaysia	**−0.18**	**−0.16**	**0.67**	**−0.93**	**0.82**
	[0.00]	[1.00]	[0.01]	[0.00]	[0.01]
Mozambique	**−1.92**	**−6.98**	**1.54**	**−0.14**	**0.44**
	[0.36]	[0.93]	[0.08]	[0.50]	[0.05]
Nigeria	**−5.50**	**−455.16**	**4.14**	**−0.01**	**0.08**
	[0.00]	[0.08]	[0.06]	[0.93]	[0.53]
Peru	**−0.44**	**−135.78**	**1.51**	**0.11**	**0.12**
	[0.05]	[0.15]	[0.01]	[0.41]	[0.58]
Qatar	**−1.04**	**48.42**	**−0.21**	**−1.18**	**0.38**
	[0.21]	[0.02]	[0.31]	[0.00]	[0.08]
Russia	**−0.26**	**−102.57**	**1.11**	**−0.25**	**−0.36**
	[0.19]	[0.04]	[0.00]	[0.00]	[0.00]

Notes: The dependent variable is *cco2*. P-values are in brackets. Sample period 1990–2020. Constant and trend were included in the regressions, but not reported here for brevity.

The unit root process, i.e., non-stationarity, suggests that the variables continuously drift over time and do not return to their previous mean value, and the mean value changes through the sub-samples of the entire sample. Any disturbance or shock to such drifting variables can have a lasting impact. Predicting future values of these variables is challenging due to the changing average and the permanent effects of shocks. It is usually recommended to employ a stationary transformation of the variables to address this issue when making predictions. The mean values (also covariance and covariance) of stationary series do not change noticeably over time, as they fluctuate around their mean values. These stationary series are known as mean-reverting processes because they tend to revert to their mean values. The cointegration test results showed that consumption-based CO2 has a long-run relationship with renewable energy consumption, TFP, GDP, exports, and imports. In other words, consumption-based CO2 shares a common trend with these variables, and they move together, establishing an equilibrium relationship in the long run. Another interpretation of cointegration is that the relationship among (the logarithmic levels of) the variables is not a chance occurrence, i.e., spurious; instead, it aligns with economic or environmental theories. Consequently, the long-run coefficients can be estimated and used for (policy) analysis and projections.

To this end, we first estimated the long-run effects of the explanatory variables on CO2 emissions in a pooled manner. The results are outlined in Table 6. Rows 2–4 report the estimation results from the Fixed-effect, Between-effects, and Mean Group methods, where the CSD effect is ignored, i.e., cross-sectional independence is assumed. At the same time, the estimation results in the last two rows are from the Common Correlated Effects Mean Group and Augmented Mean Group, accounting for the CSD effect. The estimated coefficients from the Fixed-effect and Between-effects are quite different from those in the last two rows, particularly regarding renewable energy, TFP, and imports. This might be because of the CSD effect. Put differently, ignoring the CSD effect may lead to over-estimated impacts of the mentioned explanatory variables on consumption-based CO2 emissions.

For interpretation of the estimation results, one may prefer the results from the Augmented Mean Group method to those from the other techniques, as it provides statistically significant estimates for explanatory variables with theoretically expected signs. In this regard, we also reported country-specific estimated results from the Augmented Mean Group method. Findings show that a **1 %** increase in renewable energy share in total energy consumption reduces the consumption-based CO2 by **1.1 %** in the long run ceteris paribus for the panel of the countries. The interpretation of this finding is relatively straightforward – an increase in the percentage of renewable energy in total means a decrease in the share of fossil fuel energy, leading to a reduction in CO2 emissions. This result aligns with several previous studies (Quang et al., 2023; Wang et al., 2023a; Mukhtarov, 2024). Turning to the country-specific results, the first observation is that the elasticity of consumption-based CO2 concerning renewable energy share in total energy consumption is negative for each of the nine gas exporters, as theoretically expected (see Section 3) with different statistical significance levels. The elasticities vary from a minimum of −5.5 in Nigeria to a maximum of −0.02 in Iran. Renewables' shares might explain the obtained magnitudes of the elasticities in total energy consumption in these two countries. Numerically, the share is 84.9 % in Nigeria, whereas it is only 1 % in Iran on average during the study's sample period, 1990–2020. This explanation also seems to hold for Bolivia, Peru, and Malaysia (but not Qatar), as they also have elasticities with relatively large to moderate sizes and a large share of renewable in total energy consumption.

Regarding the results for our second explanatory variable of interest, that is, TFP, for the panel of the countries, the estimation results show that to reduce consumption-based CO2 emission (Shahbaz et al., 2020; Altinoz et al., 2021; Hasanov et al., 2023) by **1 %**, TFP should be raised by **0.01 %**. The country-specific estimation results for the TFP effect are similar to those of renewable energy – the theoretically expected negative signs for all countries (except for Qatar) with diverse magnitudes at different significant levels. One worth pointing out is that the TFP elasticities of emissions are more significant than those concerning other variables. This finding might imply that levels of technological progress and efficiency gains in the GECF nations are low on average.[3] We will discuss this point below.

Numerically, TFP elasticities range from as low as −455 in Nigeria to as high as −0.16 in Malaysia. This diversity in the estimated elasticities across the countries is in line with the fact that countries with larger elasticities usually have underdeveloped climate and innovation policies, whereas countries with smaller elasticities have more developed policies. The sizeable negative elasticity of TFP concerning CO2 emissions is estimated for Nigeria, Bolivia, Peru, and Russia. It can be explained as follows. Prevailing technological progress and efficiency gains are low; hence, even small improvements yield considerable emissions reductions.[4] Indeed, Graph C of Fig. 1 illustrates that these four countries have lower TFP levels than other countries in the sample.

Quite small-size negative TFP elasticities estimated for Malaysia, Egypt, and Qatar can be attributed to the following features. First, countries with advanced innovation policies and technologies have already benefited mainly from this regarding emissions reductions. These countries usually have already adopted energy-efficient technologies, clean energy sources, and advanced industrial practices. Second, their marginal gains are smaller than those of other countries because they are already more technologically advanced. Put differently, they are characterized by diminishing returns to technological progress and efficiency gains. Therefore, additional TFP improvements lead to smaller incremental reductions in CO2 emissions.[5] In contrast, countries starting from a lower technological base experience more considerable reductions because they have more room for improvement. Thus, the smaller elasticity indicates that while TFP still contributes to emissions reductions, the marginal effect is negligible because the country is already relatively efficient in using resources and technology.

In the case of Qatar, the estimated positive elasticity of TFP, which is expected to be negative theoretically, can be attributed to the rebound effect and economic expansion. Developed innovation policies improve energy efficiency, which may trigger more energy consumption. In addition, these policies can boost economic activities, which consume more energy, including fossil fuels. For instance, technological advancements might improve the efficiency of natural gas production in Qatar, leading to rising production and exports, which can cause an expansion in economic activities that offset the potential emissions reductions from improved efficiency. Indeed, these explanations are supported by the data, as Graph C of Fig. 1 illustrates that Qatar's TFP level was the highest for most of the part of our time span.

A **1 %** increase in GDP leads to a **1.46 %** rise in the consumption-based CO2 in the long run (Boukhelkhal, 2022; Sharif et al., 2023) when the pool of natural gas exporting countries is considered. This might imply that the countries considered are pollutive as the elasticity is elastic. The country-specific estimation results also support this interpretation, as the estimated long-run GDP elasticities of CO2 are higher than unity in Bolivia, Iran, Nigeria, Russia, Mozambique, and Peru - six out of nine countries. It is slightly less than unity for Egypt and 0.67 for Malaysia (for Qatar, it is −0.21, but not statistically significant). The positive impact of income on CO2 emissions is consistent with the theoretical framework in Section 3 of this paper. The positive effect of CO2 emissions on income is also in line with other environmental theories, such as the STIRPAT and the EKC - a growth in economic activities requires more consumption of intermediate and final goods and services, leading to more CO2 emissions. The literature discusses this theoretical articulation primarily for developing economies (Dinda, 2004, 2005), such as the countries we considered in this research. To this end, our interpretation of the elastic income elasticity is that in these natural gas exporters, technologies to produce goods and services are mainly pollutive and not environmentally friendly. In addition, rules, legislation, and policies for climate mitigation are not in place or strictly followed by the economic activity sectors, while environmental awareness programs are not well disseminated.

Lastly, we estimate that a 1 % increase in exports and imports (as their shares in GDP) causes 0.32 % decrease and 0.20% rise, respectively, in the consumption-based CO2 emissions in the long run if the pool of the countries is considered. Exports' elasticity, being more significant than imports' elasticity in absolute terms, shows that exports lower consumption-based CO2 emissions more than imports can increase in the natural gas exporting economies considered here. If the individual countries are considered, the estimated export elasticities of

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[3] The opposite is also true – in advanced economies, where TFP level is very high, such elasticties are mostly lower than unity (e.g., see Hasanov et al., 2024a, Table 6 for pooled elasticity and Table A1 for country-specific elasticities)

[4] This case can be illustrated at the initial steep part of the logarithmic curve, where a slight increase in the explanatory variable leads to a large decrease in the explained variable.

[5] For instance, suppose a given country has already optimized its energy systems and implemented cutting-edge technologies, then each additional increase in TFP will lead to smaller relative reductions in emissions because the energy system is already close to its optimal efficiency.

the CO2 emissions are primarily negative and statistically significant, ranging from -1.18 in Qatar to -0.09 in Iran. As theoretically expected, the import elasticities are also primarily statistically significant but positive. Interpreting the obtained results does not require much discussion as our dependent variable is consumption-based CO2 emissions. In other words, the variable is negatively related to exports and positively associated with imports by definition.

In conclusion, this study sheds light on the intricate relationships among TFP, renewable energy use, and CO2 emissions and underscores the necessity of a multifaceted approach to energy policy in GECF countries. Integrating technological advancements, socio-economic considerations, and robust governance frameworks is essential for achieving sustainable development and addressing the pressing challenges of climate change. By adopting these insights, policymakers can better navigate the complexities of energy transitions while fostering economic resilience and environmental sustainability.

This study recognizes several limitations that may affect the findings. Unobserved variables, such as socio-economic factors, cultural attitudes toward renewable energy, and regional environmental policies, could significantly influence the relationships between Total Factor Productivity (TFP), renewable energy use, and CO2 emissions. Furthermore, accurately measuring TFP is challenging due to data quality concerns and the difficulty in isolating the impact of technological advancements from other economic factors. These issues may create uncertainty in TFP estimates and, consequently, the conclusions regarding its influence on CO2 emissions. While the findings offer valuable insights, they should be interpreted cautiously. Future research should consider additional unobserved factors affecting CO2 emissions and aim to refine TFP measurement methods to understand better the connections between economic growth, technological advancement, and environmental sustainability.

4. Conclusion and policy insights

To our knowledge, this is the first study examining the relationship between consumption-based CO2 emissions and renewable energy, total factor productivity, income, exports, and imports in natural gas exporters. We applied recent panel time series techniques using a theoretically coherent model of carbon dioxide emissions. Our empirical findings are consistent with theoretical expectations and can provide some insights into the emission mitigation policies in the GECF countries.

Empirical findings highlight the pivotal role of renewable energy in reducing consumption-based CO2 emissions. It is encouraging to find that the emission reduction feature of renewable energy consumption holds consistently across all nine gas-exporting countries. Furthermore, our study underscores the significance of improving total factor productivity in reducing environmental degradation. However, it is essential to note that the magnitudes of TFP's effect vary among countries, reflecting disparities in economic structures and their development levels. Also, economic growth was found to affect CO2 positively. From the policy-making standpoint, it would be nonsense to suggest lowering GDP as its growth leads to more CO2 emissions. Instead, decoupling strategies could lead to a higher environmental quality without punishing economic growth. Also, the findings reveal that an increase in exports size leads to a decrease in CO2 emissions in the long run, while an increase in imports size results in a rise in emissions.

Keeping in mind these empirical findings, the present empirical study can offer several policy recommendations to limit air pollution and enhance environmental quality with natural gas exporting economies. First, these countries should aim to increase the share of renewable energy sources, such as solar, wind, and hydro, in total energy consumption as a pollution mitigation policy measure. These strategies could position the GECF economies on the pathway to environmental sustainability. This would also have other benefits, such as strengthening the security and sustainability of energy supply. Moreover, increasing the share of renewables in domestic energy consumption would save the use of natural gas as an energy source. This brings opportunities, such as exporting the saved natural gas to gain additional revenues that can be used for financing renewable energy generation projects and other pollution mitigation projects. Alternatively, saved natural gas could be used as feedstock for the (further) development of the domestic petrochemical industry. It is well known that development in renewable energy technologies would positively spill over overall economic development by creating direct and indirect jobs, demand for other goods and services sectors, and innovation.

Second, governments may consider investing and financing innovative projects, start-ups, research and development and modern AI-based activities that can lead to technological progress and efficiency gains – the two main components of TFP. This policy would bring double advantages as TFP can boost economic growth while reducing carbon emissions. In addition, measures leading to efficiency gains may be considered. In particular, efficiency and saving on fossil fuel consumption appear important in emissions reduction. One of the direct ways of doing it for policies is liberalizing fossil fuel prices and removing subsidies. In this regard, countries in our sample have implemented domestic energy price reforms. Future reforms can be considered, but they should come with mitigation/support measures for low-income households and strategic economic activity sectors. The experiences of oil-producing developing countries (e.g., Saudi Arabia) can be learned for such mitigation measures. At the same time, it is well known that Artificial Intelligence (AI) represents a high percentage of TFP as it improves both technology and efficiency and can contribute to even lower carbon emissions (Liu et al., 2022; Wang et al., 2023b; 2024a,b,c,d).

Third, countries' authorities may wish to restructure their economies by prioritizing less pollutive economic activities, such as services, over fossil fuel energy-intensive sectors. In other words, economic growth decoupled from environmental degradation represents a pathway for reducing CO2 emissions while pursuing sustainable development. Principal strategies include energy efficiency and transition, circular economy practices, and sustainable consumption patterns. Decoupling allows sectors to meet production demand with fewer associated emissions, which means countries can march toward their climate targets without sacrificing economic stability. The urgent need to reduce emissions is met, and long-term economic resiliency and environmental health are promoted.

Fourth, policymakers should promote export-oriented industries and trade patterns prioritizing environmental sustainability. These measures can reduce their carbon emission locally, but globally, they will increase environmental pollution in importing countries, resulting in no mitigation for global emission reduction. Also, climate change policies and commitments are highly expected to push countries towards imposing high tariffs on carbon-contained goods and services, which implies that natural gas exports may decrease. Alternatively, these countries may consider increasing exports of goods with less or no carbon content in the future. Officials should be aware that further increases in imports might not be environmentally friendly. At the same time, policymakers have different options to mitigate the negative effect of imports on the environment. For instance, expenditure-reducing policies aim to decrease the level of domestic demand. The imports will fall, and as a consequence, emissions will fall. Also, expenditure-switching policies aim to reorient consumer spending towards domestic goods that are environmentally friendly. Also, there is a strong institutional and legal framework. The goal is incentivizing local consumers to import less or no carbon-content goods. This goal could be achieved by imposing high tariffs and duties. It will contribute to the diversification of the domestic economy with a higher share of clean production and consumption. The topic of diversification is vital for natural resource-rich countries to rely on fossil fuel windfalls. Finally, implementing strict environmental regulations and promoting best practices in the consumption of resources, including fossil fuel energy in households and economic activities, could help reduce carbon emissions.

More generally, promoting technological advancements, enhancing efficiency, and expanding renewable energy use are critical goals for GECF countries. However, achieving these goals requires navigating significant socio-economic and political obstacles. Many GECF nations, such as Nigeria and Mozambique, struggle with financial limitations due to their heavy dependence on natural resource exports and vulnerability to fluctuating commodity prices. To address these challenges, they must seek international financial support, foster public-private partnerships, and tap into climate funding to support green technology and renewable energy initiatives. Additionally, political instability in nations like Nigeria and Iran can hinder consistent policy implementation, highlighting the importance of establishing strong governance structures to ensure continuity even during political upheaval. Furthermore, shifting toward renewable energy in economies heavily reliant on fossil fuels presents social hurdles, particularly regarding employment. Countries like Qatar and Russia depend on the fossil fuel industry to sustain jobs and economic stability. To manage potential public resistance, policymakers must adopt transition frameworks focusing on retraining workers and creating new employment opportunities within the renewable energy sector. Economic diversification and investment in social safety nets will also be crucial to minimizing the social impacts of the energy transition. A final challenge is the issue of energy subsidies. Many GECF countries provide subsidies to keep fossil fuel prices low domestically, but removing these subsidies to promote cleaner energy sources could lead to public backlash and inflationary pressures. A gradual approach to subsidy reform, paired with social protection measures for vulnerable groups, will be critical. Learning from other examples, such as Saudi Arabia's gradual reduction of subsidies and introduction of cash transfer programs, can provide valuable guidance. Ultimately, the successful implementation of these policies will depend on international collaboration, strong governance, social support systems, and carefully managed reforms, given the complex socio-economic and political contexts of GECF nations.

Nevertheless, we should also acknowledge some potential shortcomings that could be addressed by future research. First, it is critical to note that environmental degradation is a complex issue and cannot be fully captured by a single indicator. Thus, creating an index that pools many indicators could be beneficial. Second, future empirical studies may include the role of policy instruments, such as carbon pricing or subsidies for renewable energy projects and alternative technologies. Policy instruments could play a key role in mediating energy use and carbon emissions. Several macroeconomic and financial-industrial production indicators can also be included, as they can affect carbon prices and air pollution as threshold variables. Another research project could investigate the potential existence of asymmetry among the variables.

CRediT authorship contribution statement

Fakhri J. Hasanov: Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Ioannis Kostakis:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Dimitrios Paparas:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Rashid Sbia:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization.

Authors' contribution

All authors contributed equally.

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The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Detailed Description of the Theoretical Framework

The literature discusses that EKC, the most widely used framework for the analysis of emissions, showed several limits, notably from a policy standpoint, as it considers income and population being the main determinants (Tisdell, 2001; Ezzati et al., 2001; Dinda, 2004, 2005; Brok and Taylor, 2010; Hasanov et al., 2021; Berk et al., 2022; Hasanov et al., 2023). Since both determinants can positively impact emissions (mainly in developing nations), their usage to make practical climate policy recommendations is quite restricted.[6] In this regard, the framework described in Section 3 has certain advantages. *First*, it theoretically links emissions to a broader set of factors than just two factors: Renewable Energy (RE), Total Factor Productivity (TFP), exports, imports, and income. *Second*, the first four factors are mostly actionable for making useful climate policy recommendations. *Third*, the factors of RE, TFP, and exports that the framework considers theoretically have dual benefits – emissions reduction and growth promotion. Hence, this framework can provide useful insights for policymakers in designing economic growth-friendly emissions reduction strategies. *Fourth*, the framework considers consumption-based CO2 emissions. The consumption-based measure is adjusted for exports and imports. Therefore, it can provide insights into the role of international trade in the formation of CO2 emissions while increasing the efficiency of emission reduction and pressing countries to reshape their international trade to lower the environmental load of production. These insights cannot be obtained from the production-based or territory-based measures of CO2 emissions (e.g., see Mózner, 2013; Knight and Schor, 2014; Liddle, 2018). *Fifth*, the framework provides research with the flexibility of considering exports and imports separately to assess their individual CO2 emissions effects or considering international trade using combinations of them, such as trade turnover (which is the sum of exports and imports), trade balance (which is the difference between exports and imports), or trade openness (which is the ratio of trade turnover to GDP) if the individual effects are not of interest.

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[6] The point is that it would not be a useful policy insight if one recommends that income and/or populations should be decreased as they have a positive effect of emissions rise. One can still recommend changing structure of an economy (e.g., giving more emphasis on service sector) in a way that it will be less emissions intensive. However, it is not easy doing it in the developing economies.

The third point above is quite crucial from the policy-making perspective, as the factors, namely RE, TFP, and exports, can provide useful insights into designing policy measures that reduce emissions while supporting economic growth. Therefore, we detail them below.

TFP – Total Factor Productivity

TFP comprises two main components: technological change and change in efficiency (e.g., see Nishimizu and Page, 1982; Färe et al., 1994). Put differently, an improvement in TFP is mainly due to technological progress and efficiency gains. Needless to say, TFP is one of the fundamental drivers of economic growth, as postulated in the neoclassical growth theories (e.g., see Solow, 1957). At the same time, TFP can help reduce carbon emissions. For example, studies have found that Artificial Intelligence (AI), often viewed as a representation of TFP as it improves both technology and efficiency, can contribute to lower carbon emissions (Liu et al., 2022; Zhang et al., 2022; Ding et al., 2023; Zhong et al., 2024; Wang et al., 2023b; 2024a,b,c,d). The emission reduction features of TFP, as predicted in the theoretical framework in Section 3, might be illustrated in Figure A1.

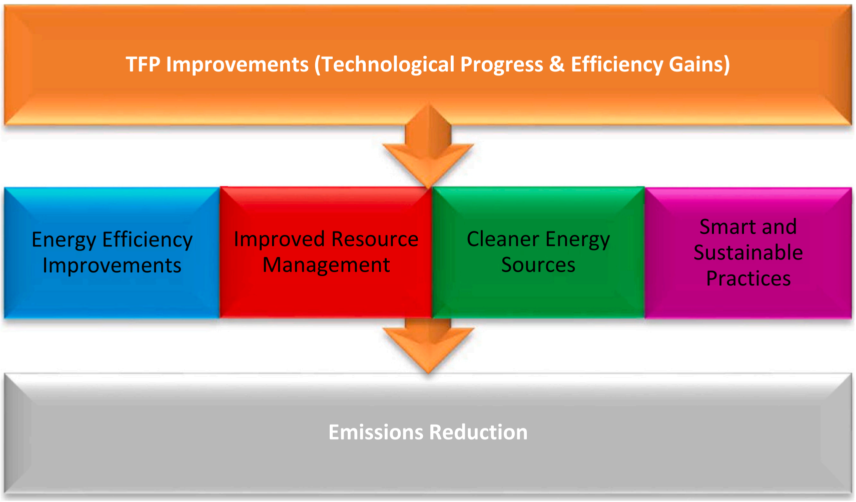

Figure A1. Emissions reduction effects of TFP.
Source: Re-produced from Hasanov (2023).

The figure illustrates a conceptual framework showing how TFP improvements, which include technological progress and efficiency gains, can contribute to emissions reduction through some main channels. TFP improvements represent advancements in both technological capabilities and production efficiency. This includes innovations that enhance the productivity of labor, capital, and other inputs. Technological progress mainly covers new and improved technologies that increase output without increasing input, including energy. At the same time, efficiency gains are about using resources, including energy, more effectively and minimizing waste across the production process. These two can lead to environmental benefits through four main channels as follows.

Energy Efficiency Improvements. This involves using less energy to produce the same output, reducing energy consumption, and minimizing carbon emissions. Efficiency can be achieved through better equipment, optimizing production processes, or reducing energy waste.

Improved Resource Management**.** This refers to strategically using resources (e.g., energy and raw materials) to maximize productivity while minimizing waste. It includes resource conservation techniques, recycling, and efficient supply chain management. Note that this channel may also include the concept of Circular Carbon Economy and its elements, such as carbon capture, utilization, and storage technologies.

Cleaner Energy Sources. The shift to less polluting energy sources (e.g., renewables, nuclear, green hydrogen) is crucial for reducing emissions. This transition reduces the reliance on fossil fuels and the associated greenhouse gas emissions.

Smart and Sustainable Practices. These involve adopting sustainable production techniques and business models that are environmentally friendly, as well as integrating intelligent systems (e.g., smart grids, energy management) to optimize processes for both economic and environmental benefits.

As discussed above, technological progress is one of the main elements of TFP improvements and, hence, emissions reduction. Therefore, a brief introduction to the classification of technologies would be informative for readers to understand their role in designing emissions reduction measures. Figure A2 illustrates this classification from the environmental standpoint.[7]

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[7] Of course, various classifications of the technologies can be considered depending on the purpose. Also, note that the figure illustrates a non-exhaustive list of technologies.

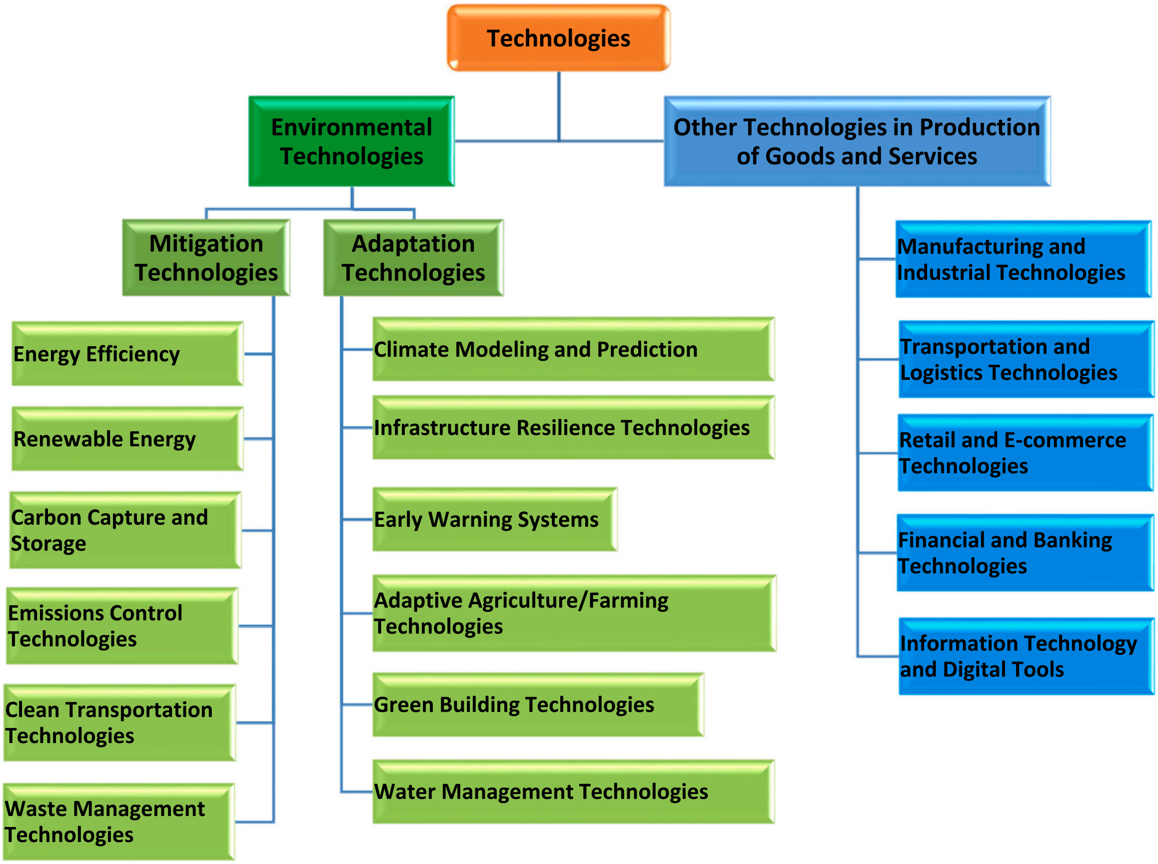

Figure A2. A breakdown of technologies.
Source: Re-produced from Hasanov (2023).

The purpose of the figure is to present the leading technologies in environmental mitigation and adaptation and differentiate them from other technologies used in producing goods and services. While progress in the technologies used to produce goods and services will support socio-economic development, they can also lead to lower carbon emissions through channels, as illustrated in Figure A2 (e.g., Negro and Hekkert, 2008; Suurs and Hekkert, 2009).

Renewable energy

The figure below illustrates the main sources of renewable energy.

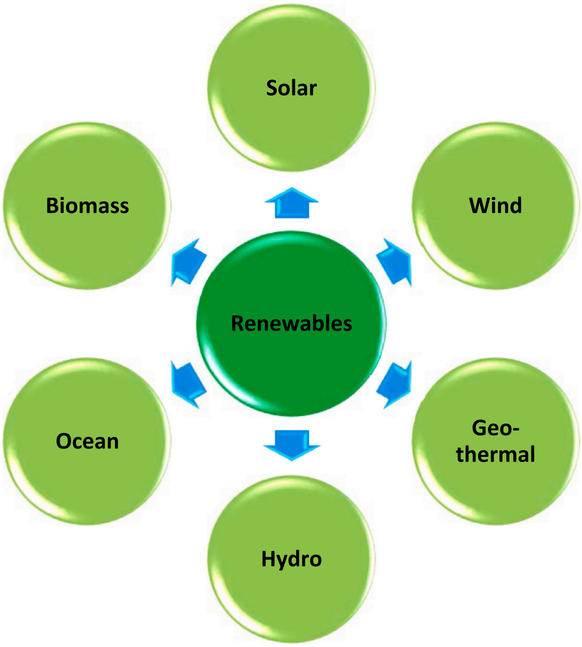

Figure A3. The primary source of renewable energy.
Source: Re-produced from Hasanov (2023). Constructed using information from UN, Climate action (https://www.un.org/en/climatechange/what-is-renewable-energy).

The figure presents an overview of renewable energy sources: Solar, Wind, Geothermal, Hydro, Ocean, and Biomass. These renewable sources harness natural processes—such as sunlight, wind, and water movement—to generate energy without depleting resources. Hence, they are environmentally friendly, contributing to a reduction in reliance on fossil fuels and helping to mitigate CO2 emissions. Conceptually, RE transition can lead to economic development through direct and indirect channels, although empirically, the nature of its impact depends upon the country or country groups under consideration. This is illustrated in Figure A4.

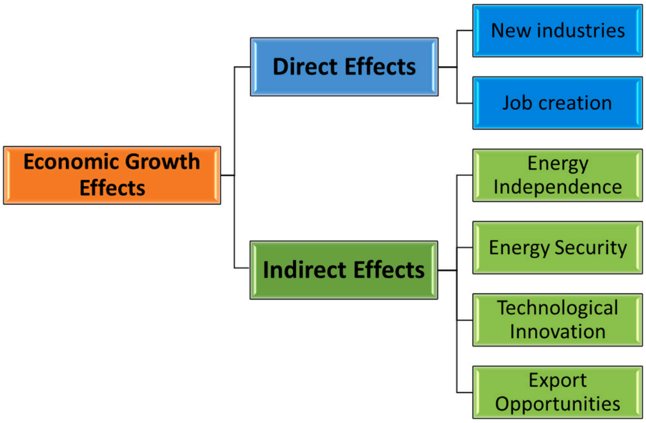

Figure A4. Economic growth effects of renewable energy.
Source: Re-produced from Hasanov (2023).

The direct channel is associated with emerging renewable energy-related industries and job openings (e.g., Barrett and Hoerner, 2002; Lehr et al., 2012; Curtis and Marinescu, 2023; Hasanov et al., 2024b). The indirect channel is related to energy independence, energy security, technological innovation, and export opportunities, which all can lead to further economic development (e.g., see Valentine, 2011; World Bank, 2022; Hasanov, 2023; Hasanov et al., 2024b; Laimon and Yusaf, 2024).

Exports

The theoretical framework and the model in Section 3 articulate that increased exports would reduce consumption-based CO2 emissions. At the same time, growing exports can boost economic development according to the Export-led Growth theory (e.g., see Balassa, 1978; Feder, 1983; Giles and Williams, 2000). Besides, attaining low levels of imports would bring less emissions. Lowering imports would also motivate a country to expand domestic production of goods and services, where clean energy and technologies should be encouraged (e.g., see Hirschman, 1968; Baer, 1972; Rodrigues, 2010).

Appendix B. The EKC and Emerging Theoretical Frameworks for Emissions

Despite its broad application, the Environmental Kuznets Curve (EKC) framework has been subject to criticism for its limitations, as highlighted by Dinda (2004) and Brock and Taylor (2010). Extensions and alternative pollution models that followed have often been criticized for being arbitrary, self-serving, and lacking solid theoretical foundations, as argued by Berk et al. (2022). To our knowledge, few studies have successfully constructed theoretical frameworks for CO2 emissions models. We will brief them below.

Brock and Taylor (2010) proposed a theoretical framework for CO2 emissions by building on Solow's economic growth model, introducing what is now known as the Green Solow Model. This framework facilitates the empirical estimation of CO2 emissions growth as a function of CO2 levels, average investment-to-GDP ratio (as a proxy for the savings rate), and population growth, all in logarithm forms, in addition to an initial level of CO2 emissions represented by a constant.

Criado et al. (2011) extended the production function to account for endogenous emission reductions. Their model links per capita pollution growth rates positively to per capita output growth and negatively to the logarithm of per capita emissions along optimal sustainable trajectories. The logarithm of per capita output can also be used as an additional explanatory variable in the model.

Berk et al. (2022) introduced a theoretical framework similar to the work by Brock and Taylor (2010), offering key refinements to Solow's model by incorporating energy depletion into the production function to better account for the generation of CO2 emissions. Their empirical analysis focuses on a model where CO2 emissions are regressed on their lagged level, physical capital accumulation's savings rate, population growth adjusted for energy depletion, and carbon intensity adjusted for technological progress. In their theoretical framework, output positively influences emissions, while technological progress negatively impacts them.

Hasanov et al. (2021) applied a production function framework, drawing on widely accepted assumptions in the literature, to construct a model where energy demand is driven by key factors such as the prices of production factors, i.e., capital, labor, energy, in addition to total factor productivity (TFP), and income. They further disaggregated energy demand into fossil fuels and renewable energy sources and accounted for the connection between fossil fuel consumption and CO2 emissions through the Kaya identity. Lastly, they derived consumption-based CO2 emissions as their dependent variable, identified by territory-based CO2 emissions, exports, and imports. Consumption-based CO2 emissions are negatively related to TFP, renewable energy, and exports and positively related to income (GDP) and imports in the final model.

The CO2 emissions framework developed by Hasanov et al. (2021) proposes some advantages as discussed above. A key difference between the traditional EKC framework and the Hasanov et al. (2021) framework is how they treat the impact of technological advancement on CO2 emissions. In the EKC, technological progress is bundled with income, making its impact indistinct while it is treated as a separate factor in the latter framework. Another merit of the latter framework compared to the existing frameworks is that it considers income and TFP separately, thereby controlling their individual effects. This is also true for renewable energy, whose effect can often be contaminated with that of technological progress.

The theoretical models discussed above, with the exception of Hasanov et al. (2021), operate under closed-economy assumptions, where domestic savings equal domestic investment, and aggregate demand consists of consumption and investment only. These models also tend to ignore the effects of international trade (i.e., exports and imports), which plays a notable role in forming CO2 emissions. Additionally, energy is treated as a homogeneous entity without distinguishing between fossil fuels and renewable energy, despite the crucial role of the latter in reducing emissions. Although Brock and Taylor (2010) and Criado et al. (2011) recognize the importance of technological progress, their empirical CO2 models do not explicitly include it. Additionally, pollution growth rates in these models are tied to output growth rates. However, since empirical research often shows that both growth rates are stationary, these models likely capture short-term dynamics, whereas CO2 emissions are better characterized by long-term relationships (e.g., Dinda, 2004). We must also mention the disadvantages of the theoretical framework developed by Hasanov et al. (2021). One of the disadvantages is that while having a broader set of factors is useful in informing policymaking, as discussed above, it limits the application of the framework to the empirical data where the time span is short. Therefore, the framework is more suitable for panel analysis unless time series data have a good sample span. The second limitation is using consumption-based CO2 emissions. While it provides valuable insights into the role of exports and imports in forming emissions, data on it are unavailable before 1990 (see Global Carbon Atlas database).

Data availability

Data will be made available on request.

References

Adebayo, T.S., Ağa, M., 2022. The race to zero emissions in MINT economies: can economic growth, renewable energy and disintegrated trade be the path to carbon neutrality? Sustainability 14 (21), 14178. https://doi.org/10.3390/su142114178.

Adebayo, T.S., Rjoub, H., 2021. Assessment of the role of trade and renewable energy consumption on consumption-based carbon emissions: evidence from the MINT economies. Environ. Sci. Pollut. Res. 28 (41), 58271–58283. https://doi.org/10.1007/s11356-021-14754-0.

Afesorgbor, S.K., Demena, B.A., 2022. Trade openness and environmental emissions: evidence from a meta-analysis. Environ. Resour. Econ. 81 (2), 287–321. https://doi.org/10.1007/s10640-021-00627-0.

Al-Iriani, M.A., 2006. Energy–GDP relationship revisited: an example from GCC countries using panel causality. Energy Policy 34 (17), 3342–3350. https://doi.org/10.1016/j.enpol.2005.07.005.

Al-Mulali, U., Ozturk, I., Lean, H.H., 2015. The influence of economic growth, urbanization, trade openness, financial development, and renewable energy on pollution in Europe. Nat. Hazard. 79, 621–644. https://doi.org/10.1007/s11069-015-1865-9.

Al-Mulali, U., Ozturk, I., Solarin, S.A., 2016. Investigating the environmental Kuznets curve hypothesis in seven regions: The role of renewable energy. Ecol. Indic. 67, 267–282. https://doi.org/10.1016/j.ecolind.2016.02.059.

Al-Mulali, U., Sheau-Ting, L., 2014. Econometric analysis of trade, exports, imports, energy consumption and CO2 emission in six regions. Renew. Sustain. Energy Rev. 33, 484–498. https://doi.org/10.1016/j.rser.2014.02.010.

Altinoz, B., Vasbieva, D., Kalugina, O., 2021. The effect of information and communication technologies and total factor productivity on CO2 emissions in top 10 emerging market economies. Environ. Sci. Pollut. Res. 28 (45), 63784–63793. https://doi.org/10.1007/s11356-020-11630-1.

Álvarez-Herránz, A., Balsalobre, D., Cantos, J.M., Shahbaz, M., 2017. Energy innovations-GHG emissions nexus: fresh empirical evidence from OECD countries. Energy Policy 101, 90–100. https://doi.org/10.1016/j.enpol.2016.11.030.

Azam, M., Rehman, Z.U., Ibrahim, Y., 2022. Causal nexus in industrialization, urbanization, trade openness, and carbon emissions: empirical evidence from OPEC economies. Environ. Dev. Sustain. 1–21. https://doi.org/10.1007/s10668-021-02019-2.

Azevedo, V.G., Sartori, S., Campos, L.M.S., 2018. CO2 emissions: a quantitative analysis among the BRICS nations. Renew. Sustain. Energy Rev. 81, 107–115. https://doi.org/10.1016/j.rser.2017.07.027.

Baer, W., 1972. Import substitution and industrialization in Latin America: Experiences and interpretations. Lat. Am. Res. Rev. 7 (1), 95–122. https://doi.org/10.1017/S0023879100041224.

Balassa, B., 1978. Exports and economic growth: Further evidence. J. Dev. Econ. 5, 181–189. https://doi.org/10.1016/0304-3878(78)90006-8.

Balcilar, M., Usman, O., Ike, G.N., 2023. Operational behaviours of multinational corporations, renewable energy transition, and environmental sustainability in Africa: Does the level of natural resource rents matter? Resour. Policy 81, 103344. https://doi.org/10.1016/j.resourpol.2023.103344.

Baltagi, B.H., 2021. Econometric analysis of panel data, Latest edition. Springer Link.

Baltagi, B.H., Pesaran, M.H., 2007. Heterogeneity and cross section dependence in panel data models: Theory and applications: Introduction. J. Appl. Econometrics 22 (2), 229–232 [Online]. JSTOR. Available from: http://www.jstor.org/stable/25146515.

Barrett, J.P., Hoerner, J.A., 2002. Clean Energy and Jobs. Economic Policy Institute and Center for a Sustainable Economy 2.

Berk, I., Onater-Isberk, E., Yetkiner, H., 2022. A unified theory and evidence on CO2 emissions convergence. Environ Sci Pollut Res 29 (14), 20675–20693. https://doi.org/10.1007/s11356-021-17131-z.

Bhattacharya, M., Inekwe, J., Sadorsky, P., 2020. Consumption-based and territory-based carbon emissions intensity: determinants and forecasting using club convergence across countries. Energy Econ. 86, 104632. https://doi.org/10.1016/j.eneco.2019.104632.

Bianchini, S., Damioli, G., Ghisetti, C., 2023. The environmental effects of the “twin” green and digital transition in European regions. Environ. Resour. Econ. 84 (4), 877–918. https://doi.org/10.1007/s10640-022-00741-7.

Boukhelkhal, A., 2022. Energy use, economic growth and CO2 emissions in Africa: does the environmental Kuznets curve hypothesis exist? New evidence from heterogeneous panel under cross-sectional dependence. Environ. Dev. Sustain. 24 (11), 13083–13110. https://doi.org/10.1007/s10668-021-01983-z.

Brock, W.A., Taylor, M.S., 2010. The green solow model. J. Econ. Growth 15 (2), 127–153. https://doi.org/10.1007/s10887-010-9051-0.

Cheng, C., Ren, X., Dong, K., Dong, X., Wang, Z., 2021. How does technological innovation mitigate CO2 emissions in OECD countries? Heterogeneous analysis using panel quantile regression. J. Environ. Manag. 280, 111818. https://doi.org/10.1016/j.jenvman.2020.111818.

Curtis, E.M., Marinescu, I., 2023. Green energy jobs in the United States: what are they, and where are they? Environ. Energy Policy Econ. 4 (1), 202–237. https://doi.org/10.1086/722677.

Dauda, L., Long, X., Mensah, C.N., Salman, M., Boamah, K.B., Ampon-Wireko, S., Dogbe, C.S.K., 2021. Innovation, trade openness and CO2 emissions in selected countries in Africa. J. Clean. Prod. 281, 125143. https://doi.org/10.1016/j.jclepro.2020.125143.

Debone, D., Leite, V.P., Miraglia, S.G.E.K., 2021. Modelling approach for carbon emissions, energy consumption and economic growth: a systematic review. Urban Clim. 37, 100849. https://doi.org/10.1016/j.uclim.2021.100849.

Dinda, S., 2004. Environmental Kuznets curve hypothesis: a survey. Ecol. Econ. 49 (4), 431–455. https://doi.org/10.1016/j.ecolecon.2004.02.011.

Dinda, S., 2005. A theoretical basis for the environmental Kuznets curve. Ecol. Econ. 53 (3), 403–413. https://doi.org/10.1016/j.ecolecon.2004.10.007.

Ding, T., Li, J., Shi, X., Li, X., Chen, Y., 2023. Is artificial intelligence associated with carbon emissions reduction? Case of China. Resour. Policy 85, 103892. https://doi.org/10.1016/j.resourpol.2023.103892.

Dogan, E., Turkekul, B., 2016. CO2 emissions, real output, energy consumption, trade, urbanization and financial development: testing the EKC hypothesis for the USA. Environ. Sci. Pollut. Res. 23, 1203–1213. https://doi.org/10.1007/s11356-015-5323-8.

Dong, M., Wang, G., Han, X., 2023. Artificial intelligence, industrial structure optimization, and CO2 emissions. Environ. Sci. Pollut. Res. 30 (50), 108757–108773. https://doi.org/10.1007/s11356-023-29859-x.

Dou, Y., Zhao, J., Malik, M.N., Dong, K., 2021. Assessing the impact of trade openness on CO2 emissions: evidence from China-Japan-ROK FTA countries. J. Environ. Manag. 296, 113241. https://doi.org/10.1016/j.jenvman.2021.113241.

Durani, F., Bhowmik, R., Sharif, A., Anwar, A., Syed, Q.R., 2023. Role of economic uncertainty, financial development, natural resources, technology, and renewable energy in the environmental Phillips curve framework. J. Clean. Prod. 420, 138334. https://doi.org/10.1016/j.jclepro.2023.138334.

Eberhardt, M., Teal, F., 2010. Productivity Analysis in Global Manufacturing Production. DEGIT, Dynamics, Economic Growth, and International Trade. Working Paper. Department of Economics (University of Oxford).

Ekwueme, D.C., Zoaka, J.D., 2020. Effusions of carbon dioxide in MENA countries: inference of financial development, trade receptivity, and energy utilization. Environ. Sci. Pollut. Res. 27, 12449–12460. https://doi.org/10.1007/s11356-020-07821-5.

Ezzati, M., Singer, B.H., Kammen, D.M., 2001. Towards an integrated framework for development and environment policy: The dynamics of environmental kuznets curves. World Dev. 29 (8), 1421–1434. Available from: https://www.sciencedirect.com/science/article/pii/S0305750X01000444.

Fan, J., Liao, Y., Yao, J., 2015. Power enhancement in high-dimensional cross-sectional tests. Econom 83, 1497–1541. https://doi.org/10.3982/ECTA12749.

Färe, R., Grosskopf, S., Norris, M., Zhang, Z., 1994. Productivity growth, technical progress, and efficiency change in industrialized countries. Am. Econ. Rev. 66–83. 〈https://www.jstor.org/stable/2117971〉.

Farhani, S., Shahbaz, M., Sbia, R., Chaibi, A., 2014. What does MENA region initially need: Grow output or mitigate CO2 emissions? Econ. Modell. 38, 270–281. https://doi.org/10.1016/j.econmod.2014.01.001.

Feder, G., 1983. On exports and economic growth. J. Dev. Econ. 12 (1-2), 59–73. https://doi.org/10.1016/0304-3878(83)90031-7.

Feenstra, R.C., Robert, I., Timmer, M.P., 2021. Penn World Table Version 10.0. Groningen Growth and Development Centre, University of Groningen⟨https://www.rug.nl/ggdc/productivity/pwt/⟩.

Giles, A., J., Williams, C.L., 2000. Export-led growth: a survey of the empirical literature and some non-causality results. Part 1. J. Int. Trade Econ. Dev. 9 (3), 261–337. https://doi.org/10.1080/09638190050086177.

Global Carbon Atlas, Global carbon atlas. http://www.globalcarbonatlas.org/en/CO2-emissions, 2023. (Accessed 20 March 2024).

Gu, J., 2022. Sharing economy, technological innovation and carbon emissions: evidence from Chinese cities. J. Innov. Knowl. 7 (3), 100228. https://doi.org/10.1016/j.jik.2022.100228.

Hasanov, F.J., 2023. Implications of technological progress and renewable energy for environmental policies from sustainable development perspectives. 6th Symposium on Agri-Tech Economics for Sustainable Futures. Harper Adams University. September 18-19.

Hasanov, F.J., Khan, Z., Hussain, M., Tufail, M., 2021. Theoretical framework for the carbon emissions effects of technological progress and renewable energy consumption. Sustain. Dev. 29 (5), 810–822. https://doi.org/10.1002/sd.2175.

Hasanov, F.J., Liddle, B., Mikayilov, J.I., 2018. The impact of international trade on CO2 emissions in oil exporting countries: territory vs consumption emissions accounting. Energy Econ. 74, 343–350. https://doi.org/10.1016/j.eneco.2018.06.004.

Hasanov, F.J., Liddle, B., Mikayilov, J.I., Bollino, C.A., 2019. How total factor productivity drives Long-Run energy consumption in Saudi Arabia. Energy Environ. Strateg. Era Glob. 195–220. https://doi.org/10.1007/978-3-030-06001-5_8.

Hasanov, F.J., Mukhtarov, S., Suleymanov, E., 2023. The role of renewable energy and total factor productivity in reducing CO2 emissions in Azerbaijan. Fresh insights from a new theoretical framework coupled with Autometrics. Energy Strategy Rev. 47, 101079. https://doi.org/10.1016/j.esr.2023.101079.

Hasanov, F.J., Mukhtarov, S., Suleymanov, E., 2024a. The role of renewable energy and total factor productivity in reducing carbon emissions: a case of top-ranked nations in the renewable energy country attractiveness index. J. Environ. Manag. 361, 121220. https://doi.org/10.1016/j.jenvman.2024.121220.

Hasanov, F.J., Mukhtarov, S., Suleymanov, E., 2024b. Analyzing CO2 emissions effect of financial development in the GCC. Is the effect asymmetric? Environ. Econ. Policy Stud. https://doi.org/10.21203/rs.3.rs-3559067/v1.

Hassan, T., Song, H., Kirikkaleli, D., 2022. International trade and consumption-based carbon emissions: evaluating the role of composite risk for RCEP economies. Environ. Sci. Pollut. Res. 29, 3417–3437. https://doi.org/10.1007/s11356-021-15617-4.

Heil, M.T., ad, Selden, T.M., 2001. International trade intensity and carbon emissions: a cross- country econometric analysis. J. Environ. Dev. 10 (1), 35–49. https://doi.org/10.1177/107049650101000103.

Hirschman, A.O., 1968. The political economy of import-substituting industrialization in Latin America. Q. J. Econ. 82 (1), 1–32. https://doi.org/10.2307/1882243.

Hübler, M., Bukin, E., Xi, Y., 2022. The effects of international trade on structural convergence and CO2 emissions. Environ. Resour. Econ. 83 (3), 579–604. https://doi.org/10.1007/s10640-022-00698-7.

Hussain, M., Lin, Y., Wang, Y., 2023. Measures to achieve carbon neutrality: what is the role of energy structure, infrastructure, and financial inclusion. J. Environ. Manag. 325, 116457. https://doi.org/10.1016/j.jenvman.2022.116457.

IEA 2023. International Energy Agency.

Jiang, Y., Hossain, M.R., Khan, Z., Chen, J., Badeeb, R.A., 2023. Revisiting research and development expenditures and trade adjusted emissions: green innovation and renewable energy R&D role for developed countries. J. Knowl. Econ. 1–36. https://doi.org/10.1007/s13132-023-01220-0.

Jiborn, M., Kander, A., Kulionis, V., Nielsen, H., Moran, D.D., 2018. Decoupling or delusion? Measuring emissions displacement in foreign trade. Glob. Environ. Change 49, 27–34. https://doi.org/10.1016/j.gloenvcha.2017.12.006.

JinRu, L., Qamruzzaman, M., 2022. Nexus between environmental innovation, energy efficiency, and environmental sustainability in G7: what is the role of institutional quality? Front. Environ. Sci. 10, 860244. https://doi.org/10.3389/fenvs.2022.860244.

Juodis, A., Reese, S., 2022. The incidental parameters problem in testing for remaining cross-section correlation. J. Bus. Econ. Stat. 40 (3). https://doi.org/10.1080/07350015.2021.1906687.

Kao, C., 1999. Spurious regression and residual-based tests for cointegration in panel data. J. Econ. 90, 1–44. https://doi.org/10.1016/S0304-4076(98)00023-2.

Khan, Z., Ali, S., Umar, M., Kirikkaleli, D., Jiao, Z., 2020. Consumption-based carbon emissions and international trade in G7 countries: the role of environmental innovation and renewable energy. Sci. Total Environ. 730, 138945. https://doi.org/10.1016/j.scitotenv.2020.138945.

Kim, J., Park, K., 2016. Financial development and deployment of renewable energy technologies. Energy Econ. 59, 238–250. https://doi.org/10.1016/j.eneco.2016.08.012.

Knight, K., Schor, J., 2014. Economic growth and climate change: a cross-national analysis of territorial and consumption-based carbon emissions in high-income countries. Sustainability 6 (6), 3722–3731. https://doi.org/10.3390/su6063722.

Kongkuah, M., Yao, H., Yilanci, V., 2022. The relationship between energy consumption, economic growth, and CO 2 emissions in China: the role of urbanisation and international trade. Environ. Dev. Sustain. 1–25. https://doi.org/10.1007/s10668-021-01628-1.

Kostakis, I., Armaos, S., Abeliotis, K., Theodoropoulou, E., 2023. The investigation of EKC within CO2 emissions framework: empirical evidence from selected cross-correlated countries. Sustain. Anal. Model. 3, 100015. https://doi.org/10.1016/j.samod.2023.100015.

Lahouel, B.B., Taleb, L., Zaied, Y.B., Managi, S., 2021. Does ICT change the relationship between total factor productivity and CO2 emissions? Evidence based on a nonlinear model. Energy Econ. 101, 105406. https://doi.org/10.1016/j.eneco.2021.105406.

Laimon, M., Yusaf, T., 2024. Towards energy freedom: exploring sustainable solutions for energy independence and self-sufficiency using integrated renewable energy-driven hydrogen system. Renew. Energy, 119948. https://doi.org/10.1016/j.renene.2024.119948.

Le, T.H., Chang, Y., Park, D., 2016. Trade openness and environmental quality: International evidence. Energy Policy 92, 45–55. https://doi.org/10.1016/j.enpol.2016.01.030.

Lehr, U., Lutz, C., Edler, D., 2012. Green jobs? Economic impacts of renewable energy in Germany. Energy Policy 47, 358–364. https://doi.org/10.1016/j.enpol.2012.04.076.

Li, B., Haneklaus, N., 2022. Reducing CO2 emissions in G7 countries: The role of clean energy consumption, trade openness and urbanization. Energy Rep. 8, 704–713. https://doi.org/10.1016/j.egyr.2022.01.238.

Li, R., Li, L., Wang, Q., 2022. The impact of energy efficiency on carbon emissions: evidence from the transportation sector in Chinese 30 provinces. Sustain. Cities Soc. 82, 103880. https://doi.org/10.1016/j.scs.2022.103880.

Li, R., Wang, Q., Guo, J., 2024. Revisiting the environmental Kuznets curve (EKC) hypothesis of carbon emissions: exploring the impact of geopolitical risks, natural resource rents, corrupt governance, and energy intensity. J. Environ. Manag. 351, 119663. https://doi.org/10.1016/j.jenvman.2023.119663.

Li, G., Yanase, A., 2022. Trade, resource use and pollution: a synthesis. Environ. Resour. Econ. 83 (3), 861–901. https://doi.org/10.1007/s10640-022-00713-x.

Li, W., Zhao, T., Wang, Y., Guo, F., 2017. Investigating the learning effects of technological advancement on CO2 emissions: a regional analysis in China. Nat. Hazard. 88, 1211–1227. https://doi.org/10.1007/s11069-017-2915-2.

Liddle, B., 2018. Consumption-based accounting and the trade-carbon emissions nexus. Energy Econ. 69, 71–78. https://doi.org/10.1016/j.eneco.2017.11.004.

Liu, J., Liu, L., Qian, Y., Song, S., 2022. The effect of artificial intelligence on carbon intensity: evidence from China's industrial sector. Socio-Econ. Plan. Sci. 83, 101002. https://doi.org/10.1016/j.seps.2020.101002.

Liu, G., Ofori, C., Ampong, S.A., Appiah-Twum, F., Alhassan, E.A., 2023. Towards a sustainable environment: examining the spatial VARIATIONS of renewable energy, environmental pollution, and economic growth in Europe. Energy Strategy Rev. 50, 101231. https://doi.org/10.1016/j.esr.2023.101231.

Maddala, G.S., Wu, S., 1999. A comparative study of unit root tests with panel data and a new simple test. Oxf. Bull. Econ. Stat. 61 (S1), 631–652. https://doi.org/10.1111/1468-0084.0610s1631.

Mensah, C.N., Long, X., Boamah, K.B., Bediako, I.A., Dauda, L., Salman, M., 2018. The effect of innovation on CO 2 emissions of OCED countries from 1990 to 2014. Environ. Sci. Pollut. Res. 25, 29678–29698. https://doi.org/10.1007/s11356-018-2968-0.

Mi, Z., Zheng, J., Meng, J., Zheng, H., Li, X., Coffman, D.M., Woltjer, J., Wang, S., Guan, D., 2019. Carbon emissions of cities from a consumption-based perspective. Appl. Energy 235, 509–518. https://doi.org/10.1016/j.apenergy.2018.10.137.

Mózner, Z.V., 2013. A consumption-based approach to carbon emission accounting–sectoral differences and environmental benefits. J. Clean. Prod. 42, 83–95. https://doi.org/10.1016/j.jclepro.2012.10.014.

Mukhtarov, S., 2024. Do renewable energy and total factor productivity eliminate CO2 emissions in Turkey? Environ. Econ. Policy Stud. 26 (2), 307–324. https://doi.org/10.1007/s10018-023-00377-x.

Mukhtarov, S., Aliyev, F., Aliyev, J., Ajayi, R., 2022. Renewable energy consumption and carbon emissions: evidence from an oil-rich economy. Sustainability 15 (1), 134. https://doi.org/10.3390/su15010134.

Namahoro, J.P., Wu, Q., Zhou, N., Xue, S., 2021. Impact of energy intensity, renewable energy, and economic growth on CO2 emissions: evidence from Africa across regions and income levels. Renew. Sustain. Energy Rev. 147, 111233. https://doi.org/10.1016/j.rser.2021.111233.

Naveed, A., Ahmad, N., Aghdam, R.F., Menegaki, A.N., 2022. What have we learned from Environmental Kuznets Curve hypothesis? A citation-based systematic literature review and content analysis. Energy Strategy Rev. 44, 100946. https://doi.org/10.1016/j.esr.2022.100946.

Negro, S.O., Hekkert, M.P., 2008. Explaining the success of emerging technologies by innovation system functioning: the case of biomass digestion in Germany. Technol. Anal. Strateg. Manag. 20 (4), 465–482. https://doi.org/10.1080/09537320802141437.

Nishimizu, M., Page Jr, J.M., 1982. Total factor productivity growth, technological progress and technical efficiency change: dimensions of productivity change in Yugoslavia, 1965-78. Econ. J. 92 (368), 920–936. https://doi.org/10.2307/2232675.

Ojekemi, O.S., Rjoub, H., Awosusi, A.A., Agyekum, E.B., 2022. Toward a sustainable environment and economic growth in BRICS economies: do innovation and globalization matter? Environ. Sci. Pollut. Res. 29 (38), 57740–57757. https://doi.org/10.1007/s11356-022-19742-6.

Olabi, A.G., Abdelkareem, M.A., 2022. Renewable energy and climate change. Renew. Sustain. Energy Rev. 158, 112111. https://doi.org/10.1016/j.rser.2022.112111.

Ordás Criado, C., Valente, S., Stengos, T., 2011. Growth and pollution convergence: Theory and evidence. J. Environ. Econ. Manag. 62 (2), 199–214. Available from: https://www.sciencedirect.com/science/article/pii/S0095069611000362.

Padhan, L., Bhat, S., 2023. Analysing the role of globalisation, institutional qualities, and renewable energy consumption in environmental degradation mitigation: the SAARC experience. Environ. Dev. Sustain. 1–25. https://doi.org/10.1007/s10668-023-04313-7.

Pedroni, P., 1999. Critical values for cointegration tests in heterogeneous panels with multiple regressors. Oxf. Bull. Econ. Stat. 61, 653–670. https://doi.org/10.1111/1468-0084.61.s1.14.

Pedroni, P., 2004. Panel cointegration: asymptotic and finite sample properties of pooled time series tests with an application to the PPP hypothesis. Econom. Theory 20 (3), 597–625. https://doi.org/10.1017/S0266466604203073.

Pesaran, M.H., 2006. Estimation and inference in large heterogeneous panels with a multifactor error structure. Econometrica 74 (4), 967–1012. https://doi.org/10.1111/j.1468-0262.2006.00692.x.

Pesaran, M.H., 2007. A simple panel unit root test in the presence of cross-section dependence. J. Appl. Econom. 22 (2), 265–312. https://doi.org/10.1002/jae.951.

Pesaran, M.H., 2015. Testing weak cross-sectional dependence in large panels. Econom. Rev. 34 (6-10), 1089–1117. https://doi.org/10.1080/07474938.2014.956623.

Pesaran, M.H., 2015b. Time series and panel data econometrics. Oxford University Press.

Pesaran, M.H., Smith, R., 1995. Estimating long-run relationships from dynamic heterogeneous panels. J. Econ. 68 (1), 79–113. https://doi.org/10.1016/0304-4076(94)01644-F.

Pesaran, M.H., Xie, Y., 2021. A bias-corrected CD test for error cross- sectional dependence in panel data models with latent factors. Cambridge Working Papers Econ. 2158. https://doi.org/10.2139/ssrn.3904536.

Peters, G.P., Davis, S.J., Andrew, R., 2012. A synthesis of carbon in international trade. Biogeosc 9 (8), 3247–3276. https://doi.org/10.5194/bg-9-3247-2012.

Quang, D.V., Milani, D., Zahra, M.A., 2023. A review of potential routes to zero and negative emission technologies via the integration of renewable energies with CO2 capture processes. Int. J. Greenh. Gas. Control. 124, 103862. https://doi.org/10.1016/j.ijggc.2023.103862.

Rodrigues, M., 2010. Import substitution and economic growth. J. Monet. Econ. 57 (2), 175–188. https://doi.org/10.1016/j.jmoneco.2009.12.004.

Sadiq, M., Hassan, S.T., Khan, I., Rahman, M.M., 2023. Policy uncertainty, renewable energy, corruption and CO2 emissions nexus in BRICS-1 countries: a panel CS-ARDL approach. Environ. Dev. Sustain. 1–27. https://doi.org/10.1007/s10668-023-03546-w.

Sarafidis, V., Wansbeek, T., 2012. Cross-sectional dependence in panel data analysis. Econom. Rev. 31 (5), 483–531. https://doi.org/10.1080/07474938.2011.611458.

Sarafidis, V., Yamagata, T., Robertson, D., 2009. A test of cross section dependence for a linear dynamic panel model with regressors. J. Econom. 148 (2), 149–161. https://doi.org/10.1016/j.jeconom.2008.10.006.

Sarkodie, S.A., Strezov, V., 2019. Effect of foreign direct investments, economic development and energy consumption on greenhouse gas emissions in developing countries. Sci. Total Environ. 646, 862–871. https://doi.org/10.1016/j.scitotenv.2018.07.365.

Saud, S., Chen, S., Danish, Haseeb, A., 2019. Impact of financial development and economic growth on environmental quality: an empirical analysis from Belt and Road Initiative (BRI) countries. Environ. Sci. Pollut. Res. 26, 2253–2269. https://doi.org/10.1007/s11356-018-3688-1.

Shahbaz, M., Raghutla, C., Song, M., Zameer, H., Jiao, Z., 2020. Public-private partnerships investment in energy as new determinant of CO2 emissions: the role of technological innovations in China. Energy Econ. 86, 104664. https://doi.org/10.1016/j.eneco.2020.104664.

Sharif, A., Mehmood, U., Tariq, S., Haq, Z.U., 2023. The role of financial inclusion and globalization toward a sustainable economy in ASEAN countries: evidence from advance panel estimations. Environ. Dev. Sustain. 1–18. https://doi.org/10.1007/s10668-023-03145-9.

Shi, J., Visas, H., Ul-Haq, J., Abbas, S., Khanum, S., 2023. Investigating the impact of export product diversification on environmental degradation: evidence from Chinese Provinces. Environ. Dev. Sustain. 25 (10), 11455–11486. https://doi.org/10.1007/s10668-022-02536-8.

Shouwu, J., Xu, T., Shehzad, K., Zaman, B.U., Wuyue, L., 2023. The role of environmental technologies and clean energy transition in shaping the N-shaped environmental Kuznets curve: A North African perspective. Environ. Technol. Innov., 103463 https://doi.org/10.1016/j.eti.2023.103463.

Solow, R.M., 1957. Technical change and the aggregate production function. Rev. Econ. Stat. 39, 312–320. https://doi.org/10.2307/1926047.

Stern, D.I., Common, M.S., Barbier, E.B., 1996. Economic growth and environmental degradation: the environmental Kuznets curve and sustainable development. World Dev. 24 (7), 1151–1160. https://doi.org/10.1016/0305-750X(96)00032-0.

Suurs, R.A.A., Hekkert, M.P., 2009. Cumulative causation in the formation of a technological innovation system: the case of biofuels in the Netherlands. Technol. Forecast. Soc. Change 76 (8), 1003–1020. https://doi.org/10.1016/j.techfore.2009.03.002.

Tamazian, A., Rao, B.B., 2010. Do economic, financial and institutional developments matter for environmental degradation? Evidence from transitional economies. Energy Econ. 32 (1), 137–145. https://doi.org/10.1016/j.eneco.2009.04.004.

Tisdell, C., 2001. Globalisation and sustainability: Environmental kuznets curve and the WTO. Ecol. Econ. 39 (2), 185–196. Available from: https://www.sciencedirect.com/science/article/pii/S0921800901002348.

Udeagha, M.C., Breitenbach, M.C., 2023. On the asymmetric effects of trade openness on CO2 emissions in SADC with a nonlinear ARDL approach. Discov. Sustain. 4 (1). https://doi.org/10.1007/s43621-022-00117-3.

Valentine, S.V., 2011. Emerging symbiosis: Renewable energy and energy security. Renew. Sustain. Energy Rev. 15 (9), 4572–4578. https://doi.org/10.1016/j.rser.2011.07.095.

Wang, Q., Hu, S., Li, R., 2024e. Could information and communication technology (ICT) reduce carbon emissions? The role of trade openness and financial development. Telecommun. Policy 48 (3), 102699. https://doi.org/10.1016/j.telpol.2023.102699.

Wang, Q., Li, Y., Li, R., 2024a. Ecological footprints, carbon emissions, and energy transitions: the impact of artificial intelligence (AI). Humanit. Soc. Sci. Commun. 11 (1), 1–18. https://doi.org/10.1057/s41599-024-03520-5.

Wang, J., Li, J., 2021. Exploring the impact of international trade on carbon emissions: new evidence from China's 282 cities. Sustainability 13 (16), 8968. https://doi.org/10.3390/su13168968.

Wang, Q., Sun, T., Li, R., 2023b. Does artificial intelligence promote green innovation? An assessment based on direct, indirect, spillover, and heterogeneity effects. Energy Environ., 0958305X231220520 https://doi.org/10.1177/0958305X231220520.

Wang, Q., Zhang, F., Li, R., 2023a. Revisiting the environmental kuznets curve hypothesis in 208 counties: the roles of trade openness, human capital, renewable energy and natural resource rent. Environ. Res. 216, 114637. https://doi.org/10.1016/j.envres.2022.114637.

Wang, Q., Zhang, F., Li, R., 2024c. Artificial intelligence and sustainable development during urbanization: perspectives on AI R&D innovation, AI infrastructure, and AI market advantage. Sustain. Dev. 09680802. https://doi.org/10.1002/sd.3150.

Wang, Q., Zhang, F., Li, R., Sun, J., 2024d. Does artificial intelligence promote energy transition and curb carbon emissions? The role of trade openness. J. Clean. Prod. 447, 141298. https://doi.org/10.1016/j.jclepro.2024.141298.

WDI, 2023. The World Development Indicators Database. World Bank.

Westerlund, J., 2007. Testing for error correction in panel data. Oxf. Bull. Econ. Stat. 69 (6), 709–748. https://doi.org/10.1111/j.1468-0084.2007.00477.x.

Wiebe, K.S., Yamano, N., 2016. Estimating CO2 emissions embodied in final demand and trade using the OECD ICIO 2015: Methodology and Results. OECD Science, Technology and Industry Working Papers, No. 2016/05. OECD Publishing, Paris. https://doi.org/10.1787/5jlrcm216xkl-en.

World Bank, 2022. Gulf Economic Update: Green Growth Opportunities in the GCC. World Bank.

Yu, Y., Du, Y., 2023. Does ICT change the relationship between trade openness and CO2 emissions? Evidence for RCEP countries. Environ. Dev. Sustain. 1–23. https://doi.org/10.1007/s10668-023-03879-6.

Zhang, X., Liu, P., Zhu, H., 2022. The impact of industrial intelligence on energy intensity: evidence from China. Sustainability 14 (12), 7219. https://doi.org/10.3390/su14127219.

Zhong, J., Zhong, Y., Han, M., Yang, T., Zhang, Q., 2024. The impact of AI on carbon emissions: evidence from 66 countries. Appl. Econ. 56 (25), 2975–2989. https://doi.org/10.1080/00036846.2023.2203461.