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Research article

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

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ABSTRACT

On the one hand, economies, particularly developing ones, need to grow. On the other hand, climate change is the most pressing issue globally, and nations should take the necessary measures. Such a complex task requires new theoretical and empirical models to capture this complexity and provide new insights. Our study uses a newly developed theoretical framework that involves renewable energy consumption (REC) and total factor productivity (TFP) alongside traditional factors of CO2 emissions. It provides policymakers with border information compared to traditional models, such as the Environmental Kuznets Curve (EKC), being limited to income and population. Advanced panel time series methods are also employed, addressing panel data issues while producing not only pooled but also country-specific results.

20 Renewable Energy Country Attractiveness Index (RECAI) nations are considered in this study. The results show that REC, TFP, and exports reduce CO2 emissions with elasticities of 0.3, 0.4, and 0.3, respectively. Oppositely, income and imports increase emissions with elasticities of 0.8 and 0.3. Additionally, we show that RECAI countries are commonly affected by global and regional factors. Moreover, we find that shocks can create permanent changes in the levels of the factors but only temporary changes in their growth rates.

The main policy implication of the findings is that authorities should implement measures boosting TFP and REC. These factors are driven mainly by technological progress, innovation, and efficiency gains. Thus, they can simultaneously reduce emissions while promoting long-run green economic growth, which addresses the complexity mentioned above to some extent.

1. Introduction

Carbon dioxide (CO2) emissions are recognized as a threat to humanity and sustainable development worldwide. Human activities have resulted in an excess of CO2 emissions, contributing to the phenomenon of global warming and subsequent climate change (Esmaeili et al., 2023). In 2022, global CO2 emissions surged by approximately 1805%, reaching 37.15 billion tons, compared to the 1900 levels of 1.95 billion ton (Global Carbon Budget, 2023). The trajectory of CO2 emissions exhibited a steeper incline from the 1950s onwards, with levels reaching 25.45 billion metric tons by 2000. Subsequently, emissions experienced a notable surge of 31.1% between 2000 and 2010, culminating in a total of 37.15 billion metric tons in 2022 (Global Carbon Budget, 2023). Despite efforts to expand renewable energy and adopt decarbonized

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fuels to mitigate environmental harm, oil remains indispensable across various economic sectors, including transportation, industry, and electricity generation. Its role in powering vehicles, aircraft, ships, and industrial machinery underscores its significance in modern life. Despite its historical role in driving economic progress, there is a growing recognition of the need to transition towards more sustainable and environmentally friendly energy sources. This transition is motivated by concerns regarding climate change, air pollution, and the finite nature of fossil fuel resources. Consequently, the global economy is increasingly prioritizing energy efficiency measures and embracing renewable energy alternatives.

Decreasing carbon emissions is crucial for achieving global sustainability goals as well (Dagar et al., 2024). Thus, global and country-specific programs have been launched to curb emissions. These programs include the Kyoto Protocol, the Paris Agreement, and the United Nations, 2015 (UN) Sustainable Development Goals. Amid this international deliberation, governments throughout the world have investigated options for reducing carbon dioxide emissions. Many countries (particularly developing and less-developed ones) confront the challenge of raising their populations' standard of living. This typically entails a rise in industrialization, energy consumption, urbanization, and infrastructure development, all of which historically have been linked to increased CO2 emissions. Maintaining environmental sustainability while balancing the need for economic growth is a complex task. Countries must offer opportunities for their citizens to succeed while mitigating adverse ecological effects. Such a complex task requires new theoretical and empirical models to capture this complexity and provide new insights, sine the traditional models consider quite limited factors of CO2 emissions (such as the Environmental Kuznets Curve (EKC) being limited to income and population) in designing climate change policies and measures. Therefore, this study uses the theoretical framework developed by Hasanov et al. (2021), as it links CO2 emissions to total factor productivity (TFP) and renewable energy consumption (REC) in addition to income, exports, and imports. One may prefer this new framework to traditional ones for two reasons. First, it theoretically validates TFP and REC, in addition to income and international trade to be the determinants of CO2 emissions. Thus, it offers a broader framework in informing the decision-making process. Second, the determinants such as TFP, REC, and exports are useful also to consider for other policy considerations. TFP has long been considered the main factor of economic growth (Solow, 1957). Its two primary elements, technological progress, and efficiency gains, offer opportunities not only for economic prosperity but also reducing CO2 emissions (e.g., Huang et al., 2020). A significant technological progress is required in energy storage, transportation, carbon capture, and clean energy sources to achieve a zero-carbon society. Such progress driven by innovations may also support long-term economic growth in a green way.

Besides, the importance of renewable energy is highlighted by international agencies, such as the International Energy Agency, the International Renewable Energy Agency, and UN environmental programs. It is among the key drivers of energy security, pollution reduction, and sustainable economic growth (e.g., United Nations, 2015; IEA, 2019). Globally, renewable energy is the most widely utilized mitigation technology to achieve a net zero-carbon energy system. Thus, to mitigate the alarming rise in global temperatures, it is imperative to promptly and sufficiently allocate resources towards renewable energy sources such as solar, wind, and biofuels (e.g., Balsalobre Lorente et al., 2023).

Lastly, exports, one of the factors in reducing CO2 emissions in the framework by Hasanov et al. (2021), is a long-recognized driver of economic growth as articulated by the Export-led Growth theory (e.g., Balassa, 1978; Feder, 1983; Krueger, 1995).

Thus, examining the driving forces of CO2 emissions is crucial for all economies, including Renewable Energy Country Attractiveness Index (RECAI) nations. The objective of this study is therefore to investigate the impacts of REC, TFP, and exports alongside income and imports on CO2 emissions. Our research aims is to propose novel insights for carbon emission reduction policies in the selected RECAI countries.

The RECAI, developed by Ernest and Young, identifies the 40 most attractive countries globally in terms of renewable energy investment and deployment opportunities. The index has five pillars: macroeconomic fundamentals, the energy imperative, policy, project delivery, and technology (Ernst & Young, 2022). We consider RECAI countries for the following reasons. First, their experience in reducing carbon emissions without harming economic growth can serve as a benchmark for other countries. Our sample countries represent 65.4% of global CO2 emissions as of 2021 (Calculated using World Bank, 2022; WorldinData, 2021). Second, RECAI countries are diverse in development levels and geographic locations. Third, these countries are world leaders in renewable energy investments and deployments. The per-capita renewable energy on average in these countries has exceeded the global average over the last two decades (World Bank, 2022). Thus, it is interesting to investigate the extent to which their renewable energy use affects CO2 emissions reduction. We consider the top 20 out of 40 RECAI countries owing to data availability.

We apply advanced panel time series methods to the 20 RECAI countries' data in a broader theoretical framework of CO2 emissions. Our econometric analysis shows that CO2 emissions have a long-run relationship with REC, TFP, exports, income, and imports among the top 20 RECAI countries. The first three determinants reduce CO2 emissions with the estimated elasticities of −0.3, −0.4, and −0.3. Whereas the latter two factors increase emissions with the elasticities of 0.8 and 0.3. It is worth noting that these estimated negative and positive effects from the polled panel are largely supported by the country-specific estimations. Numerically, REC and TFP demonstrate a negative effect on CO2 emissions in 17 and 14 countries, making up 85% and 70% of the total country sample, respectively. Likewise, imports, exports, and GDP have the expected positive, negative, and positive impacts for 17, 16, and 16 countries, respectively (See Table A1). In addition, the analysis indicates that the RECAI countries are commonly affected by global and regional factors, albeit different magnitude of the effects. Moreover, it is revealed that shocks can lead to permanent changes in the levels of the factors of CO2 emissions while their changes in the growth rates of the factors are temporary.

In general, the unique contribution of this study lies in the used theoretical framework, methodology, and obtained empirical findings, which collectively advance our understanding of how economic and energy factors have shaped carbon emissions in the context of RECAI countries, which is quite useful information for sustainable development and economics-energy-environment nexus stand points.

In specific, the following merits can be pointed out. *First*, to the best of our knowledge, this study is the first study to investigate CO2 emissions in RECAI countries using a broader theoretical framework, which incorporates new factors, such as TFP and REC, in addition to factors used in prior studies (i.e., income, exports, and imports). Our research provides a useful context regarding addressing critical challenges of Sustainable Development Goals (SDGs). Precisely, the context brings together three important SDGs, namely Affordable and clean energy (SDG 7), Industry, innovation, and infrastructure (SDG 9), and Climate action (SDG 13). *Second*, we model CO2 emissions using a theoretically grounded framework rather than selecting our variables in an ad hoc manner or out of our interest. Many existing studies follow the latter approach. As a result, their findings mainly indicate correlation rather than causation, casting doubt upon the usefulness of their policy recommendations. *Third*, we consider exports and imports separately rather than aggregating them using, for example, trade openness or trade turnover. We can therefore observe the impacts of exports and imports on CO2 emissions separately and propose variable-specific policy recommendations. Additionally, we use consumption-based CO2 emissions. This emissions measure is adjusted for international trade and, thus, has advantages over territory-based CO2 emissions (Peters et al., 2011; Wiebe and Yamano, 2016; Liddle, 2018). The role of international trade in economic development is growing (Dagar and Malik, 2023; Udemba et al., 2024). *Fourth*, we use modern panel methods that account for the main characteristics of panel time-series data, such as non-stationarity (integration and cointegration), cross-sectional dependence (CSD), and heterogeneity. Many panel studies of carbon emissions ignore these features. Thus, they are fraught with serious econometric problems and misleading policy recommendations. Our methods produce estimation and test results not only for the aggregate panel but also for each country in the panel, which allows one to propose country specific policy insights. A few previous panel studies examined CO2 emissions in RECAI countries using a theory-guided framework while considering the characteristics of panel time-series data.

The remainder of this paper is organized as follows. Section 2 reviews existing studies that are relevant to RECAI countries. Section 3 presents the theoretical framework of the study. Sections 4 and 5 discuss the data and econometric methodology, respectively. Section 6 presents the econometric analysis, and Section 7 discusses the findings. Finally, Section 8 concludes and provides policy implications.

2. Literature review

In this section, we review studies examining the effects of renewable energy consumption (REC and technical progress (TP) on CO2 emissions for the top RECAI countries.[1] Table 1 provides a concise summary of the reviewed studies that may be useful to the reader. As the table shows, most studies examine the effects of REC and TP on carbon dioxide emissions separately. A few studies examine both variables simultaneously. Numerous studies have found negative effects of REC and TP on carbon dioxide emissions, which is relevant to our study objective.

3. Theoretical framework

The Environmental Kuznets Curve (EKC) has been the most extensively utilized theoretical framework for studying environmental pollution. There is not much need for discussion since this framework is well recognized (Grossman and Krueger, 1991; Shafik and Bandyopadhyay, 1992; Panayotou, 1993). The traditional EKC hypothesis suggests an inverted-U relationship between environmental pollution and per capita income that as per capita income increases, emissions initially rise and then decrease after hitting a peak level. Subsequent developments in EKC theory can be found in the studies of Munasinghe (1999), Andreoni and Levinson (2001), Dinda (2002), Dessus and Bussolo (1998), Jaeger (1998), and Selden and Song, 1995. In addition, Dinda (2004) offers a detailed review of the EKC's historical background, conceptual framework, theoretical bases, policy implications, and criticisms.

Despite its widespread use, the EKC framework has faced criticisms due to its limitations, as noted by Dinda (2004) and Brock and Taylor (2010). Subsequent extensions or alternative pollution models have been largely ad hoc, self-interested, and theoretically weak, according to Berk et al. (2022). Few studies, as far as we know, have developed theoretical frameworks for their CO2 emissions models, which we will briefly discuss below.

Brock and Taylor (2010) developed a theoretical framework for CO2 emissions by expanding Solow's economic growth model, known as the Green Solow Model. This theoretical framework enables the empirical estimation of the CO2 emissions growth rate, which is expressed as a function of the logarithm of CO2 emission levels, the logarithm of the average investment-to-GDP ratio representing the savings rate, and the logarithm of average population growth plus a constant. Moreover, Criado et al. (2011) expanded the production function to include endogenous emission cut. In this framework, the growth rates of per capita pollution are influenced positively by the growth rate of per capita output and negatively by the logarithm of per capita emissions along optimal sustainable paths. The logarithm of per capita output can be incorporated into the model as an extra regressor.

Berk et al. (2022) suggested a theoretical framework for CO2 emissions closely resembling that of Brock and Taylor (2010). They enhanced Solow's model by incorporating energy depletion into the production function and delineated the pathway through which CO2 emissions are generated. Their empirical analysis involves estimating a model where factors such as the lagged level of CO2, the savings rate for physical capital accumulation, the adjusted population growth rate considering energy depletion, and the carbon dioxide intensity adjusted for technology contribute to determining CO2 emissions. According to their framework, CO2 emissions are positively associated with production but negatively associated with technological advancement.

Hasanov et al. (2021) utilized a production function and adopted common assumptions found in literature[2] to establish an energy demand model. Initially, they formulated an energy demand equation, which is dependent on capital, labor, energy prices, total factor productivity (TFP), and income. Subsequently, they segregated energy demand into two categories: fossil fuels and renewable sources. By acknowledging the connection between fossil fuel energy and CO2 emissions through the Kaya identity, and incorporating an identity that relates consumption-based CO2 emissions to territory-based CO2 emissions, exports, and imports, they proposed a comprehensive framework for consumption-based CO2 emissions. Their framework suggests that consumption-based CO2 emissions are inversely influenced by TFP and renewable energy, as well as exports, while positively influenced by income (GDP) and imports.

The framework proposed by Hasanov et al. (2021) offers several advantages, notably its incorporation of factors like TFP and renewable energy, which not only mitigate emissions but also stimulate economic growth. This feature can enhance the informational value of the policy-making process by providing insights useful for both emission reduction and economic development. The main distinction between the traditional EKC framework and Hasanov et al., 2021 framework lies in how they treat the impact of technological progress on emissions. In the former, this effect is assimilated into income, making it indistinct, whereas in the latter, it is explicitly identified as a distinct factor.

Except for Hasanov et al. (2021), the theoretical frameworks mentioned above operate under closed economy assumptions, where domestic investment equals domestic savings, and aggregate demand comprises solely investment and consumption. Apart from these restrictive assumptions, these models overlook international trade dynamics, which significantly influence the formation of consumption-based CO2 emissions. Moreover, they treat energy as a unified entity without distinguishing between fossil fuels and renewables, despite the latter's importance in emission reduction. While Brock and Taylor (2010) and Criado et al. (2011) acknowledge the importance of technological progress, their empirical CO2 models do not explicitly incorporate it. Brock and Taylor (2010) even pose a question for future research: what is the significance of technological progress in emission reduction? Additionally, the pollution growth rates in these models are linked to explanatory variables like output growth rates. However, since applied research typically finds that growth rates of both variables are

[1] Since climate change and energy transition literature is very vast, we do not review studies examining other aspects of CO2 emissions and/or renewable energy. For example, a number of studies analyzed convergence in CO2 emissions or renewables among countries (e.g., see Bigerna and Polinori, 2022 for EU-28 countries or Bigerna et al., 2021 for 176 countries).

[2] The assumptions made were: (i) the existence of a cost function as the dual of the production function; (ii) factor pricing being determined by average cost and a fixed markup; (iii) the economy includes a preference function, meaning that the demand for goods and services depends on both price and income; (iv) all functions adhere to a Cobb-Douglas type specification; and (v) first-order conditions are obtained by assuming cost minimization.

Table 1
Summary of reviewed empirical studies.

Study	Time period	Country or region	Method	Variables	Effect of REC on CO_2 found	Effect of TP on CO_2 found
Apergis et al. (2010)	1984–2007	19 developed and developing economies (Argentina, Belgium, Brazil, Canada, Finland, France, India, Japan, Netherlands, Pakistan, South Korea, Spain, Sweden, Switzerland, the UK, and the US)	Panel error correction model	GDP, REC, NREC, CO2	P&S	
Apergis et al. (2013)	1998–2011	Germany, France, and the UK	TAR	CO2, R&D, GDP, OP, TO		N&S
Zhou et al. (2013)	1995–2009	China	System GMM	CO2, TFP, GDP, POP, TO, URB, Infra		N&IS (TFP as the proxy) through the upgrading of the industrial structure
Yin et al. (2015)	2000–2012	China	GLS with random effects	CO2, R&D intensity, POP, EE, ES, IS, TO, FDI		N&S
Bilgili et al. (2016)	1977–2010	17 OECD economies (Argentina, Belgium, Denmark, Canada, Finland, France, Netherlands, Norway, Portugal, Spain, Sweden, Turkey, and the US)	Panel FMOLS and DOLS	GDP, GDP^2 CO2, REC	N&S	
Jebli et al. (2016)	1980–2010	25 OECD countries (Australia, Belgium, Canada, Chile, Denmark, Finland, France, Greece, Italy, Japan, Mexico, Netherlands, Norway, Portugal, South Korea, Spain, Sweden, Switzerland, Turkey, the UK, and the US)	Panel FMOLS and DOLS	GDP, CO2, REC, NREC, Exp, Imp	N&S	
Dogan and Seker (2016)	1980–2012	15 European economies (Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Netherlands, Portugal, Spain, Sweden, and the UK)	Panel DOLS	GDP, GDP^2, CO2, REC, NREC, TO	N&S	
Zoundi (2017)	1980–2012	25 African countries (Egypt, South Africa, and Kenya)	Panel DOLS and FMOLS	GDP, CO2, REC, Primary EC, POP	N&S	
Alvarez-Herranz et al. (2017)	1990–2014	28 OECD countries (Australia, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Japan, Korea, Netherlands, Norway, Poland, Portugal, Spain, Sweden, Switzerland, Turkey, the UK, and the US)	GLS	GDP, CO2, EC, RD&D		N&S
Jin et al. (2017)	1995–2012	China	Regression	CO2, GDP, EE, CPOL, IS, ER&D		N&S
Li et al. (2017)	1997–2014	China	FE	GDP, CO2, R&D, FT, Imp, TR		N&S
Zhang et al. (2017)	2000–2013	China	SGMM	GDP, CO2, EE, R&D, NPAT, TI, PG, GR		N&S
Bhattacharya et al. (2017)	1991–2012	85 developed and developing countries	System GMM and FMOLS	GDP, CO2, LF. GFCF, REC, NREC	N&S	
Danish et al. (2017)	1970–2012	Pakistan	ARDL	GDP, CO2, GDP^2, REC, NREC	N&S	
Khoshnevis Yazdi and Shakouri (2018)	1992–2014	13 EU countries	Panel DOLS and FMOLS	GDP, CO2, GDP^2, REC, URB, EI	N&S	
Khoshnevis Yazdi and Ghorchi Beygi, 2017	1985–2015	25 African economies (Egypt, Kenya, and South Africa)	PMG	GDP, CO2, GDP^2, REC, URB, EC, TO	N&S	
Waheed et al. (2018)	1990–2014	Pakistan	ARDL	CO2, AP, F	N&S	
Mensah et al. (2018)	1990–2014	28 OECD countries	ARDL	CO2, GDP, REC, NREC, R&D	N&S for 10 countries, P&S for 2 countries, IS for 16 countries	N&S for 9 countries, P&S for 3 countries, IS for 16 countries (R&D as the proxy)
Mahmood et al. (2019)	1980–2014	Pakistan	3SLS	CO2, GDP, REC, NREC, HC, TO	N&S	
Adams and Acheampong (2019)	1980–2015	46 sub-Saharan African countries (including Kenya and South Africa)	IV-GMM	CO2, GDP, REC, POP, TO, URB, DEM	N&S	
Cheng et al. (2019a)	2000–2013	BRIICS countries	Pooled OLS	CO2, GDP, RES, Exp, DERT, FDI		P&IS
Dong et al., 2020	1995–2015	120 economies		CO2, GDP, GDP^2, REC, NREC, TO	N&IS	
Gu et al. (2019)	2005–2016	China	GMM	CO2, EC, GDP, FDI, IS		P&S
Yu and Du (2019)	1997–2015	China	RE	CO2, GDP, R&D investment, FDI, IS, POP		P&S

(continued on next page)

Table 1 (*continued*)

Study	Time period	Country or region	Method	Variables	Effect of REC on CO_2 found	Effect of TP on CO_2 found
Cheng et al. (2019b)	1996–2015	OECD countries	PQR	CO2, GDP, GFCF, RES, NPAT, Exp		P&IS
Huang et al. (2020)	2000–2016	China	FE and GMM	CO2, GDP, TFP, IS, URB, EM		N&IS (TFP as the proxy)
Akram et al. (2020)	1990–2014	66 developing countries (Argentina, Brazil, Chile, China, India, Indonesia, Israel, Jordan, Kenya, Pakistan, Philippines, Turkey, Morocco, Mexico, and South Africa)	FE PQR	CO2, GDP, GDP^2, REC, EE, EC, URB, NEC	N&S	
Leitão and Balsalobre Lorente (2020)	1995–2014	28 EU countries	System GMM, FMOLS, and DOLS	CO2, GDP, REC, T, TO	N&S	
Saidi and Omri (2020)	1990–2018	15 OECD economies	VECM	CO2, GDP, REC, NEC, CRD, TO	N&S	
Piłatowska et al. (2020)	1970–2018	Spain	TVAR	CO2, GDP, REC, NEC	N&IS	
Shahnazi and Shabani, 2021	2000–2017	EU countries (including Finland and Poland)	System GMM	CO2, GDP, REC, NREC, EF, URB	N&S	
Hasanov and Mikayilov, 2021	1990–2017	BRICs economies	CS-ARDL	CO2, GDP, TFP, REC, Exp, Imp	N&S	N&S (TFP as the proxy)
Ali and Kirikkaleli (2022)		Italy	NARDL	CO2, GDP, REC, Exp, Imp	N&S	
Adebayo et al. (2022)	1980–2019	Portugal	Morlet wavelet analysis	CO2, GDP, REC, TP, TO	N&S	P&S
Abid et al. (2022)	1990–2019	G8 countries	FMOLS	CO2, GDP, EC, TP, TO, FD, URB		N&S
Mukhtarov et al. (2023)	1993–2019	Azerbaijan	DOLS	CO2, GDP, REC, Exp, Imp	N&S	
Hasanov et al. (2023)	1991–2019	Azerbaijan	Autometrics	CO2, GDP, TFP, REC, Exp, Imp	N&IS	N&S
Mukhtarov (2023)	1990–2019	Turkey	ARDL	CO2, GDP, TFP, REC, Exp, Imp	N&S	N&S
Rafei et al. (2022)	1995–2017	118 countries	PVAR	ECF, FDI, REC, ECI, NR	N&S	
Balsalobre-Lorente et al. (2024a)	1991–2018	G-7 countries	Cup-FMOLS	ECF, ECI, HDI, R&D and RNW	N&S	N&S (R&D as the proxy)
Balsalobre-Lorente et al. (2024b)	1997–2018	G-20 countries	Panel FMOLS	ECI, CF, CO2, REC, GDP, GR, EPU	N&S	
Mukhtarov et al. (2024a)	1993–2020	Kazakhstan	Autometrics	CO2, GDP, FD, REC, Exp	P&IS	
Mukhtarov et al. (2024b)	1996–2021	Canada	FMOLS	CO2, GDP, IQ, REC, TFP, TO	N&S	N&S
Murshed et al. (2021)	1990–2016	Bangladesh, India, Pakistan, and Sri Lanka	AMG, CCEMG	EF, GNI, NREC, REC, FDI, ER	N&S	N&S
Islam et al. (2021)	1972–2016	Bangladesh	Dynamic ARDL	CO2, GDP, IQ, EC, FDI, TO, Glob., Innov.		N&S
Cao et al. (2022)	1985–2018	thirty-six OECD countries	PMG	CO2, GDP, IQ, FD, SM, Glob., Elec.	N&S	

Note: ARDL = autoregressive distributed lags, CS-ARDL = cross-sectional autoregressive distributed lags, DOLS = dynamic ordinary least squares, FE = fixed effect, FMOLS = fully modified ordinary least squares, GLS = generalized least squares, GMM = generalized method of moments, IV-GMM = instrumental variable generalized method of moments, NARDL = nonlinear autoregressive distributed lags, OLS = ordinary least squares, PMG = pooled mean group, PQR = panel quantile regression, RE = random effect, SGMM = system generalized method of moments, TAR = threshold autoregressive model, 3SLS = three-stage least squares, TVAR = threshold vector autoregression, VECM = vector error correction method.

AP = agricultural production, CO2 = carbon dioxide emissions, CRD = domestic credit to the private sector, CPOL = climate policy, DEM = democracy, DERT = development of environment-related technologies, EC = energy consumption, EE = energy efficiency, EF = economic freedom, EI = energy intensity, EM = energy mix, ER&D = research and development in the energy sector, ES = energy structure, Exp = exports, F = forests, FD = financial development, FDI = foreign direct investment, FT = foreign technology, GDP = gross domestic product, GDP^2 = GDP squared, GFCF = gross fixed capital formation, GR = government regulations, HC = human capital, Imp = imports, Infra = infrastructure, IS = industrial structure, LF = labor force, NEC = nuclear energy consumption, NPAT = number of patents, NREC = non-renewable energy consumption, OP = oil price, PG = pollution governance, POP = population, R&D = research and development, RD&D = research, development, and demonstration, REC = renewable energy consumption, RES = renewable energy supply, T = tourism, TFP = total factor productivity, TI = technology innovation level, TO = trade openness, TP = technological progress, TR = technical renovation, URB = urbanization, HDI= Human development indicator, ECF = ecological footprint, ECI = economic complexity, CF= Carbon footprint, GR= Geopolitical Risk, NR = natural resources rent, EPU = Economic Policy Uncertainty, GNI= Real gross national income per capita, ER = Environment-related patents, GLOB = Globalization, SM= Stock market, Innov. = Innovation, Elec. = electricity, GFCFY = gross fixed capital formation % share in GDP, EXPY = exports % share in GDP, FDIY=FDI % share in GDP.

N&S = negative and statistically significant.
P&S = positive and statistically significant.
N&IS = negative and statistically insignificant.
P&IS = positive and statistically insignificant.

BRICs = Brazil, Russia, India, and China.
BRIICS = Brazil, Russia, India, Indonesia, China, and South Africa.
EU = European Union.

stationary processes, these models likely represent short-term dynamics , whereas CO2 emissions are better characterized by long-term relationships (see, e.g., Dinda, 2004). Thus, our theoretical framework comes from Hasanov et al. (2021). As an empirical approach, expressible in econometric estimable form, it can be represented by the model in equation (1) below.

$$co2 = c_0 + c_1 ex + c_2 imp + c_3 gdp + c_4 rec + c_5 tfp + e. \quad (1)$$

The variables in the equation are all in natural logarithmic transformations. *co*2 is consumption-based carbon dioxide emissions. *ex* and *imp* are the shares of exports and imports in gross domestic product (GDP), respectively. $gdp, rec,$ and *tfp* are income measured by GDP, the share of renewable energy consumption in total energy, and total factor productivity, respectively. *e* is the error term. In equation (1), consumption-based CO2 emissions are negatively affected by renewable energy consumption, TFP, and exports, whereas the impacts of imports and GDP are positive. Mathematically, $c_1, c_4, c_5 < 0,$ and $c_2, c_3 > 0$.

4. Data

Fig. 1 shows the amount of CO2 emitted across the RECAI countries we consider in this research.

China's total emissions increased steadily over the study period. By contrast, emissions in the US, the second-largest emitter, fell by 12% from 2007 to 2009. Its emissions then plateaued in subsequent years.

Furthermore, the recently published RECAI report shows changes in renewable energy adoption rates compared with the previous index (Ernst & Young, 2022). As can be seen Fig. 2, different countries exhibit differing trends. For instance, the attractiveness index increased in 10 of the sample countries (the UK, Germany, Australia, Spain, the Netherlands, Denmark, Ireland, Canada, Sweden, and Poland). However, it decreased compared to the previous index in seven countries (France, India, Brazil, Chile, Italy, Israel, and Morocco). Lastly, the attractiveness index experienced no change over the study period in three sample countries (the US, China, and Japan) (Ernst & Young, 2022).

We use a panel of annual time-series data spanning from 1990 to 2018 for the above mentioned 20 RECAI countries. The following variables are used in the empirical analysis.

Consumption-based carbon dioxide emissions (*CO2*). This variable, our dependent variable, is calculated from territory-based CO2 emissions. Specifically, we exclude CO2 emissions embodied in exports from territory-based CO2 emissions and include CO2 emissions embodied in imports. It is measured in millions of tonnes and taken from the Global Carbon Atlas (2019).

Renewable energy consumption (*REC*). This variable is the consumption of energy obtained from renewable sources as a percentage of total energy consumption.

Total factor productivity (*TFP*). This variable is the TFP index collected from the Penn World table 10.0 database.

Income (*GDP*). This variable reflects the final value of goods and services produced within the boundaries of each RECAI country at a specific time. It is measured in constant 2010 US dollars and adjusted for purchasing power parity.

Exports (*EX*). This variable is the exports of goods and services at constant 2010 US dollars as a percentage of GDP.

Imports (*IM*). This variable is the imports of goods and services at constant 2010 US dollars as a percentage of GDP.

Time series values of *REC*, *GDP*, *EX*, and *IM* are obtained from the World Development Indicators Database (World Bank, 2020).

Table 2 shows the descriptive statistics of the variables in their natural logarithmic transformations, denoted by lower-case letters.

5. Empirical analysis strategy and econometric methods

Fig. 3 below illustrates the overall methodology for the empirical analysis through its milestones.

Econometric analysis is the key milestones of the methodology. In addition, it is more scoped than other milestones. Therefore, we present the strategy for the econometric analysis in Fig. 4.

The structure of the strategy is heavily dictated by the characteristics of the panel time-series data, such as cross-sectional dependency (CSD) and nonstationary. The panel time-series data are often cross-sectionally correlated, and not accounting for this dependency can cause serious estimation issues, such as inconsistent estimates. Pesaran (2015a, chap. 29, inter alia) summarizes these concerns.[3] Hence, as Fig. 4 illustrates, we start our econometric analysis by testing for the CSD effect in the data. Pesaran (2007) shows that cross-sectional independence is a strong assumption for panel time-series data. Thus, he develops another test with the null hypothesis of a weak CSD effect and the alternative hypothesis of a strong CSD effect. We use his test in this study. If the test confirms the CSD effect, then first-generation panel tests and estimation methods are invalid (e.g., Baltagi and Hashem Pesaran, 2007; Kapetanios et al., 2011; Sarafidis and Wansbeek, 2012; Pesaran, 2015a).

If the CSD effect is present, we then use a second-generation unit root test to test whether the variables are nonstationary. In other words, we check whether they follow a unit root process. One such test is the cross-sectionally augmented Dickey and Fuller, 1979 (CADF) test by Pesaran (2007). If the variables are nonstationary, we then use the Westerlund (2007) test, which accounts for the CSD effect, to check for cointegration. However, the Westerlund (2007) cointegration test is prone to over-rejection, particularly in small samples. Thus, for robustness, we also employ the Engle and Granger, 1987 cointegration test by applying the CADF test to the residuals of the long-run carbon dioxide equations.

If the Westerlund (2007) test confirms that the variables are cointegrated, then we estimate the long-run relationship for carbon dioxide emissions. For the estimation and to obtain robust results, we use 2 s-generation methods. The first is the common correlated effect mean group estimator (CCEMGE) by Pesaran (2006). The second is the augmented mean group estimator (AUGMGE) by Eberhardt and Teal (2010) and Bond and Eberhardt, 2009. If the Westerlund (2007) test shows that the nonstationary variables are not cointegrated, we can transform them into first differences. Then, we can estimate a short-run relation for the growth rate of carbon dioxide emissions.

If the CADF test shows that the variables are stationary, we can use their logarithms to estimate a short-run relation for carbon dioxide emissions. If Pesaran's (2007) test shows that the data do not have the CSD effect, we implement the same sequence of procedures using first-generation panel methods. This process is shown in the green boxes in Fig. 3.

We prefer Westerlund's (2007) cointegration test and the CCEMGE and AUGMGE methods to other second- or third-generation methods. They can produce cointegration test and long-run estimation results, respectively, for individual countries in addition to the full panel. Thus, we can understand the relationship between carbon dioxide emissions and their determinants both in aggregate and for each country. This study mainly focuses on the results for the aggregate panel, and the

[3] As Pesaran (2015a, chap. 29, inter alia) and the references therein discuss, first-generation panel methods assume that the data are cross-sectionally independent. Thus, these methods can lead to serious estimation issues if the data have CSD. The estimates are likely to be inconsistent if the factors driving the CSD, which are embedded in the residuals, are correlated with the explanatory variables.

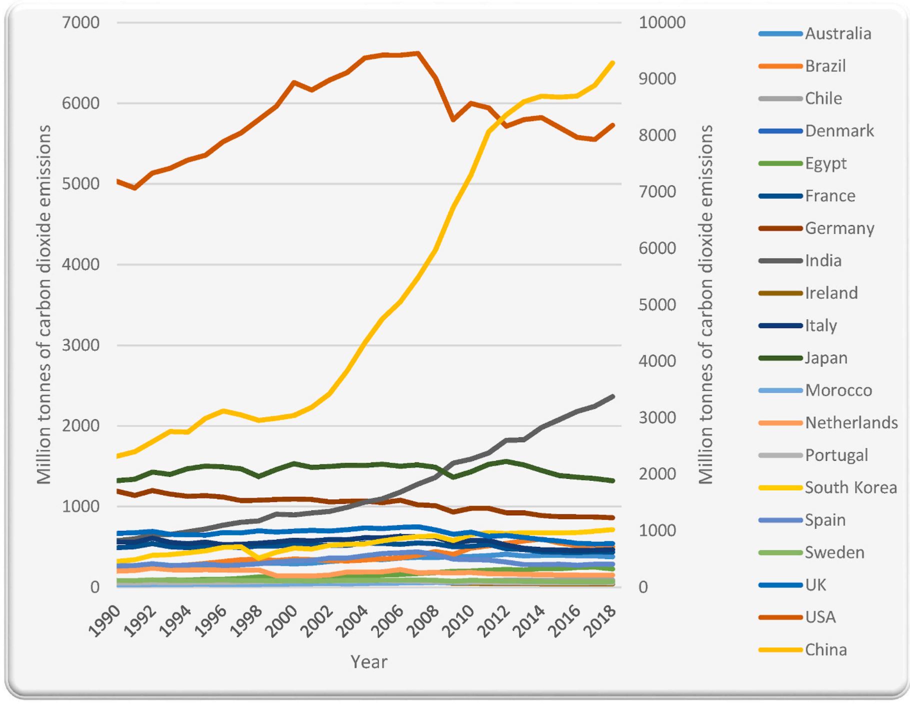

Fig. 1. CO2 emissions in selected RECAI countries.
Source: Global Carbon Atlas, 2019. *Note*: RECAI = Renewable Energy Country Attractiveness Index.

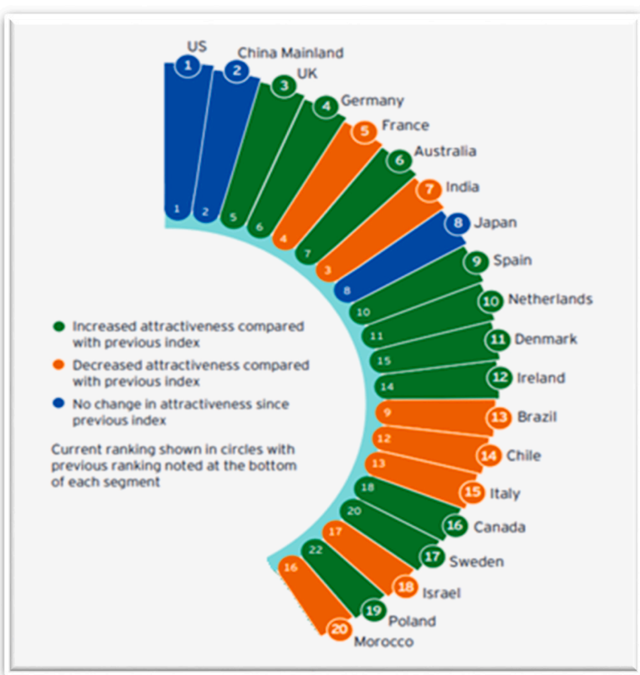

Fig. 2. RECAI index 2022.
Source: Modified from Ernst & Young , 2022. *Note*: RECAI = Renewable Energy Country Attractiveness Index.

results for the individual countries are complementary. Although these results create a useful avenue for future research, country-level research is beyond the scope of our work. Such analyses would require detailed investigations for each country, including accounting for stylized facts.

To obtain additional insights, we use the fixed effect estimator (FEE) and random effect estimator (REE), which are first-generation methods.

Table 2
Descriptive statistics of the variables.

	co2	*ex*	*gdp*	*im*	*rec*	*tfp*
Mean	5.80	3.28	9.74	3.29	2.26	4.55
Median	5.89	3.28	10.32	3.33	2.25	4.58
Maximum	9.14	4.81	11.19	4.66	4.07	4.83
Minimum	3.44	1.91	6.27	1.94	−0.82	4.18
Standard deviation	1.43	0.57	1.21	0.51	1.12	0.11
Number of observations	580	580	580	580	580	580

These methods are intended to supplement CCEMGE and AUGMGE, although they assume cross-sectional independence and, hence, may not provide consistent estimates. The FEE and REE methods are described by StataCorp (2019, 440–71), Baltagi (2013, chap. 2), and Wooldridge (2020, chap. 14), among other sources. We use these methods to check the results when not accounting for the CSD effect. We check whether REC, TFP, and other factors in CO2 emissions take the signs predicted by the theoretical framework of Hasanov et al. (2021).

Before moving to the next section of econometric analysis, we think that it would be insightful for readers if we briefly presented societal benefits of our research in terms of factors of CO2 emissions we consider in this study. Because by focusing on societal benefits, the readers can better understand how this research, through the factors considered, can contribute to the overall well-being and quality of life within a society. Fig. 5 illustrates this.[4]

6. Results of the econometric analysis

Table 3 shows the results of Pesaran's (2015b) CSD test.

The test results profoundly reject the null hypothesis of a weak CSD effect against the alternative hypothesis of a strong CSD effect. Thus, we employ a second-generation panel test and estimation methods to account for the CSD effect, as discussed in the previous section. The results

[4] We thank an anonymous referee for suggesting this to us.

Fig. 3. The flowchart of the methodology for the empirical analysis.

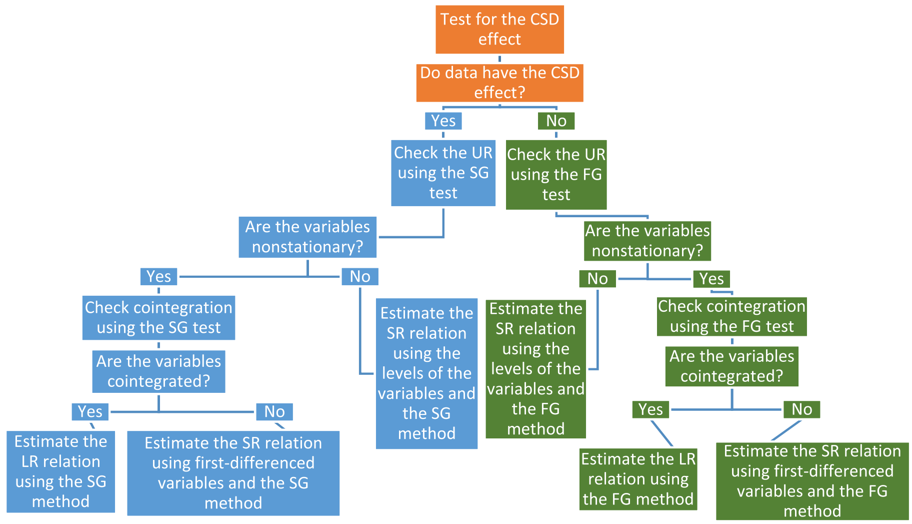

Fig. 4. Strategy for the econometric analysis.
Note: CSD = cross-sectional dependence, FG = first generation, LR = long run, SG = second generation, SR = short run, UR = unit root.

Fig. 5. Societal benefits of the factors considered in this research.

Table 3
Pesaran's (2015b) CSD test.

Variable	CSD test value	Variable	CSD test value
co2	74.126[a]	*ex*	74.043[a]
rec	63.978[a]	*im*	74.081[a]
tfp	74.214[a]	*gdp*	74.197[a]

Note.
[a] indicates the rejection of the null hypothesis at the 1% significance level. The null hypothesis is a weak cross-sectional dependence (CSD) effect.

of the CADF test are presented in Table 4.

We first test the log levels of the variables. The sample values of the Z-test reported in the second column of Table 4 are less than the critical values in absolute terms. Thus, the null hypothesis of a unit root cannot be rejected at any conventional significance level for the log levels of the variables. The variable *ex* is an exceptional case, as the test value is greater than the critical value at the 5% significance level. The null hypothesis can therefore be rejected in favor of the alternative hypothesis of trend stationarity.

Table 4
Pesaran's (2007) CADF panel unit root test results.

Variable	Test value	Variable	Test value
co2	−2.275	Δ*co2*	−1.525**
rec	−0.013	Δ*ep*	−3.850***
tfp	−1.740	Δ*gdp*	−2.448***
ex	−2.810**	Δ*ec*	−4.159 ***
im	−1.148	Δ*ep*	−5.222***
gdp	−0.178	Δ*tfp*	−3.749***

Note: The null hypothesis is that the series follows a unit root process, that is, I (1). The test value is the Z-test value. ** and *** indicate the rejection of the null hypothesis at the 5% and 1% significance levels, respectively. Δ is the first difference operator. Two lags are included in the test equations; the test assumes that cross-sectional dependence takes the form of a single unobserved common factor. An intercept and trend are included in the tests of log levels, but only an intercept is included in the tests of first differences. The log levels of the variables trend or drift typically over time, but their first differences do not. We run the *multipurt* command in STATA to obtain these results. CADF = cross-sectionally augmented Dickey–Fuller.

It is difficult to believe that the exports variable follows a trend-stationary process. This result implies that this variable's development trend is deterministic rather than stochastic. However, many of the domestic and foreign factors determining exports evolve in stochastic rather than deterministic ways. These factors include exchange rate movements, that is, appreciations and depreciations; domestic and foreign prices; and other market conditions.

Thus, we also run Karavias and Tzavalis, 2014 unit root test for the exports variable. This test accounts for the CSD effect and cross-sectional heterogeneity in addition to possible structural breaks. It takes the null hypothesis that all panel time series follow unit root processes. The alternative hypothesis is that some or all panel time series follow stationary processes with structural breaks. We include an intercept and trend in the test specifications and allow for two possible structural breaks. The test sample value (i.e., the minimized Z-statistic) is 0.005. This value is significantly smaller in absolute terms than the bootstrapped test critical value of −0.027 at the 5% significance level. This finding indicates that the null hypothesis of a unit root process cannot be rejected for *ex*.

We then test the first differences of the log levels of the variables. The sample values of the Z-test reported in the fourth column of Table 3 are greater than the critical values in absolute terms. Hence, the null hypothesis of a unit root can be rejected at the 5% significance level for $\Delta co2$. It can be rejected at the 1% significance level for the remaining variables. To summarize the results of the unit root tests, we can conclude that all our variables follow unit root processes at their log levels. However, they are stationary in the first differences of their log levels. In other words, the variables are integrated in the order of one, that is, they are I(1) variables.

The stochastic trends (i.e., unit root processes) in the variables may cancel each other out such that a linear combination of them is stationary. Cointegration theory states that these unit root variables can establish a relationship that is consistent with economic theory. Such relationships are considered long-run relationships (e.g., Enders, 2015). We test this possibility for our variables by conducting a Westerlund (2007) cointegration test. Table 5 presents the results.

We first focus on the results when the test equation includes an individual intercept but not a trend. In this case, Westerlund's (2007) G_t and P_a test statistics reject the null hypothesis of no cointegration at the 10% significance level. Moreover, the G_t test rejects the null hypothesis at the 16% significance level when a trend is included in the test specification. Westerlund (2005, 2007) explains that it is difficult to reject the null hypothesis for the G_t statistic in small samples. In this case, few lags and leads should be included in the test equation to conserve the degrees of freedom for efficient estimations. However, doing so can cause serial correlation in the residuals of the test equation, which, in turn, leads to the under-rejection of the null hypothesis. Thus, we can conclude that the variables under consideration establish a co-integrated relationship.

Table 5
Westerlund (2007) cointegration test results.

Test statistic	Individual intercept and trend	Individual intercept and no trend
G_t	−3.217 (p-value = 0.16)	−2.970[a]
G_a	−5.266	−6.540
P_t	−9.935	−11.357
P_a	−9.861	−11.005[a]

Note.
[a] indicates that the null hypothesis is rejected at the 10% significance level. P_t and P_a are panel test statistics for the null hypothesis of no cointegration. The alternative hypothesis is that the panel is cointegrated as a whole. G_t and G_a are group-mean test statistics for the null hypothesis of no cointegration. The alternative hypothesis is that at least one element in the panel is cointegrated. We specify one lag and no leads given the number of observations and the degrees of freedom in running the test. The values in the table are the results of 50 bootstraps.

Table 6 shows the results of the CADF test of the residuals of the level equations for *co2*. The tests profoundly demonstrate the stationarity of the residuals when we use the CCEMGE and AUGMGE methods. This result holds regardless of whether the intercept and trend or only the intercept is included in the CADF test equation. Thus, the CADF test supports the results for the G_t and P_a statistics when the equation includes an individual intercept and no trend. Together, they indicate cointegration among the variables.

Because the data support the existence of cointegration among the variables, we can estimate the parameters of the long-run relationship. As discussed in the previous section, we run the CCEMGE and AUGMGE methods with robust standard errors in addition to the FEE and REE methods. The results of the long-run estimations for *co2* are presented in Table 6 along with the unit root-based cointegration test results described above.

For readers convenience, Fig. 6 graphically summarizes our main findings from the econometric estimations regarding the impacts of the factors on CO2 emissions.[5]

7. Discussion

The results reported in Table 3 show that our data have a strong CSD effect. This result suggests that the 20 RECAI countries in our sample are interdependent by means of common factors. Empirical studies investigating CO2 emissions (or energy consumption) find that common international and intraregional factors may lead to interdependence in economic, energy, and environmental indicators across countries in the panel sample (e.g., see ; Liddle and Hasanov, 2022; Ullah et al., 2023; Yadav et al., 2024). Examples of such factors include, but not limited to, climate change policies adopted by international and or regional organizations; dynamics, shocks, and tendencies in the global energy markets; energy transition policies; technology transfers and spillovers; global trade, financial, and labor flows; memberships in the regional and international organizations (Rao et al., 2023; Alvarado et al., 2022). For

Table 6
Long-run estimation results.

		FEE	REE	CCEMGER	AUGMGER
rec		−0.215***	−0.213***	−0.135***	−0.277***
		(0.000)	(0.000)	(0.000)	(0.000)
tfp		−0.673***	−0.636***	−0.370	−0.350*
		(0.000)	(0.000)	(0.167)	(0.053)
ex		−0.331***	−0.337***	−0.267***	−0.275***
		(0.000)	(0.000)	(0.003)	(0.001)
im		−0.370***	−0.372***	−0.240***	−0.288***
		(0.000)	(0.000)	(0.006)	(0.000)
gdp		−0.836***	−0.821***	−0.724***	−0.819***
		(0.000)	(0.000)	(0.000)	(0.000)
CADF	C&T	−1.516	−1.516	−14.559	−8.711
		(0.065)	(0.065)	(0.000)	(0.000)
	C	−1.645	−1.569	−16.636	−11.399
		(0.950)	(0.942)	(0.000)	(0.000)

Note: p-values are in parentheses. Deterministic terms, such as the constant and trend, are not reported for simplicity. The trend was excluded from the estimations, as it was not statistically significant. Number of time-series observations = 29. Number of countries = 20. FEE = fixed-effects (within) regression estimation, REE = random-effects generalized least squares regression estimation, CCEMGER = common correlated effects mean group estimator with robust standard errors, AUGMGER = augmented mean group estimator with robust standard errors. Cross-sectionally augmented Dickey–Fuller (CADF) indicates Pesaran's (2007) cross-sectionally augmented Dickey–Fuller unit root test. The test equation is run with a constant and trend (C&T) and with a constant but no trend (C). Both include zero lags, which is the most relevant lag order.

[5] We thank an anonymous referee for this suggestion.

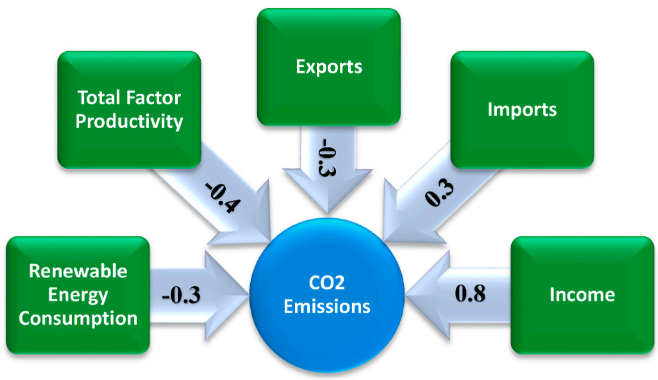

Fig. 6. The findings regarding the impacts of the factors on CO2 emissions in equation (1).

example, we find strong interdependencies in CO2 emissions variables across the 20 RECAI countries (and the same is true for renewable energy consumption and TFP), which can be caused by the factors listed above. The key interpretation of this finding is that CO2 emissions of the selected countries are also influenced by the mentioned common factors in addition to the explanatory variables considered in the theoretical model.

We also find that our variables are non-stationary in their log levels but they are stationary when their growth rates are considered (Table 4). This result implies that shocks can create permanent changes in the log levels of the variables. Hence, mean values of the variables drift over time, which makes it difficult to predict the future paths of them. In contrast, shocks cannot create permanent changes in the growth rates of the variables. Therefore, it is relatively easy to predict their future paths as these growth rates usually move around their mean values, which do not change considerably over time.

Another implication of the non-stationarity is that regressing such variables one on others can yield spurious results unless cointegration, that is, a long-run relationship among them is confirmed statistically though formal test. The cointegration test results in Tables 5 and 6 confirm that CO2 emissions and determinants considered have common stochastic trends that cancel each other out. The interpretation of the cointegration here is that CO2 emissions establish a long-run relationship with the determinants that can be explained using the theoretical framework considered. Cointegrated relationship also implies that deviations from the long run relationship that CO2 emissions establish with REC, TFP, GDP, exports, and imports are temporary, that is, short-lived and will restore back to this relationship.

A discussion of the estimation results from the long-run relationship reported in Table 6 is of more interest. Hence, we discuss some observations below regarding the signs, sizes, and significance levels of the long-run estimations. *First*, the signs of the impacts of the explanatory variables on CO2 emissions are in line with the theoretical articulation in Section 3. In addition, the coefficients of the explanatory variables have the same signs regardless of whether we account for common factors, that is, the CSD effect or not. Precisely, consumption-based CO2 emissions are negatively related to renewable energy consumption, TFP, and exports while positively associated with imports and GDP in all cases (see Fig. 6).

It is worth noting that country-specific estimation results from the CCEMGER and AUGMGER methods (with robust standard errors), are greatly consistent with the pooled results mentioned above. Discussing in detail, Table A1 in the Appendix documents the estimation results for the relationship between CO2 emissions and their determinants for each country. A key observation from this table is that the individual country-level data profoundly support the theoretical framework in Section 3. We observe negative impacts of REC, TFP, and exports and positive impacts of imports and GDP on consumption-based CO2 emissions. For instance, REC negatively impacts CO2 emissions in 17 out of 20 countries, or 85% of the total sample. More strikingly, 16 of these 17 coefficients are statistically significant. TFP exerts a negative impact on CO2 emissions in 14 countries, or 70% of the entire sample. Similarly, exports, imports, and GDP have the expected negative, positive, and positive impacts for 16, 17, and 16 countries, respectively.

These results discussed above for individual countries still hold, even if we did not account for country-specific characteristics in the estimations. The country-level estimation results using the CCEMGER method (with robust standard errors) are similar to those from the AUGMGER above. For example, REC has a negative impact on CO2 emissions in 18 countries. The results are not reported for brevity but can be obtained from the authors on request.

Second, the sizes of the impacts of the explanatory variables on CO2 emissions do not change significantly across methods except in the case of TFP. The magnitudes of the impacts of REC, exports, imports, and GDP are around −0.2, −0.3, 0.3, and 0.8, respectively across all four estimation methods (see Table 6). This shows that not accounting for common unobserved factors changes the magnitudes of elasticities only marginally for the 20 RECAI countries under consideration. To be numerically precise, although the differences are quite small, the elasticities estimated from the first-generation estimations (that is, FEE and REE) are systematically higher than those from the second-generation estimations (i.e., CCEMGER and AUGMGER) in the table. However, the estimated elasticities of CO2 emissions with respect to TFP is greater if unobserved common factors are ignored than when they are accounted for. In other words, the estimated impact of TFP is greater from the first-generation estimation methods assuming cross-sectional independence than those of the second-generation methods. Another notable observation comes from the country-specific estimates in Table A1 regarding the size of the impact of the factors. Overall, the elasticity of CO2 emissions with respect to TFP is high for developed economies and low for developing ones. For example, for the US and the UK, the elasticities are -1.5 and -2.1, respectively, whereas for Egypt, it is -0.2.

We may therefore surmise that TFP is associated with unobserved factors being common to the 20 RECAI countries considered. Technological progress and efficiency gains, the components of TFP, are among common factors discussed in the literature (e.g., Ahmad and Wu, 2022; Ditzen, 2018; Ertur and Koch, 2007, 2011). Moreover, previous panel studies consider unobserved common factors as a proxy for TFP (e.g., Eberhardt and Teal, 2010). Econometrically, the decrease in the magnitude of the coefficient of TFP when moving from first-generation to second-generation estimations is reasonable from an omitted variable perspective. If the impacts of the unobserved common factors are not accounted for, they are embedded in the effect of TFP, increasing its magnitude. However, CCEMGER and AUGMGER (with robust standard errors) include the cross-sectional averages of the variables in the estimations as separate regressors, proxying unobserved common factors. Thus, these second-generation estimators account for and estimate effects of TFP and common factors separately.

Third, the findings in Table 6 show that the impacts of REC, exports, imports, and GDP are statistically significant at the 1% level. The effect of TFP is also statistically significant at the 1% level when we use first-generation methods. When we use second-generation methods, TFP's impact is still statistically significant, but the significance level falls to around 10%. This change may be caused by the association between TFP and unobserved common factors, as discussed above.

The results of the unit root test on the long-run disequilibrium errors estimated using first-generation methods, shown in Table 6, are also noteworthy. Specifically, deviations from the long-run equilibrium relationship of CO2 emissions become trend-stationary when the trend is included in the unit root test equation. These deviations are nonstationary if only a constant and not a trend is included in the test equation. This finding indicates that unobserved common factors embedded in the errors of the long run equilibrium relationship make them nonstationary. If the trend is included, however, it captures these unobserved factors. As a result, the deviations from the long-run equilibrium relationship that CO2 emissions establish with their determinants become stationary around this deterministic trend. In other words, they follow a trend-stationary or I(0) process with a non-zero trend.

This finding of a long-run relationship between CO2 emissions and their determinants using first-generation methods can be explained by the stochastic long-run relationship. Campbell and Perron, 1991, Perron and Campbell (1994), and Ogaki and Park (1997), among others, discuss stochastic versus deterministic cointegration. We can conclude that the level estimations from the first-generation methods of FEE and PEE are not spurious. Thus, they can be used for discussions considering the trends that most likely capture common unobserved factors in the data.

If we consider the estimation results from AUGMGER, numerically, holding other factors constant, a 1% increase (decrease) in renewable energy, TFP, and exports leads to a reduction (rise) in the consumption-based CO2 by about 0.3%, 0.4%, and 0.3%, respectively, in the long run. Similarly, consumption-based carbon dioxide emissions decrease (increase) by 0.3% and 0.8%, respectively, if imports and GDP decrease (increase) by a 1% in the long run. These results are reported in Table 6. The remainder of this section explains obtained results above in more detail.

From theoretical and empirical perspectives, the negative association between REC and CO2 emissions for the RECAI countries is reasonable. More renewable energy as a share of total energy consumption means a lower share of fossil fuel energy and, thus, lower CO2 emissions. Conceptually, assume that additional energy demand is met by renewable energy and the amount of fossil fuel energy does not change. In this case, renewable energy, and its share in total energy increase. If all other drivers of CO2 emissions remain unchanged, the amount of fossil fuel energy and, hence, carbon dioxide emissions remain constant.[6] In this situation, renewables have no statistically significant effect on CO2 emissions, as the former increases and the latter remains constant over time.

In our sample of RECAI countries, however, renewable energy has statistically significant negative effects on consumption-based CO2 emissions. This finding implies that the sample RECAI countries, in aggregate, increased REC while reducing CO2 emissions during the study period. They most likely achieved this outcome by decreasing fossil fuel energy consumption. Any other finding would be unexpected, as RECAI countries rank highest globally in terms of REC. Our estimation results are in line with those of the studies surveyed in Table 1 that include RECAI countries in their analysis.

The negative impact of TFP on consumption-based CO2 emissions is articulated in the framework discussed in Section 3. Empirical studies that include RECAI countries in their analyses also find the negative relationship, as Table 1 shows. Economically, the negative impact of TFP on consumption-based CO2 emissions can be explained as follows. TFP has two major components: technological progress and efficiency gains. Increases in these components are likely to result in reduced energy consumption and lower CO2 emissions. Hasanov et al. (2021) derive theoretical results for the case in which the estimated coefficient of TFP is unity. In this case, the production of goods and services in the given country (or country group) has constant returns to scale. Similarly, if the estimated coefficient of TFP is greater (or less) than unity, then the production process has increasing (decreasing) returns to scale. In this regard, we can conclude that our country group, as a panel, exhibits decreasing returns to scale. This result may arise because our sample includes developing economies, such as China, India, Brazil, Egypt, and Morocco, in addition to developed economies.

We do not explain the negative impacts of exports and the positive effects of imports on consumption-based CO2 emissions in detail. The impacts of the former variables are straightforwardly related to the definition of the latter variable. Specifically, consumption-based CO2 emissions are derived from territory-based carbon dioxide emissions by considering imports and exports. First, the carbon dioxide embedded in exported goods and services is subtracted from territory-based CO2 emissions. Second, CO2 contained in imported goods and services is added to territory-based CO2 emissions (e.g., Liddle, 2018; Hasanov et al., 2021; Mikayilov et al., 2020; Hasanov et al. 2018). From this definition, it is clear that if more goods and services are exported, less CO2 is emitted domestically. Conversely, if more goods and services are imported, more CO2 is emitted in the domestic economy. Lastly, the positive impact of GDP on CO2 emissions is consistent with the theoretical framework in Section 3. This finding also supports conventional environmental theories, such as the EKC and stochastic impacts by regression on population, affluence, and technology.

8. Conclusion and policy insights

Carbon dioxide emissions are a recognized threat to humanity, and many global and country-specific programs have been launched to reduce them. Given their importance, we analyzed their drivers with a focus on RECAI countries. Our sample includes a diverse set of developing and developed countries from different regions. These countries can serve as benchmarks for other countries in terms of their renewable energy consumption and technological development levels. The traditional theoretical framework regarding environmental pollution, like the EKC, offers restricted insights into policies aimed at reducing emissions. Consequently, there is a necessity to explore comprehensive and theoretically sound frameworks when examining CO2 emissions. To this end, this study considered the theoretical framework proposed by Hasanov et al. (2021), as it articulates explanatory factors of CO2 emissions that are policy relevant such as technological progress, renewable energy, and exports having both emission reduction and growth enhancing features. We applied advanced panel time series methods to the sample of 20 RECAI countries over the period 1990–2018. The key advantages of these methods are that they can tackle the main issues of the panel data (e.g., cross-sectional dependence, non-stationarity, and heterogeneity) and can produce not only common panel but also country specificities estimation results, which allow to propose country specific policy insights. Using this sample, we estimated long-run relationships between CO2 emissions and renewable energy consumption, TFP, exports, imports, and GDP.

A few insights derived from this empirical analysis may be useful for policymaking. Policymakers in RECAI countries should be aware that these countries are interdependent or affected by common factors. Such factors may include climate protection policies and agreements adopted by international and/or regional organizations, energy transition policies, technology transfers, global energy and financial shocks, institutional memberships, and regional and international trade, finance, and labor flows. Particularly in times of crisis or shock, the economy becomes vulnerable to contagious effects that could hinder advancement (Bekaert et al., 2005; Kakran et al., 2023).These factors should be considered when designing policies to reduce CO2 emissions. Authorities should focus on measures that boost renewable energy consumption, TFP, and exports. These factors not only reduce CO2 emissions but also support green economic growth. They should also consider that GDP and import growth will be accompanied by increases in CO2 emissions. Moreover, policy-related and other shocks may change or eliminate the relationships between CO2 emissions and their abovementioned determinants in the short run. Over time, however, the long-run relationships will emerge again.

To boost TFP, decision makers can focus on either technical innovation, efficiency, or both components, depending upon available resources. It may be easier to achieve efficiency through awareness programs than to achieve a high level of technical innovation.

[6] Here, we assume that CO2 emissions are from fossil fuels. This assumption is not unreasonable given that about 90% of total carbon dioxide emissions are from fossil fuels (https://www.deepmarkit.com/carbon-markets; Le Quéré et al., 2012).

Investment, particularly foreign direct investment, and openness play important roles in fostering renewable energy consumption and TFP. Policymakers can adopt measures to reduce imports without compromising economic growth. For example, they can impose tariffs on goods and services with high CO2 content. They can take measures to produce alternative goods and services domestically to substitute imports with high CO2 content. The authorities in RECAI economies can take measures to increase exports. Such measures may include market search, improving trade infrastructure, easy access to finance, having new trade agreements, lowering tariffs and duties. However, although increasing exports will lead to emission reduction and economic growth in home countries, they may increase consumption-based emissions in importing economies. Thus, importing economies will eventually try to import fewer such goods and services to comply with pollution mitigation strategies and develop local content. Finally, GDP as a measure of income is associated with high CO2 emissions in our sample. Thus, policymakers, particularly those in the developing economies, may want to implement strategies and measures that can encourage the growth of the service sector. This is because industrial-based economic growth is usually more pollutive than service-based growth.

In summary, the transition to a low-carbon society is a difficult task that requires balancing economic growth and environmental protection. Effectively addressing these serious global concerns requires a confluence of factors, including international collaboration, technological progress, policy formulation, and active involvement of the public. The key in ensuring a sustainable and fair future for all countries is striking a balance between the need for wealth and environmental sustainability.

It is important to point out the main limitations of our study. First, since the data of all countries are not available, only the top 20 RECAI countries were analyzed in this study. The RECAI, developed by Ernest and Young, identifies the 40 most attractive countries globally in terms of renewable energy investment and deployment opportunities. In future studies, including all countries in the scope of analysis may provide more insights for researchers and practitioners. Another limitation of our research is that we have conducted analysis using national level data, but it also would be beneficial to delve into sectors of economy such as industry, transport, commercial, and agriculture when examining CO2 emissions. This would enable one to propose more targeted policies tailored to each sector's specific needs.

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Fakhri J. Hasanov: Writing – review & editing, Writing – original draft, Resources, Methodology, Investigation, Data curation, Conceptualization. **Shahriyar Mukhtarov:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation. **Elchin Suleymanov:** Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Investigation. **Sa'd Shannak:** Writing – review & editing, Writing – original draft, Visualization, Resources, Investigation, Data curation, Conceptualization.

Declaration of competing interest

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.

Data availability

Data will be made available on request.

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Appendix A. Results for Individual Countries

Table A1
AUGMGER estimation results for individual countries.

	rec	*tfp*	*ex*	*im*	*gdp*
Australia	−0.006	−0.043	0.117	−0.186	0.996
Brazil	−0.576	−1.302	−0.313	0.170	1.503
China	−0.571	0.392	−0.419	0.174	0.312
US	−0.169	−1.477	−0.331	0.390	1.013
UK	−0.150	−2.061	−0.340	0.239	1.052
France	−0.355	0.007	−0.302	0.129	−0.020
India	−0.732	−0.741	−0.075	0.243	0.853
Germany	−0.211	−0.140	0.239	0.081	−0.329
Japan	−0.257	1.878	−0.356	0.103	0.349
Netherlands	0.096	−0.566	0.815	−1.233	−1.226
Spain	−0.287	−0.665	−0.405	0.326	0.810
Chile	−0.505	0.597	−0.040	0.504	1.014
Italy	−0.089	0.721	−0.602	0.483	0.270
Ireland	−0.387	−0.840	−0.526	0.389	1.003
Denmark	−0.334	−0.378	0.387	−0.412	0.875
South Korea	0.027	−0.641	−0.662	0.537	0.911
Morocco	−0.051	−0.529	−0.052	0.418	0.743
Egypt	0.101	−0.226	−0.445	0.341	1.388
Portugal	−0.545	−0.275	−0.551	0.372	0.650
Sweden	−0.557	0.272	−0.704	0.949	−0.429

Note: The values in the table are estimated coefficients. Each value is the elasticity of CO2 emissions with respect to a given regressor for the given country. The coefficients of deterministic terms, such as the constant and trend, are not reported for brevity. The number of time-series observations for each country is 29. The number of countries is 20. AUGMGER = augmented mean group estimator with robust standard errors.

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