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Article

Carbon emission drivers in the Belt and Road Initiative countries—An empirical analysis based on countries with different income levels

Baihe Gu[1,2,✉], Jing Liu[1], Yuhui Sheng[2], Ryna Cui[3]

[1]*Institutes of Science and Development, Chinese Academy of Sciences, Beijing 100190, China*
[2]*School of Public Policy and Management, University of Chinese Academy of Sciences, Beijing 100049, China*
[3]*Center for Global Sustainability, School of Public Policy, University of Maryland, College Park 20742, USA*

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ABSTRACT

Many Belt and Road Initiative (BRI) countries, being developing nations, are likely to experience rising carbon emissions due to rapid economic and social development. Promoting a low-carbon transition is essential for meeting the Paris Agreement goals. This paper employs a two-stage decomposition model to examine carbon emission trends and drivers across different income levels within BRI countries. Emission changes are attributed to four factors: economic scale, population, energy intensity and carbon intensity of energy consumption. Additionally, carbon intensity is further decomposed into coal, oil, natural gas, and non-fossil energy to assess the contributions of each energy source to emissions. Our findings reveal that while carbon emissions in BRI countries are gradually increasing, per capita emissions remain much lower than those in developed nations. Economic scale emerged as the primary driver of emission growth from 1987 to 2022, while energy and carbon intensity contributed to emission reduction. During economic crises, most BRI countries often rely on high-carbon energy for transition and relax energy efficiency standards. In low- and lower-middle-income BRI countries, energy efficiency contributes to carbon emissions growth, underscoring the significant potential for energy efficiency improvements in these regions. Notably, many BRI countries are lagging or have not yet to initiate a low-carbon transition, particularly lower-income countries, which are increasingly reliant on fossil fuels. Higher-income BRI countries have gradually shifted the energy mix from oil and coal to natural gas. Finally, recommendations are made to facilitate carbon emission reductions in BRI countries, emphasizing the importance of international cooperation.

KEYWORDS

Belt and Road Initiative, carbon emission drivers, income level, carbon intensity of energy consumption, LMDI (log-mean Divisia index).

1 Introduction

The Paris Agreement, adopted in December 2015, set the goal of holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels. Subsequently, countries across the world proposed and updated their intended nationally determined contributions (INDCs). As of September, 1 2024, 101 countries have set net-zero emission targets in the form of legislation, policy pledges, and verbal commitment[1]. However, these emission reduction ambitions fall far short of the Paris Agreement goals. Even if all conditional NDCs are successfully implemented, global warming can only be limited to 2.5 °C by the end of this century (with a 66% probability). If all net-zero emission pledges are also successfully achieved, global warming could be limited to 1.9 °C (with a 66% probability)[2]. Recognizing the huge gap between climate ambitions and actual actions, it is imperative to act in a more aggressive and pragmatic way.

Developed countries are cumulatively responsible for about 79% of global carbon emissions from 1850 to 2011[3]. In recent years, however, developing countries have represented a larger share of global carbon emissions than developed countries and seen their emissions increasing at a rapid pace[4]. Global CO_2 emissions reached 38.50 Gt in 2019, of which 66% came from developing countries. Thanks to the first-mover advantage brought about by industrialization, economic growth, carbon emissions of developed countries are in a state of strong decoupling, which has been constantly enhanced. In developing countries, there is no clear decoupling trend, while large fluctuations are observed[5]. Considering the relatively weak financial and technological capacity of developing countries, the United Nations Framework Convention on Climate Change (UNFCCC) set down the principle of “common but differentiated responsibilities”, which requires developed countries to help developing countries better address climate change. At the Copenhagen Climate Summit, developed countries pledged to provide at least 100 billion US dollars per year by 2020 to developing countries in climate finance. However, only 83.3 billion US dollars were mobilized in 2020, of which most went to middle-income countries and only 8% to low-income countries[6].

The Belt and Road Initiative has received positive responses from more and more countries and international organizations since launched. As of January 2024, China has signed cooperation documents on jointly building the Belt and Road Initiative with 153 countries[7]. Green development has gradually become an underlying principle of this initiative, with climate change of

✉Address correspondence to Baihe Gu, E-mail: gubaihe@casisd.cn

growing concern. The "Vision and Actions on Jointly Building Silk Road Economic Belt and 21st-Century Maritime Silk Road" unveiled in 2015 called for efforts to promote green and low-carbon infrastructure construction and operation management, taking into full account the impact of climate change on the construction. The "Vision and Actions on Energy Cooperation in Jointly Building Silk Road Economic Belt and 21st-Century Maritime Silk Road" published in 2017 proposed to strengthen cooperation in seven key areas, including policy coordination, energy infrastructure connectivity, unimpeded trade, energy investment cooperation, energy production capacity cooperation, sustainable energy for all, and better global energy governance structure. The "Opinions on Jointly Promoting Green Development of the Belt and Road" released in 2022 urged efforts to jointly promote green development of the Belt and Road, taking climate change as a key area of cooperation.

It should be noted that 80% of the Belt and Road Initiative countries are developing countries, and more than 50% are lower-middle and low-income countries, indicating significant differences economic development levels. In 2022, the Belt and Road Initiative countries accounted for over 64% of both the global population and global carbon emissions and approximately 60% of global energy consumption, yet contributed less than 40% to the global gross domestic product (GDP). As efforts towards sustainable development goals and poverty eradication progress worldwide, there remains substantial potential for economic and emission growth in the Belt and Road Initiative countries. Building a green Belt and Road will become an important endeavor of development in the future and play a significant role in global climate governance. Therefore, it is necessary to analyze the driving forces of carbon emission changes for the Belt and Road Initiative countries in different periods of time and at different levels of development, so that differentiated emission reduction proposals can be developed for different groups of the Belt and Road Initiative countries in respect of local conditions.

Existing studies on carbon emission drivers primarily utilize the factor decomposition approach[8] and the econometric modeling approach[9, 10]. Models such as STIRPAT (Stochastic Impacts by Regression on Population, Affluence, and Technology) and IPAT are widely used in econometric modeling for regression analysis[11, 12], allowing for the flexible incorporation of various influencing factors based on research needs. While econometric modeling estimates the elasticity coefficients of influencing factors, factor decomposition measures the actual contribution of each influencing factor to carbon emissions. The factor decomposition approach includes structural decomposition analysis (SDA) and index decomposition analysis (IDA). SDA, based on the input-output table, can be used to analyze influencing factors by sectors[13], consumption and investment[14], and embedded carbon emissions[15]. IDA requires less data than SDA and is suitable for factor decomposition with fewer factors over different time series. The log-mean Divisia index (LMDI) approach, introduced by Ang[16], has been widely used in the factor decomposition analysis of carbon emissions due to its advantages of full decomposition and zero residuals[17–19].

The main drivers of carbon emissions vary among countries and regions due to differences of economic development and technological levels. Existing studies paid more attention to carbon emission drivers at the global level as well as of developed economies. Taking into account income levels and time periods, they analyzed carbon emission drivers at different spatial scales, including global[20, 21], OECD[22], G20[23], and EU[24]. There are fewer studies analyzing emission drivers at an overall level for developing countries, except for case studies of individual countries or regions, such as China[25, 26], Pakistan[27], Asia-Pacific[28], and Indonesia[29]. Globally, economic development is the primary factor driving the increase in CO_2 emissions. However, in some regions, such as Africa, population growth is the main contributor. Developed economies such as European countries and the United States have achieved CO_2 emission reduction by raising energy efficiency and optimizing energy mix, but most developing countries exhibit continuous growth in carbon emissions[30]. Coal consumption is a significant factor driving emission growth in countries with lower levels of development[31].

Existing studies have explored various factors influencing carbon emissions in the Belt and Road Initiative. These factors include population and urbanization[32, 33], economic and industrial development[34, 35], energy consumption[36], international trade[37], and foreign direct investment[38]. Researchers have also examined carbon emission drivers in sectors such as power generation[39] and transportation[40]. Hu et al. utilized the Kaya identity and the LMDI approach to divide CO_2 emission drivers into five factors, and analyzed these drivers across seven regions in Belt and Road Initiative countries[41].

Among the studies on the influencing factors of carbon emissions in the Belt and Road Initiative countries, few have compared the driving forces in countries with different income levels across various development periods. Jia et al.[42] is one of the few studies that examine the drivers of carbon emission reduction in Belt and Road Initiative countries by income levels. However, the study's scope is limited to 55 Belt and Road Initiative countries, with a relatively short data span from 1992 to 2014. Additionally, the analysis of energy structure lacks sufficient detail, which restricts a more granular understanding of how different energy types contribute to emission reduction. To address this gap, this paper explores the patterns and heterogeneity of carbon emission drivers in 102 Belt and Road Initiative countries across different income levels, and further examines the contributions of different energy sources to changes in carbon emissions. First, we review the current status of Belt and Road Initiative countries in terms of their carbon emissions, energy consumption, GDP, and population. Second, we decompose changes in carbon emissions in these countries into four factors: economic scale, population size, energy intensity, and carbon intensity of energy consumption. This analysis covers four development periods (1987–1997, 1998–2008, 2009–2019, and 2020–2022). Third, we analyze the differences in the influencing factors of carbon emissions among countries with different income levels—high, upper-middle, lower-middle, and low. Finally, we further decompose the carbon intensity of energy consumption into the effects of four energy sources: coal, oil, natural gas, and non-fossil energy. This paper makes significant contributions by constructing a two-stage carbon emission factor decomposition model that accounts for income levels, analyzing the carbon emission drivers of Belt and Road Initiative countries and regions across different development periods, and exploring the impacts of different energy sources on carbon emission changes from the perspective of energy transition.

2 Methods and data

2.1 Kaya identity

The Kaya identity is a decomposition that expresses the level of carbon emissions as the product of per capita GDP, population, and other factors[43]. It has been widely used in decomposition analysis of GHG emission factors, including by well-known organizations such as the International Energy Agency (IEA). The Kaya identity is written as Eq. (1):

$$C = \frac{C}{E} \cdot \frac{E}{GDP} \cdot \frac{GDP}{P} \cdot P = ECI \cdot EI \cdot PG \cdot P \tag{1}$$

C represents overall carbon emissions (unit: MMtonnes CO_2); E represents total primary energy consumption (unit: quad Btu); GDP represents the gross regional product (unit: constant 2015 US\$); and P represents total population (unit: person). $\frac{C}{E}$ denotes carbon emissions per unit of energy consumption (referred to as carbon intensity of energy consumption or ECI); $\frac{E}{GDP}$ denotes energy consumption per unit of GDP (referred to as energy intensity or EI); and $\frac{GDP}{P}$ denotes GDP per capita (PG). The carbon emissions of country i can be calculated using Eq. (2):

$$C_i = ECI_i \cdot EI_i \cdot PG_i \cdot P_i \tag{2}$$

The carbon intensity of energy consumption (ECI) can be further decomposed into the carbon emission coefficients of different types of fossil energy (including coal, oil, and natural gas), the share of different fossil energy sources, and the overall share of fossil energy sources. This can be expressed as Eq. (3):

$$ECI_i = \frac{C_i}{E_i} = \sum\nolimits_j \frac{C_{ij}}{E_{ij}} \cdot \frac{E_{ij}}{E_{iFos}} \cdot \frac{E_{iFos}}{E_i} = \sum\nolimits_j EC_{ij} \cdot ES_{ij} \cdot EF_i \tag{3}$$

E_i represents the primary energy consumption of country i; C_{ij} represents the carbon emissions from energy source j in country i; E_{ij} represents the consumption of energy source j in country i; E_{iFos} represents the total fossil energy consumption of country i. $\frac{C_{ij}}{E_{ij}}$ is the carbon emission coefficient of energy source j (EC_{ij}); $\frac{E_{ij}}{E_{iFos}}$ is the consumption of fossil energy source j as a share of the total fossil energy consumption (ES_{ij}); and $\frac{E_{iFos}}{E_i}$ is the ratio of fossil energy consumption to the total energy consumption (EF_i).

2.2 Kaya-LMDI based decomposition framework

To examine the contribution of various drivers to CO_2 emissions, the LMDI approach and the Kaya identity are combined to decompose the drivers of carbon emissions (ΔC) in the Belt and Road Initiative countries into carbon intensity of energy consumption (ΔC_{ECI}), energy intensity (ΔC_{EI}), GDP per capita (ΔC_{PG}), and population (ΔC_P), written as Eq. (4):

$$\Delta C = \Delta C_{ECI} + \Delta C_{EI} + \Delta C_{PG} + \Delta C_P \tag{4}$$

The Eqs. (5)–(9) can be obtained by applying the LMDI decomposition:

$$\Delta C_{ECI} = \sum\nolimits_i \lambda_i^t \ln\left(\frac{ECI_i(t)}{ECI_i(t-1)}\right) \tag{5}$$

$$\Delta C_{EI} = \sum\nolimits_i \lambda_i^t \ln\left(\frac{EI_i(t)}{EI_i(t-1)}\right) \tag{6}$$

$$\Delta C_{PG} = \sum\nolimits_i \lambda_i^t \ln\left(\frac{PG_i(t)}{PG_i(t-1)}\right) \tag{7}$$

$$\Delta C_P = \sum\nolimits_i \lambda_i^t \ln\left(\frac{P_i(t)}{P_i(t-1)}\right) \tag{8}$$

$$\lambda_i^t = \frac{C_i^t - C_i^{t-1}}{\ln\left(\frac{C_{ij}^t}{C_i^{t-1}}\right)} \tag{9}$$

To measure the contribution of different energy sources to carbon emissions, the carbon intensity of energy consumption is further decomposed based on Eq. (3):

$$\begin{aligned}\Delta C_{ECI} &= \Delta C_{EC} + \Delta C_{ES} + \Delta C_{EF} = \Delta C_{EC_{Coal}} + \Delta C_{EC_{Oil}} + \Delta C_{EC_{NaG}} \\ &\quad + \Delta C_{ES_{Coal}} + \Delta C_{ES_{Oil}} + \Delta C_{ES_{NaG}} + \Delta C_{EF}\end{aligned} \tag{10}$$

$\Delta C_{EC_{Coal}}$, $\Delta C_{EC_{Oil}}$, and $\Delta C_{EC_{NaG}}$ denote the contributions related to carbon emission coefficients of coal, oil, and natural gas respectively; $\Delta C_{ES_{Coal}}$, $\Delta C_{ES_{Oil}}$, and $\Delta C_{ES_{NaG}}$ denote the contributions related to the share of coal, oil and natural gas in fossil energy consumption; and ΔC_{EF} denotes the contribution related to the share of fossil energy consumption.

Since the share of fossil energy consumption is equal to 1 minus the share of non-fossil energy consumption, Eq. (11) can be obtained, where ΔC_{Clean} is the contribution related to the share of non-fossil energy consumption.

$$\Delta C_{EF} = \Delta C_{Clean} \tag{11}$$

In addition, due to data limitations, the carbon emission factors of different energy types in previous years could not be obtained. This paper assumes that the carbon emission factors of different energy types do not change during the study period, so $\Delta C_{EC_{Coal}}$, $\Delta C_{EC_{Oil}}$, and $\Delta C_{EC_{NaG}}$ are all zero.

Based on Eqs. (10) and (11), the contributions of coal, oil, natural gas, and non-fossil energy consumption to changes in carbon emissions can be calculated using the LMDI decomposition, as shown in Eq. (12) to Eq. (17). $Coal_i(t)$, $Oil_i(t)$, $NaG_i(t)$, and $Clean_i(t)$ are the consumption of coal, oil, natural gas, and non-fossil energy in country i, respectively. ΔC_{coal}, ΔC_{Oil}, ΔC_{NaG}, and ΔC_{Clean} are the contributions of coal, oil, natural gas, and non-fossil energy consumption to changes in carbon emissions, respectively.

$$\Delta C_{ECI} = \Delta C_{Coal} + \Delta C_{Oil} + \Delta C_{NaG} + \Delta C_{Clean} \tag{12}$$

$$\Delta C_{coal} = \sum\nolimits_i \sum\nolimits_j \lambda_{ij}^t \ln\left(\frac{Coal_i(t)}{Coal_i(t-1)}\right) \tag{13}$$

$$\Delta C_{Oil} = \sum\nolimits_i \sum\nolimits_j \lambda_{ij}^t \ln\left(\frac{Oil_i(t)}{Oil_i(t-1)}\right) \tag{14}$$

$$\Delta C_{NaG} = \sum\nolimits_i \sum\nolimits_j \lambda_{ij}^t \ln\left(\frac{NaG_i(t)}{NaG_i(t-1)}\right) \tag{15}$$

$$\Delta C_{Clean} = \sum\nolimits_i \sum\nolimits_j \lambda_{ij}^t \ln\left(\frac{Clean_i(t)}{Clean_i(t-1)}\right) \tag{16}$$

$$\lambda_{ij}^t = \frac{C_{ij}^t - C_{ij}^{t-1}}{\ln\left(\frac{C_{ij}^t}{C_{ij}^{t-1}}\right)} \tag{17}$$

2.3 Data

Data from the Belt and Road Initiative countries from 1987 to 2022 were collected, including GDP, population, carbon emissions, and primary energy consumption. The final dataset includes 102 out of the 153 countries along the route after removing samples with missing data. GDP and population data are derived from the World Development Indicators of the World Bank[44], with GDP expressed at the constant 2015 prices in US dollars. The GDP data for Bhutan, Syria and Tonga in 2022 are missing, so the average GDP from 2017 to 2021 was used instead. Carbon emissions and energy consumption data were sourced from the US Energy Information Administration[45]. The energy types covered include coal, oil, natural gas, and non-fossil energy, including nuclear and renewable energy.

We classify the 102 Belt and Road Initiative countries, hereinafter referred to as the BRI countries, into four groups based on the World Bank's income level standard: low, lower-middle, upper-middle, and high[46]. More than half (55%) of the BRI countries are lower-middle-income and low-income countries, primarily located in Sub-Saharan Africa and East Asia & Pacific. Upper-middle-income countries are largely found in Latin America and high-income countries are mainly in Europe and Latin America, as shown in Table 1.

Table 1 List of the BRI countries by income level and geographic region.

Income level	Region	Countries
Low income (17)	Middle East & North Africa (1)	Syria
	Sub-Saharan Africa (16)	Burundi, Chad, Congo-Kinshasa, Ethiopia, Guinea, Gambia, Madagascar, Mali, Mozambique, Malawi, Niger, Rwanda, Sudan, Sierra Leone, Togo, Uganda
Lower-middle income (39)	East Asia & Pacific (11)	Indonesia, Kiribati, Laos, Myanmar, Mongolia, Philippines, Papua New Guinea, Samoa, Solomon Islands, Vietnam, Vanuatu
	Latin America & Caribbean (3)	Bolivia, El Salvador, Nicaragua
	Middle East & North Africa (5)	Algeria, Egypt, Iran, Morocco, Tunisia
	South Asia (5)	Bangladesh, Bhutan, Nepal, Pakistan, Sri Lanka
	Sub-Saharan Africa (15)	Angola, Benin, Cape Verde, Cameroon, Comoros, Congo-Brazzaville, Côte d'Ivoire, Ghana, Kenya, Lesotho, Mauritania, Nigeria, Senegal, Zambia, Zimbabwe
Upper-middle income (26)	East Asia & Pacific (5)	China, Fiji, Malaysia, Thailand, Tonga
	Europe & Central Asia (3)	Albania, Bulgaria, Turkey
	Latin America & Caribbean (12)	Argentina, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, Grenada, Guyana, Jamaica, Panama, Peru, Suriname
	Middle East & North Africa (2)	Iraq, Jordan
	Sub-Saharan Africa (4)	Botswana, Gabon, Equatorial Guinea, South Africa
High income (20)	East Asia & Pacific (4)	Brunei, New Zealand, Republic of Korea, Singapore
	Europe & Central Asia (6)	Austria, Cyprus, Greece, Italy, Luxembourg, Portugal
	Latin America & Caribbean (5)	Antigua and Barbuda, Barbados, Chile, Trinidad and Tobago, Uruguay
	Middle East & North Africa (4)	Bahrain, Malta, Oman, Saudi Arabia
	Sub-Saharan Africa (1)	Seychelles

We also divide the study period from 1987 to 2022 into four time periods: 1987–1997, 1998–2008, 2009–2019, and 2020-2022, to minimize the impact of the 1997 and 2008 financial crises and the COVID-19 pandemic on the decomposition results.

3 Results

3.1 Historical trends of carbon emissions in BRI countries and regions

Following a continuous upward trend since 1987, total carbon emissions of the 102 BRI countries studied in this paper reached 21.02 Gt CO_2 in 2022, accounting for 54.58% of the global total as of 2022 (Figure 1). Emissions grew at an average annual rate of 4.20% from 1987 to 2022, which is significantly higher than the world average of 1.72% and the average across developed countries of 0.79%[47]. Across multiple temporal scales, carbon emissions of the BRI countries increased fastest in the second period (1998–2008) with an average annual rate of 6%, compared with 3.7% in the first period (1987–1997), 3.01% in the third period (2009–2019) and 0.19% during the COVID-19 pandemic (2020–2022).

Overall, carbon emissions in the BRI countries continue to grow alongside economic growth and have not yet been effectively decoupled from economic development. Recently, the increase in carbon emissions has slowed down significantly, becoming much slower than GDP growth (4.87% in the third period). It is noteworthy that per capita carbon emissions in the BRI countries are at a much lower level, at 4.70 tonnes per person in 2022. In comparison, per capita carbon emissions were 9.83 tonnes per person in developed countries, 10.59 tonnes per person in the G7, 8.58 tonnes per person in OECD countries, and 4.84 tonnes per person globally. Generally, the overall carbon emissions of developed countries peak after per capita carbon emissions. Per capita carbon emissions of developed European countries and the United States generally exceed 10 tonnes per person when their overall carbon emissions reach their peak. The numbers are around 14 tonnes per person in Germany, Denmark and Finland and as high as 22 tonnes per person and 17 tonnes per person in the United States and Canada, respectively[48]. It can be expected that, under a no-intervention scenario, carbon emissions of the BRI countries will expand substantially in the future.

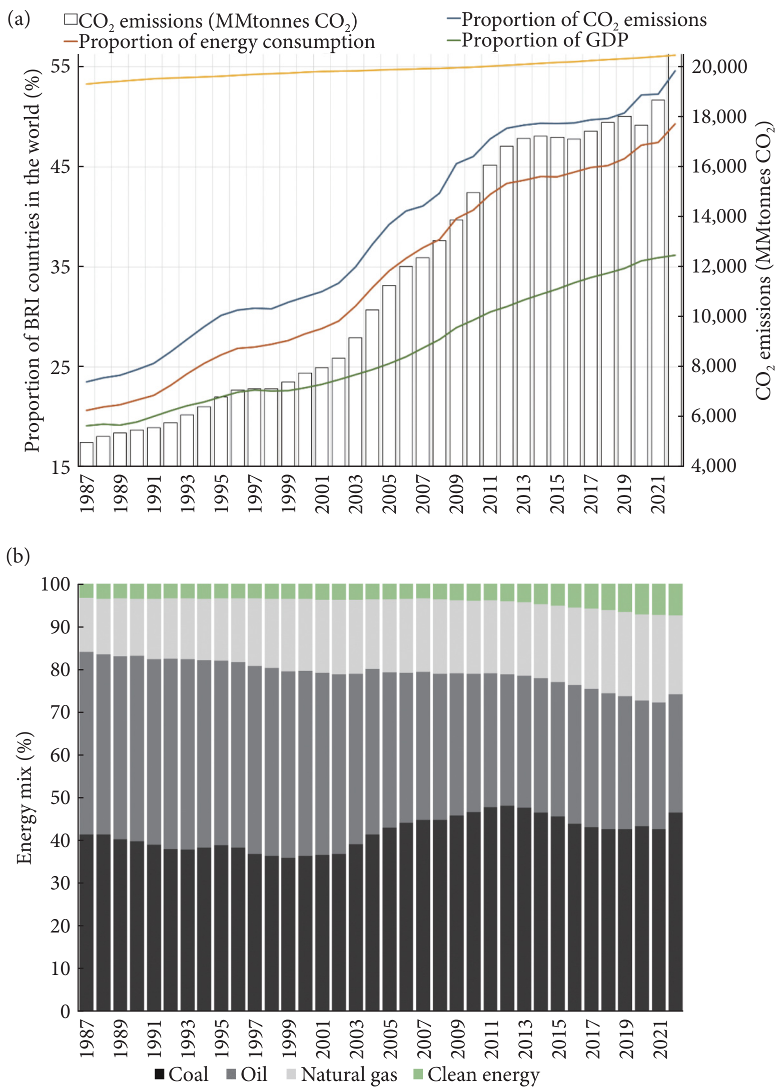

Fig. 1 Economic, demographic, emission and energy mix of the BRI countries, 1987–2022. (a) Global proportion of carbon emissions, population, and energy consumption of the BRI countries, 1987–2022. **(b)** Energy structure of the BRI countries, 1987–2022.

Energy consumption in the BRI countries accounted for 49.28% of the global total in 2022. It exhibited an upward trend similar to carbon emissions, growing at a rate of 5.70% in the second period, faster than 4.06% in the first period and 3.7% in the third period. Highly dependent on fossil energy, the BRI countries sourced 92.59% of their energy from fossils in 2022, compared to 84.47% in developed countries. Specifically, coal was the dominant source with a share of 46.44%, followed by oil, natural gas, and non-fossil energy, which represented 27.69%, 18.46%, and 7.41%, respectively. In contrast, the energy structure of developed countries is cleaner and less coal-dependent. Oil and natural gas made up 37.65% and 33.43%, respectively, while non-fossil energy accounted for 16.08%, and coal for only 13.40%.

In short, the BRI countries have experienced continuous growth in both energy consumption and carbon emissions, with high dependence on fossil fuels such as coal and a low level of non-fossil energy development. Despite sustained economic growth, BRI countries contributed only about 36.16% of the global GDP in 2022. The percentage of the global population has not changed much overall, but it is trending slightly upward. Driven by huge space for economic development, carbon emissions in the BRI countries will continue to grow rapidly if no steps are taken to change the current high-carbon development path.

3.2 Decomposition results of carbon emission drivers in the BRI countries and regions

3.2.1 Analysis of carbon emission drivers in the BRI countries as a whole

Overall, carbon emissions in the BRI countries are rising with increases of 2.16 billion tonnes, 5.92 billion tonnes, 4.14 billion tonnes and 3.35 billion tonnes during the periods 1987–1997, 1998–2008, 2009–2019 and 2020–2022, respectively. Economic scale (*PG*) is the primary driver of carbon emissions, contributing 58.76%, 81.62%, 55.36% and 10.82% in those periods, respectively. This is primarily due to the substantial potential for economic development in BRI countries, which are starting from a relatively low level. From 1987 to 2022, the average annual GDP growth rate of the BRI countries was 4.86%, significantly higher than the global average of 2.97% and the 2.50% growth rate in developed countries. Particularly during the second period, GDP grew at an average annual rate of 5.33%, accelerating the increase in carbon emissions. Gradual population expansion (*P*), which increases the demand for energy services[49], is also a significant factor driving up carbon emissions in the BRI countries, as illustrated in Figure 2. In the foreseeable future, both GDP and carbon emissions in the BRI countries are expected to continue growing rapidly, which may hinder the achievement of Paris Agreement goals. However, this does not warrant condemnation of the BRI countries. It should be acknowledged that, compared to developed countries, developing countries currently have lower levels of economic development and per capita carbon emissions. They face considerable challenges in transitioning to low carbon economies due to development and limited capacity to address climate change. Developed countries should recognize these challenges in international climate negotiations and fulfill their climate assistance commitments promptly, supporting developing countries with finance, technology, and capacity building.

Energy intensity (*EI*) is a key indicator of the input–output characteristics of an energy system, reflecting the overall efficiency of energy consumption relative to economic activities. Generally, a decrease in *EI* signifies an improvement in energy efficiency, often driven by technological advancement[50]. In the BRI countries, a lower *EI* has been the most significant factor contributing to reduced carbon emissions, with contribution rates of 29.91%, 8.95%, and 27.03% in 1987–1997, 1998–2008, and 2009–2019, respectively. From 1987 to 2022, the *EI* of the BRI countries declined slowly, at an average annual rate of 0.45%, indicating improving energy efficiency, although a gap remains compared to developed countries. In 2019, the *EI* of the BRI countries was approximately twice that of developed countries. The significant reduction in China's *EI* has greatly contributed to the decrease in carbon emissions in the BRI countries. China's *EI* continued to decline at an average annual rate of 2.92% from 1987 to 2022, due to substantial adjustment in industrial structure, the widespread adoption of energy-efficient and low-carbon technologies, and the implementation of dual-control policies for energy consumption and intensity[51].

Carbon intensity of energy consumption (*ECI*) refers to carbon emissions per unit of energy consumption and is primarily influenced by changes in the energy mix. An increase in the substitution rate of renewable energy for fossil fuels directly leads to a reduction in carbon emissions. Thus, the degree of cleanliness in the energy mix determines *ECI*'s contribution to carbon emission reduction. During all four periods of 1987–1997, 1998–2008, 2009–2019, and the COVID-19 pandemic (2020–2022), *ECI* played a role in reducing carbon emissions in the BRI countries, with contribution rates of 3.33%, 3.32%, 8.29% and 2.54%, respectively. *ECI* in the BRI countries decreased gradually at an average annual rate of 0.3%, slightly lower than the 0.4% observed on developed countries. The impact of *ECI* was most pronounced during 2009–2022, as non-fossil energy sources grew the fastest in this period, achieving an average annual increase rate of 4.5% in their share of energy consumption since 2010. However, it is noteworthy that in 2022, *ECI* in the BRI countries remained high-1.2 times that of developed countries[45]. Compared to the BRI countries, developed countries have significant comparative advantages in non-fossil energy technology and development.

Further decomposition of carbon emission drivers for the BRI countries, excluding China, reveals that *PG* and *P* remain the primary factors contributing to carbon emissions. However, the role of *EI* in mitigating carbon emissions for non-China BRI countries has diminished significantly. Specifically, *EI* contributed to a 5.01% increase in carbon emissions during 1987–1997 and reduced emissions by 4.76% and 6.67% during 1998–2008 and 2009–2019, respectively. This trend is linked to changes in *EI* among non-China BRI countries—where *EI* continuously increased in the first period but decreased following an increase in both the second and third periods. Overall, *EI* for non-China BRI countries did not change substantially from 1987 to 2022, with the 2022 level being slightly higher than that of 1987, as shown in Figure 3.

In summary, economic growth is currently the dominant driver of increasing carbon emissions in the BRI countries, while energy intensity and carbon intensity of energy consumption contribute

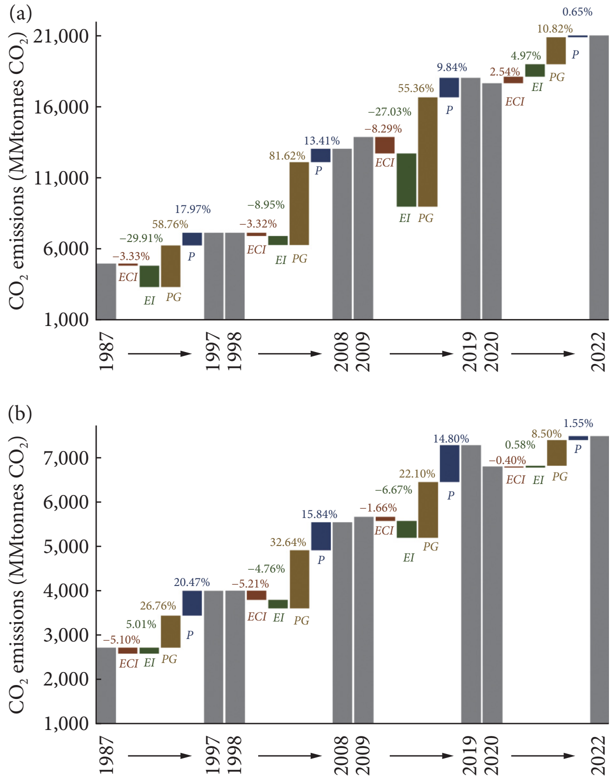

Fig. 2 Decomposition results of carbon emission drivers for the BRI countries in four development periods. **(a)** BRI countries; **(b)** Non-China BRI countries.

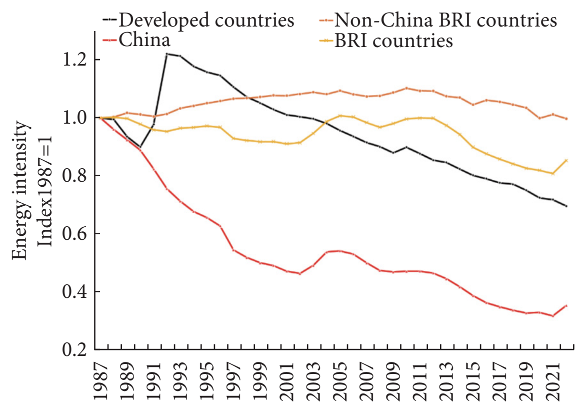

Fig. 3 Historical changes in energy intensity of BRI countries and developed countries from 1987 to 2022. 1987 was used as the base year, and therefore, the value of energy intensity in each region in 1987 was set as 1.

to emissions reduction. Nevertheless, the increase in carbon emissions driven by economic growth outweighs the reduction achieved through decreases in energy intensity and carbon intensity of energy consumption, aligning with global trends in carbon emission drivers[52].

3.2.2 Analysis of the impact of economic crises on carbon emission drivers in the BRI countries

To assess the changes in carbon emissions and key drivers amid global economic crisis, we further analyzed the carbon emission drivers of the BRI countries during two major global economic crises (1997 and 2008) and the COVID-19 pandemic (2020) over the study period from 1987 to 2022.

The economic crises exerted a significant impact on the carbon emission drivers of the BRI countries. For non-China BRI countries, the effects of *EI* and *PG* on carbon emissions were completely opposite to the results of the previous analysis, as shown in Figure 4. With a substantial decline in the economic growth rate, the contraction of *PG* directly suppressed the increase of carbon emissions. The GDP growth rates of non-China BRI countries were 0.87%, −0.66%, and −3.90% in 1998, 2009, and 2020, respectively, far below the average of 3.23% during 1987–2022.

Meanwhile, *EI* had the effect of boosting carbon emissions in

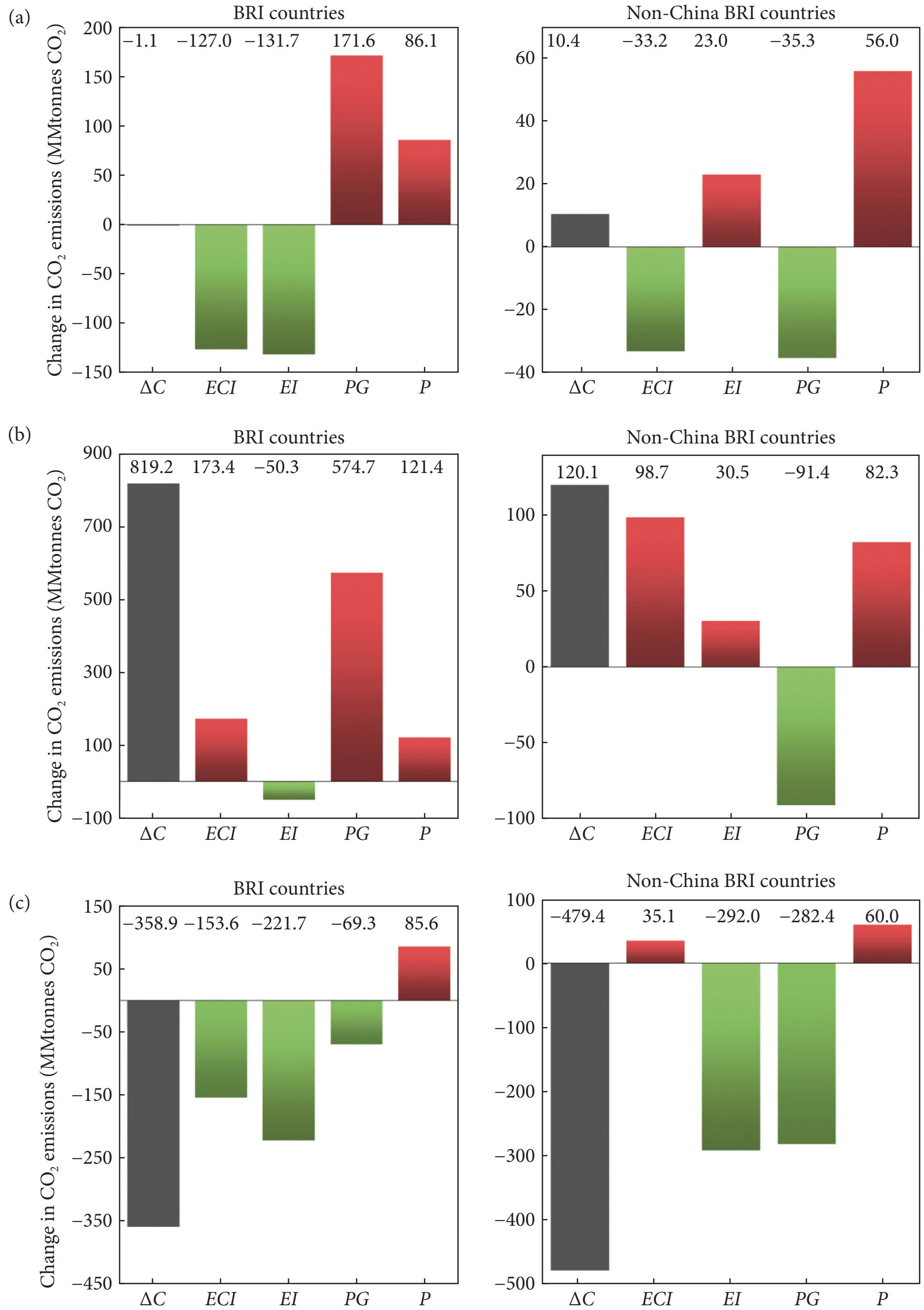

Fig. 4 Decomposition results of carbon emission drivers in the BRI countries during the economic crises. **(a)** Economic crisis at 1997–1998; **(b)** economic crisis at 2008–2009; **(c)** COVID-19 pandemic at 2019–2020.

non-China BRI countries during the economic crises. *EI* increased during both economic crises because energy consumption was less negatively affected than GDP. It is important to note that lower-cost, traditional fossil energy sources were preferred in these areas to stimulate economic recovery from economic crises. The share of fossil energy in energy consumption rose during both economic crises, notably during the second one, as shown in Figure A1 in Appendix. As a result, *ECI* gave a direct boost to carbon emissions in 2008–2009.

3.2.3 Analysis of carbon emission drivers for the BRI countries with different income levels

For low-income BRI countries, *P* was the main driver of increased carbon emissions. *PG* generated an effect of increasing emissions from 1987 to 2008 and an effect of reducing emissions from 2009 to 2019 due to war-related sharp economic downturns in some countries (e.g., Syria). As a result, carbon emissions of low-income BRI countries in 2019 (101.33 MMtonnes CO_2) were smaller compared to 2009 (104.82 MMtonnes CO_2). *EI* tended to increase emissions in low-income BRI countries from 1998 to 2008, 2009–2019, and 2020–2022. It is noteworthy that these areas have the cleanest energy mix, with non-fossil energy representing 13.00% in 2021. In particular, biomass fuel consumption is significant in most low-income countries, making up more than 50%, and in some cases, more than 85% of end-use energy consumption, as shown in Table 2[53]. *ECI* was thus the lowest in low-income BRI countries, contributing most to emission reduction during 1987–1997, 1998–2008 and 2009–2019, with rates of 7.29%, 19.38%, and 0.42%, respectively, as shown in Figure 5(d). However, the dependence on fossil energy (mainly oil and coal) is increasing in low-income BRI countries, rendering *ECI* an emission growth effect as coal and oil consumption surged.

In lower-middle-income BRI countries, both *P* and *PG* have driven up carbon emissions. Additionally, *EI* has also contributed to increasing emissions, similar to the trend observed in low-income BRI countries as shown in Figure 5(c). This indicates that energy efficiency is relatively low in these countries, suggesting significant potential for the implementation of energy-efficient and low-carbon technologies. Furthermore, the share of non-fossil energy in their energy consumption was only 4.34% in 2022, the lowest among the BRI countries. Their reliance on coal has been increasing annually, with the average growth rate of coal consumption reaching 10.07% between 2009 and 2022. Consequently, *ECI* has been a major factor contributing to rising carbon emissions in these countries during this period.

The carbon emission drivers for upper-middle and high-income BRI countries are consistent with those of the BRI countries as a whole. Both *P* and *PG* contributed to the growth of carbon emissions, while *EI* and *ECI* played roles in emission reduction across all three periods as shown in Figures 5(a) and 5(b). The contribution of *EI* to emission reduction was the highest in upper-middle-income countries among all BRI countries, reaching 49.40%, 13.79%, and 36.51% in the three periods, respectively. The effect of *EI* and *ECI* on carbon emissions reduction were more prominent in upper-middle and high-income countries compared to lower-middle and low-income countries. Therefore, it is essential to strengthen energy-saving and low-carbon cooperation and exchanges among the BRI countries. This would leverage the technological and capacity advantages of higher-income countries to promote energy efficiency improvement and accelerate renewable energy deployment in lower-middle and low-income countries.

3.3 Decomposition results of carbon intensity of energy consumption

3.3.1 Decomposition results of carbon intensity of energy consumption for the BRI countries with different income levels

For high-income BRI countries, *ECI* contributed to carbon emission reduction across all three periods. From 1987 to 1997, carbon emissions decreased due to a reduction in the proportion of coal consumption. However, from 1998 to 2008, carbon emissions rose sharply as coal consumption rebounded and energy mix shifted towards natural gas as shown in Figure 6. During this period, cumulative carbon emissions reached 104.93 Gt CO_2, nearly 1.5 times higher than those in the first period. From 2009 to 2019, the share of coal in the energy mix decreased, and the share of oil fell gradually, while the share of natural gas increased and became the primary driver of rising carbon emissions. The growth of non-fossil energy consumption in high-income BRI countries was slow, averaging only 1.34% annually from 2009 to 2019, resulting in a limited contribution to carbon emission reduction.

For upper-middle-income BRI countries, *ECI* contributed low to carbon emission reduction in the first and second periods, at 1.83% and 0.57%, respectively. However, the contribution rate increased significantly to 10.85% in the third period. In the first period, *ECI*'s contribution was limited due to the slow reduction in coal consumption. In the second period, the share of coal consumption rebounded significantly, with coal consumption rising to 1.6 times higher than before, becoming the primary

Table 2 Proportion of biomass fuels in end-use energy consumption in some low-income BRI countries (The year 2021).

Country	Biofuels and waste consumption (Unit: TJ)	Total (Unit: TJ)	Proportion of biofuels and waste
Congo-Kinshasa	791,136	866,890	91.26%
Ethiopia	1,606,916	1,821,899	88.20%
Uganda	611,138	704,307	86.77%
Rwanda	112,922	131,694	85.75%
Madagascar	223,836	263,857	84.83%
Niger	117,670	148,076	79.47%
Togo	73,383	99,588	73.69%
Mozambique	225,179	350,082	64.32%
Sudan	316,573	576,583	54.91%
Syria	180	211,349	0.09%

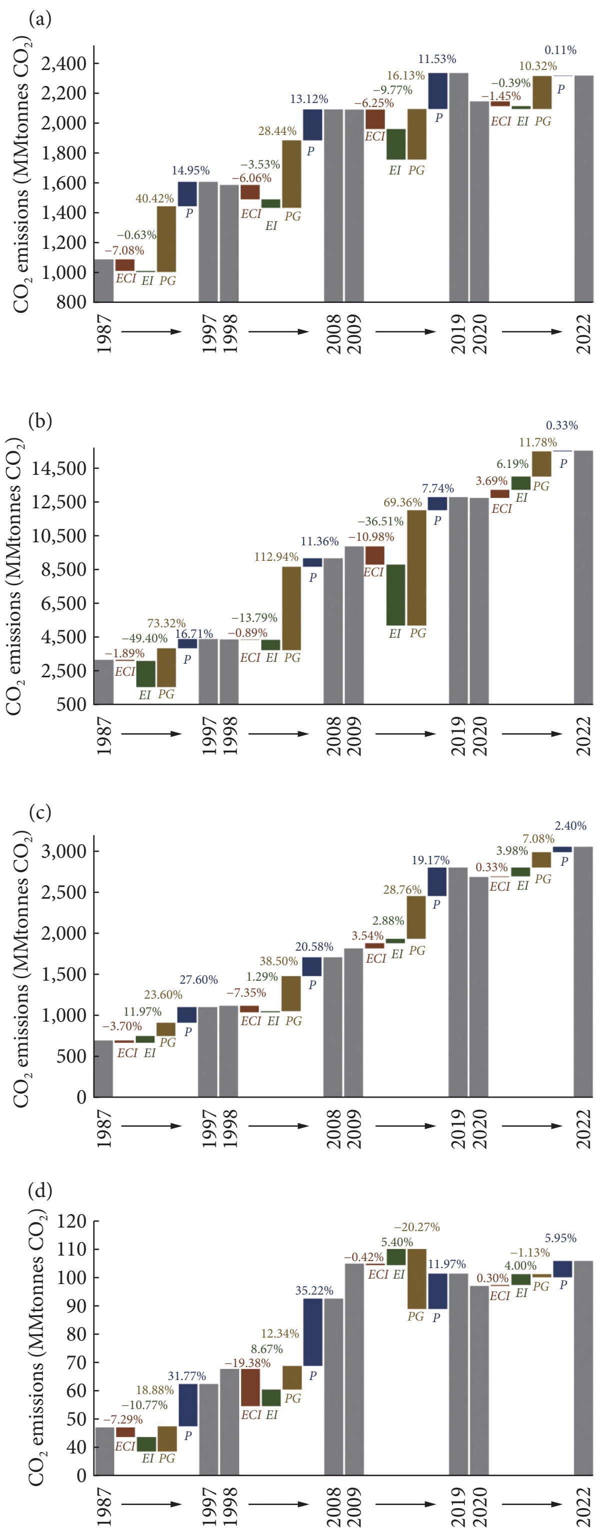

Fig. 5 Decomposition results of carbon emission factors for the BRI countries with different income levels during 1987–2022. (a) High-income BRI countries; **(b)** upper-middle-income BRI countries; **(c)** lower-middle-income BRI countries; **(d)** low-income BRI countries.

source of increased emissions. In the third period, the energy mix gradually became cleaner. The share of coal and oil in energy consumption decreased, while non-fossil energy grew rapidly, with an average annual rate of 10.97%, raising its share to 7.95% in 2022 as shown in Figure 7.

For lower-middle-income BRI countries, *ECI* contributed to emission reduction in the first and second periods but had a positive effect on carbon emissions in the third period. The share of oil consumption decreased sharply from 62.27% in 1987 to 36.95% in 2022, contributing significantly to emission reduction across all three periods. In contrast, natural gas consumption grew rapidly, reaching a share of 40.10% in 2022, which exceeded that of oil consumption and contributed to carbon emissions in all three periods. Coal consumption also increased, with a notable average annual growth rate of 10% in the third period as shown in Figure 7. This is a major factor driving up *ECI*. The development of non-fossil energy remained at the lowest level in these countries, with its share fluctuating and showing an overall downward trend, thereby contributing positively to carbon emissions throughout all periods.

Low-income BRI countries have the cleanest energy mix as shown in Figure 7. However, this does not necessarily indicate a smooth transition towards cleaner energy. While biomass energy constitutes a significant portion of their energy mix, the share of non-fossil energy sources, such as solar and wind power, remains low. Similar to lower-middle-income BRI countries, emission reductions in low-income countries were primarily driven by a decline in the share of oil consumption. In the third period, however, coal consumption surged, with an average annual growth rate of 16.19%, increasing its share in the energy mix. This surge, combined with a recent decline in the share of non-fossil energy and natural gas, resulted in *ECI* contributing to higher emissions in low-income BRI countries during this period.

3.3.2 Key region analysis for the BRI low-carbon energy transition

From 1987 to 2022, *ECI* led to a reduction in emissions for 64 out of the 102 BRI countries (Table A1 in Appendix), while it contributed to increased emissions in nearly half of them. This indicates that around half of the BRI countries have either not made sufficient efforts or have not yet commenced a green and low-carbon energy transition. Most of these countries are at low or middle-income levels and are primarily located in East Asia & Pacific, South Asia, and Sub-Saharan Africa. Among the top 20 countries where *ECI* significantly contributed to emission reduction, only one is low-income and two are lower-middle-income countries as shown in Table 3. Regionally, the top 20 countries are predominantly concentrated in Asia and Europe, with a few from Latin America and North Africa.

In terms of incremental emissions, Southeast Asia experienced the largest growth in emissions driven by *ECI*. Between 1987 and 2022, *ECI* contributed to carbon emission increases of 92.27 MMtonnes in Indonesia, 15.98 MMtonnes in Laos, and 18.73 MMtonnes in the Philippines. Both Indonesia and the Philippines are heavily reliant on coal, with Indonesia being the world's largest exporter of power coal. Although the two countries have signed the Global Coal to Clean Power Transition Statement, coal consumption continues to rise, and coal phase-out seems unlikely under current conditions. Laos, a key hub of the ASEAN (Association of Southeast Asian Nations) power grid, primarily exports hydropower. It aims to strengthen its position as an energy producer and exporter by further developing hydropower[54]. However, environmental and climatic factors, such as droughts, affect hydropower availability, leading Laos to increase its reliance on coal to ensure a stable electricity supply. Since the Hongsa coal power plant began operations in 2015, coupled with weak local climate and environmental regulations,

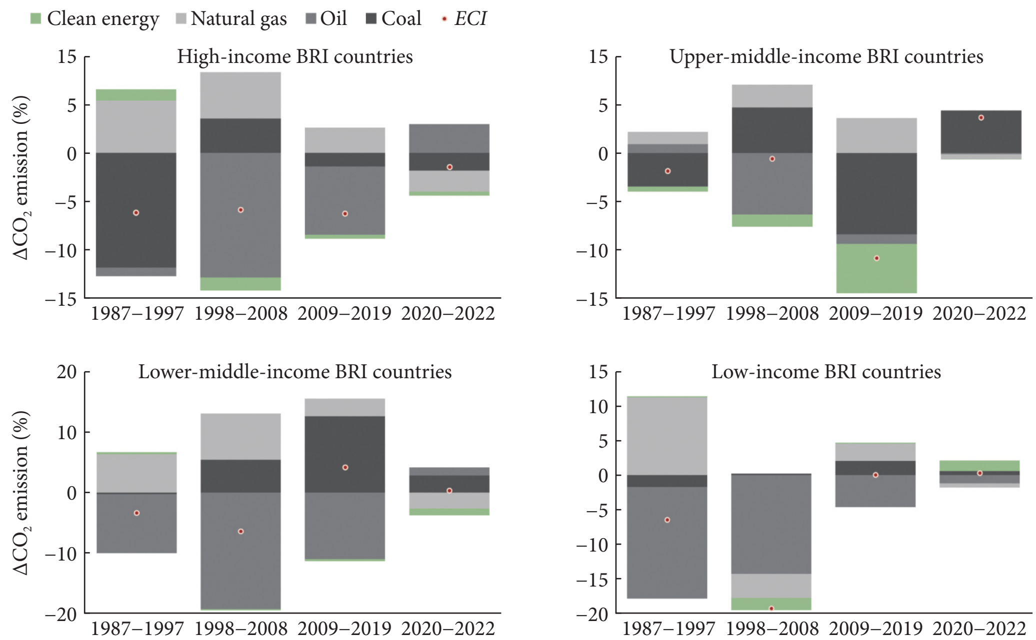

Fig. 6 Decomposition results of carbon intensity of consumption for the BRI countries with different income levels.

Fig. 7 Energy mix of the BRI countries with different income levels.

coal consumption in Laos has surged[55], as shown in Figure A2 in Appendix. Meanwhile, renewable energy has been growing rapidly in Southeast Asia, with the share of installed capacity climbing from 19.1% in 2005 to 33.5% in 2020[56]. Southeast Asia is now at a crossroads of energy transition[57]. It is crucial for the region to achieve carbon neutrality through a green and low-carbon energy transition by leveraging its excellent renewable energy sources to overcome challenges in infrastructure, finance, and policy environment.

China achieved the largest reduction of carbon emissions through *ECI* among the BRI countries, with emission reductions reaching 734.94 MMtonnes CO_2 from 1987 to 2022. The main contributors to this reduction were the increased share of non-fossil energy sources and the deceased share of coal, representing 20.29% and 20.17%, respectively. China began to phase down coal in 2011. Since then, the proportion of coal has been declining at an average annual rate of about 1.8%, while the proportion of non-fossil energy sources has been rising at an average annual rate of about 7.2%, as shown in Figure A3 in Appendix. The progress was enabled through several key initiatives: In 2011, China included carbon intensity as a binding indicator in its 12th Five-Year Plan (2011–2015) and introduced the dual-control policy for energy

Table 3 Factor decomposition of carbon intensity of energy consumption during 1987–2022 (MMtonnes CO_2).

Rank	Country	Income group	Region	*ECI*	Clean	Coal	Oil	NaG
1	China	Upper middle income	East Asia & Pacific	−734.94	−458.60	−455.88	−108.36	287.90
2	Republic of Korea	High income	East Asia & Pacific	−85.65	−6.81	−105.08	−44.17	70.41
3	Italy	High income	Europe & Central Asia	−66.21	−24.06	−23.95	−86.87	68.67
4	Saudi Arabia	High income	Middle East & North Africa	−31.57	−0.17	0.44	−56.44	24.60
5	Iran	Lower middle income	Middle East & North Africa	−20.88	0.05	−5.44	−187.55	172.06
6	South Africa	Upper middle income	Sub-Saharan Africa	−15.11	−4.38	−17.42	−2.12	8.80
7	Greece	High income	Europe & Central Asia	−13.57	−5.37	−19.97	1.94	9.83
8	Argentina	Upper middle income	Latin America & Caribbean	−12.30	−0.74	−5.14	−28.56	22.14
9	Bulgaria	Upper middle income	Europe & Central Asia	−11.95	−11.35	8.88	−10.13	0.65
10	Thailand	Upper middle income	East Asia & Pacific	−10.76	−6.24	4.64	−32.30	23.14
11	Egypt	Lower middle income	Middle East & North Africa	−8.95	0.32	−1.63	−57.51	49.87
12	Austria	High income	Europe & Central Asia	−8.38	−6.11	−4.80	−0.07	2.60
13	Turkey	Upper middle income	Europe & Central Asia	−6.06	−8.90	−19.34	−46.81	68.99
14	Iraq	Upper middle income	Middle East & North Africa	−5.49	−0.45	0.01	−24.09	19.04
15	Peru	Upper middle income	Latin America & Caribbean	−4.93	−1.38	−0.21	−11.78	8.44
16	Cuba	Upper middle income	Latin America & Caribbean	−4.57	0.39	−0.45	−5.79	1.28
17	Portugal	High income	Europe & Central Asia	−4.12	−3.52	−7.06	−4.67	11.13
18	Albania	Upper middle income	Europe & Central Asia	−3.08	−1.84	−1.74	1.02	−0.52
19	Ecuador	Upper middle income	Latin America & Caribbean	−2.41	−2.24	0.06	−0.43	0.21
20	Sudan	Low income	Sub-Saharan Africa	−2.01	−0.90	0.00	−1.11	0.00

Note: Countries are listed in order of carbon intensity of energy consumption contribution to emission reduction. The top 20 countries are shown in this table, and the complete list is shown in Table A1 in Appendix.

consumption and energy intensity in the 13th Five-Year Plan (2016–2020). Under this regulation, energy conservation and carbon reduction efforts have yielded remarkable results. By 2017, China's CO_2 emissions per unit of GDP had dropped by about 46% from the 2005 level, exceeding the 2020 target of a reduction of 40%–45% three years ahead of schedule[58]. Regarding coal, the Chinese government issued the "Action Plan on Clean and Efficient Utilization of Coal" and the "Opinions on Promoting Safe and Green Development and Clean and Efficient Utilization of Coal" to spur the development of clean coal technology. Additionally, the "Opinions of the State Council on Promoting the Healthy Development of the Photovoltaic Industry", along with various renewable energy incentives and preferential policies such as feed-in tariffs and the Frontrunner Photovoltaic Program, have driven the rapid development of photovoltaic (PV) and wind power in China.

Sub-Saharan Africa is of high concern. Rich in renewable energy resources, the region has significant potential for the development of renewable energy sources such as wind, solar, and biomass[59, 60]. However, the development of non-fossil energy in this predominantly low-income region is progressing very slowly. From 2009 to 2019, the proportion of non-fossil energy consumption rose by only 1.3%, primarily due to severe constraints in capital, technology, and capacity[61, 62]. Additionally, electricity accessibility remains low in the region. The challenges of achieving a just transition to renewable energy in Sub-Saharan Africa require focused attention from the international community[63].

In Middle East countries such as Iran, Iraq, and Saudi Arabia, emission reductions are primarily derived from a lowered proportion of oil consumption and a rapid increase in natural gas consumption. This is highly correlated with local resource endowments. The Middle East is rich in hydrocarbon resources, with 835.9 billion barrels of proven oil reserves and 2,677.1 trillion cubic feet of natural gas reserves, making it the world's largest oil producing region in 2020[64]. However, some Middle East countries, such as Saudi Arabia and Egypt, lag behind in the development of non-fossil energy sources. Consequently, the share of non-fossil energy sources had an effect of increasing emissions.

For European BRI countries, the reduction in the share of coal consumption and the development of non-fossil energy sources have both contributed to emission reduction, facilitated by relatively high economic and social development levels and advanced non-fossil energy technologies. The most significant contribution to emission reduction came from the increased share of natural gas consumption. However, Europe faces a shortage of natural gas supply in the context of the Russia–Ukraine conflict. Accelerating the establishment of a self-sufficient renewable energy system is crucial for safeguarding national energy security achieving climate goals.

4 Conclusions and implications

4.1 Conclusions

Using the proposed two-stage carbon emission factor decomposition model, this paper analyzes the carbon emission drivers of the BRI countries and regions with different income levels from 1987 to 2022, and investigates the impact of various energy types on carbon emission changes. This analysis enhances the understanding of the low-carbon transition in BRI countries.

Overall, carbon emissions have been increasing in the BRI countries, representing more than half of the global total. In 2022, per capita carbon emissions in the BRI countries were only 4.70 tonnes per person, less than half the level of G7 and OECD countries, and lower than the world average. In terms of energy mix, the BRI countries are highly reliant on fossil energy. Fossil energy, predominantly coal, accounted for nearly 90%, and non-fossil energy, only 12%.

The broader literature studying the driving factors of CO_2 emissions suggests that economic development tend to lead to higher emissions, while energy intensity is the main driver in reducing emissions[65–67]. However, the contribution of the carbon intensity of energy consumption to emissions remains uncertain[31, 68].This study finds that, economic development (*PG*) was the primary driver of carbon emissions in the BRI countries from 1987 to 2022, while population growth(*P*) also contributed to increased carbon emissions. Energy intensity (*EI*) reduction was the major driving force behind emission reduction in the BRI countries, with carbon intensity of energy consumption (*ECI*) also playing a significant role, especially in recent years. For the 101 non-China BRI countries, economic development and population growth remained the main factors driving up carbon emissions, while energy intensity and carbon intensity (*ECI*) of energy consumption contributed less to emission reduction.

Few studies have focused on the impact of economic crises on carbon emissions, and this study addresses that gap, particularly in the context of BRI countries. The results indicate that, the impact of economic crises on carbon emission drivers was significant for non-China BRI countries. During economic contraction, economic scale (*PG*) became a driver of emission reduction. Simultaneously, energy intensity (*EI*) increased emissions during both economic crises due to its sensitivity to economic fluctuations. This is consistent with previous research findings[69, 70], suggesting that the medium-to long-term impact of economic crises on decarbonization is not always positive. Crises may lead to the rebuilding of carbon-intensive economies, reinforcing the medium- to long-term carbon lock-in effect.

For low-income BRI countries, carbon emissions have been on a downward trend since 2009, largely due to economic declines caused by war and other factors. These countries currently have the cleanest energy mix, with *ECI* making the greatest contribution to emission reduction. However, over the past decade, there has been a growing reliance on fossil fuels such as oil and coal, which has turned *ECI* into a driver of carbon emissions. Energy efficiency has consistently contributed to carbon emissions growth, emphasizing the substantial potential for improvements in this area. For low- and middle-income BRI countries, all four factors (*P, PG, EI, ECI*) have driven emissions upward. As these countries hold significant economic growth potential, greater attention must be directed towards improving energy efficiency and promoting clean energy utilization moving forward. For upper-middle and high-income BRI countries, the results were consistent with the overall BRI trends, with energy intensity (*EI*) and carbon intensity of energy consumption (*ECI*) contributing more significantly to emission reduction in higher-income countries.

Further decomposition of *ECI* reveals that *ECI* produced an effect of increasing emissions in more than half of the BRI countries, predominantly low- and middle-income countries. Upper-middle and high-income BRI countries have gradually reduced the share of coal and oil consumption, shifting to natural gas and non-fossil energy sources. Low-and lower-middle-income BRI countries are also decreasing the share of oil consumption, but the share of coal consumption showing an upward trend. China achieved the largest reduction in emissions driven by declining *ECI*, while Southeast Asia, particular Indonesia, Laos, and the Philippines, saw the fastest growth in emissions due to increasing *ECI*. Some Middle Eastern countries are gradually shifting energy consumption from oil to natural gas but are lagging behind in renewable energy development.

4.2 Implications

Developed countries should take the lead in low-carbon transformation and support developing countries through multiple channels of assistance. Carbon emissions are still on the rise in the BRI countries, while per capita carbon emissions remain much lower relative to developed countries. International climate cooperation is an effective way to accelerate low-carbon transition of the BRI countries. Developed countries should fulfill their climate finance commitments, prioritizing the provision of assistance funds, promoting the establishment of relevant transition funds, and strengthening technology transfer and cooperation. This will reduce the challenges of just transition and the risk of stranded assets brought about by the gradual and orderly withdrawal of fossil energy sources, making the BRI countries more capable of pursuing their NDC commitments and energy transition.

Enhancing energy-saving and low-carbon cooperation and exchanges among BRI countries is a prudent approach. The BRI countries vary widely in income levels and emission drivers. For upper-middle and high-income countries, *EI* and *ECI* play a more prominent role in emission reduction. A mechanism for low-carbon and energy cooperation and exchanges among the BRI countries should be established and improved. This will strengthen the discussion on use of non-fossil energy sources, and facilitate the transfer of more applicable low-carbon technologies from higher-income countries to lower-income countries. Relevant financial cooperation mechanisms may also be built through South–South cooperation.

BRI countries should consider renewable energy development as a key driver of future economic growth and social development. The BRI countries have relied on fossil energy to stimulate economic recovery from past economic crises. Given the high uncertainties in the current international economic and political context, these countries should recognize the potential of non-fossil energy as a significant driver of economic growth. As COP28 set a target of tripling the installed capacity of renewable energy by 2030, the BRI countries should respond positively by setting and updating more ambitious targets and formulating supportive policies for renewable energy. These policies could include feed-in tariffs, financial subsidies, and preferential loans. It is essential to consider the cross-cutting impacts of renewable energy development and its multiplier effect on economic and social development, such as the contribution of renewable energy to sustainable development goals in poverty alleviation, health, and employment. Integrating renewable energy development with local production and daily life is also feasible. For example, the innovative "photovoltaic + agricultural" model supports agriculture while advancing renewable energy, thereby generating significant economic and social benefits.

Low-income BRI countries should establish practical energy transition roadmaps that align with their specific economic and

social development needs. Some low-income BRI countries become more dependent on fossil energy in the process of accelerating industrialization and modernization. These countries should adopt a long-term perspective for low-carbon transition, clearly define the role of fossil energy sources, such as coal and natural gas, and formulate a timetable and roadmap for phasing them out. Additionally, they should develop progressive renewable energy substitution strategies that align with their stages of development.

Appendix

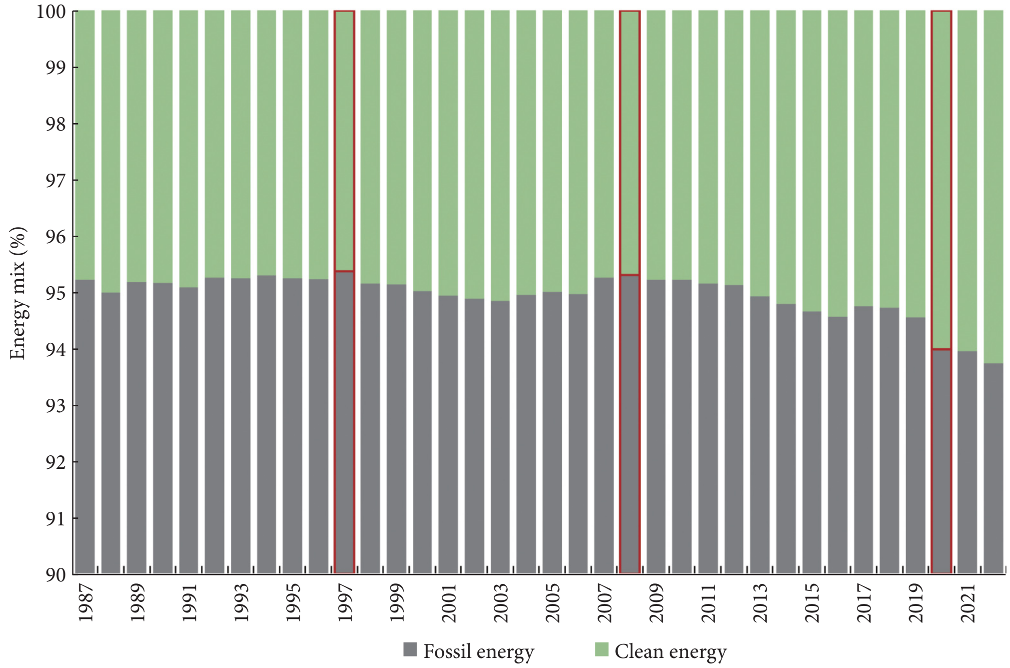

Fig. A1 **Energy consumption structure of non-China BRI countries during 1987–2022.**

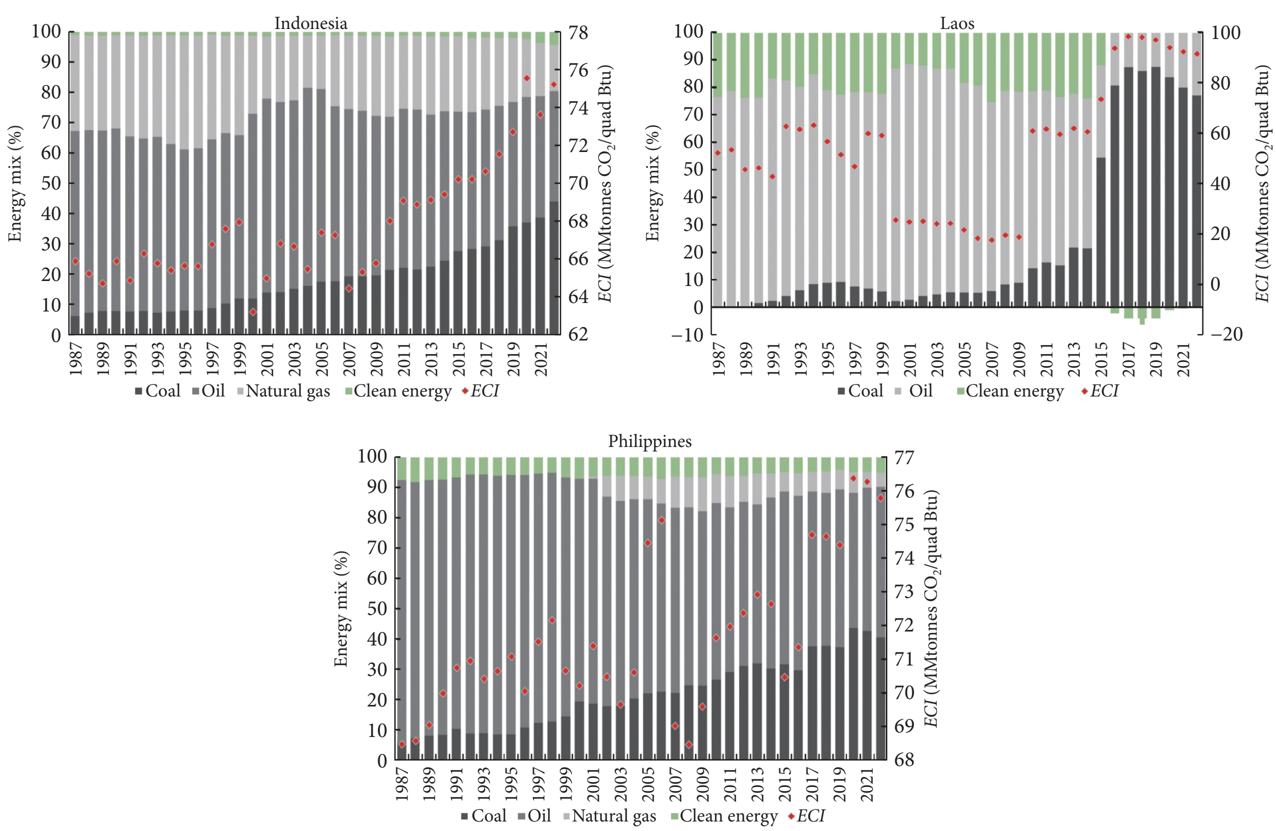

Fig. A2 **Energy consumption structure of Indonesia, Laos, and Philippines during 1987–2022.**

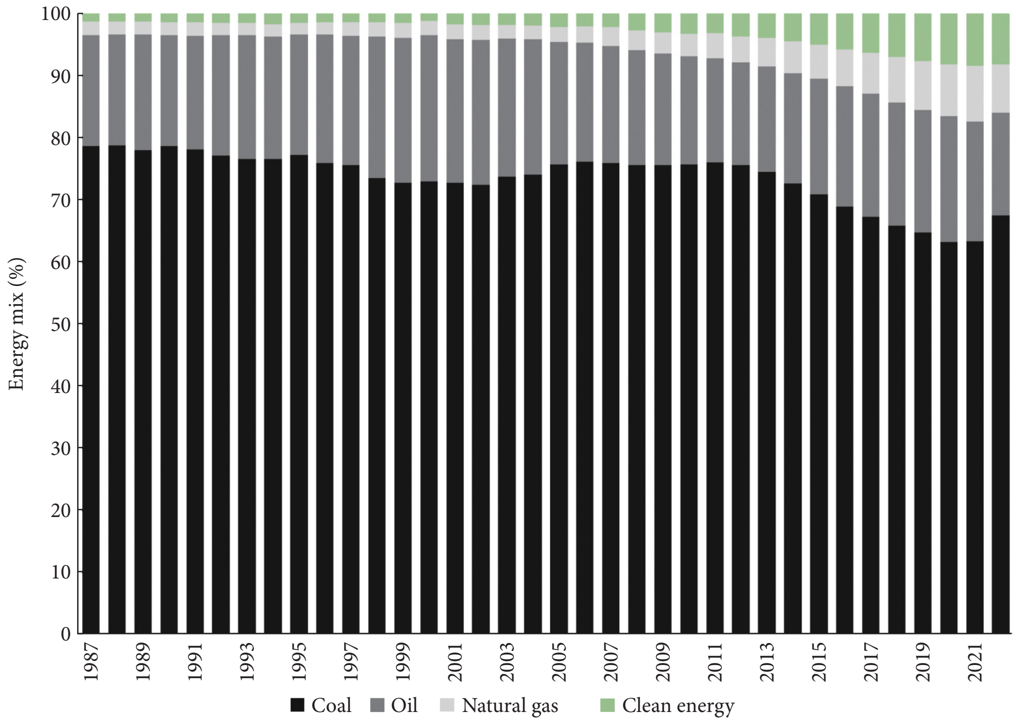

Fig. A3 Energy consumption structure of China during 1987–2022.

Table A1 List of 102 BRI countries that *ECI* contributed to reducing carbon emissions during 1987–2022 (MMtonnes CO_2).

Rank	Country	Region	Income group	*ECI*	Clean	Coal	Oil	NaG
1	China	East Asia & Pacific	Upper middle income	−734.9401	−458.5992	−455.8772	−108.3604	287.8965
2	Republic of Korea	East Asia & Pacific	High income	−85.6493	−6.8054	−105.0825	−44.1685	70.4071
3	Italy	Europe & Central Asia	High income	−66.2055	−24.0566	−23.9515	−86.8720	68.6747
4	Saudi Arabia	Middle East & North Africa	High income	−31.5735	−0.1742	0.4372	−56.4366	24.6001
5	Iran	Middle East & North Africa	Lower middle income	−20.8826	0.0471	−5.4416	−187.5469	172.0588
6	South Africa	Sub-Saharan Africa	Upper middle income	−15.1120	−4.3772	−17.4211	−2.1162	8.8025
7	Greece	Europe & Central Asia	High income	−13.5688	−5.3673	−19.9684	1.9390	9.8279
8	Argentina	Latin America & Caribbean	Upper middle income	−12.2987	−0.7430	−5.1418	−28.5584	22.1446
9	Bulgaria	Europe & Central Asia	Upper middle income	−11.9494	−11.3474	8.8786	−10.1325	0.6519
10	Thailand	East Asia & Pacific	Upper middle income	−10.7627	−6.2445	4.6420	−32.3043	23.1442
11	Egypt	Middle East & North Africa	Lower middle income	−8.9456	0.3209	−1.6279	−57.5115	49.8728
12	Austria	Europe & Central Asia	High income	−8.3799	−6.1056	−4.8012	−0.0746	2.6014
13	Turkey	Europe & Central Asia	Upper middle income	−6.0615	−8.8967	−19.3445	−46.8088	68.9885
14	Iraq	Middle East & North Africa	Upper middle income	−5.4942	−0.4478	0.0064	−24.0938	19.0409
15	Peru	Latin America & Caribbean	Upper middle income	−4.9307	−1.3842	−0.2124	−11.7777	8.4436
16	Cuba	Latin America & Caribbean	Upper middle income	−4.5685	0.3901	−0.4535	−5.7899	1.2848
17	Portugal	Europe & Central Asia	High income	−4.1230	−3.5179	−7.0624	−4.6708	11.1281
18	Albania	Europe & Central Asia	Upper middle income	−3.0825	−1.8391	−1.7351	1.0156	−0.5240
19	Ecuador	Latin America & Caribbean	Upper middle income	−2.4076	−2.2432	0.0559	−0.4279	0.2076
20	Sudan	Sub-Saharan Africa	Low income	−2.0086	−0.8962	0.0008	−1.1132	0.0000
21	Tunisia	Middle East & North Africa	Lower middle income	−1.9864	−0.1046	−0.4650	−3.5539	2.1371
22	Luxembourg	Europe & Central Asia	High income	−1.9285	3.0243	−5.2791	0.4334	−0.1071
23	Syria	Middle East & North Africa	Low income	−1.8059	0.5173	0.0971	−7.3673	4.9470
24	Mongolia	East Asia & Pacific	Lower middle income	−1.7317	−0.8283	−4.0933	3.1899	0.0000

(Continued)

Rank	Country	Region	Income group	*ECI*	Clean	Coal	Oil	NaG
25	Chile	Latin America & Caribbean	High income	−1.6948	−0.4468	0.7397	−6.5811	4.5934
26	Nigeria	Sub-Saharan Africa	Lower middle income	−1.6493	0.2747	4.0844	−17.0876	11.0792
27	Zimbabwe	Sub-Saharan Africa	Lower middle income	−1.6480	−0.4961	−2.5062	1.3543	0.0000
28	Oman	Middle East & North Africa	High income	−1.6178	−0.0089	0.0237	−4.5128	2.8802
29	Angola	Sub-Saharan Africa	Lower middle income	−1.4165	−1.0957	0.0081	0.2440	−0.5730
30	Uruguay	Latin America & Caribbean	High income	−1.2929	−1.0366	0.0449	−0.4699	0.1688
31	Congo-Kinshasa	Sub-Saharan Africa	Low income	−1.1220	−0.7295	−0.5964	0.2040	0.0000
32	Vietnam	East Asia & Pacific	Lower middle income	−0.9110	−7.6811	15.1175	−14.3391	5.9916
33	Panama	Latin America & Caribbean	Upper middle income	−0.8550	−0.7451	1.8904	−2.7596	0.7592
34	Bahrain	Middle East & North Africa	High income	−0.6728	−0.0042	−0.0045	0.0310	−0.6950
35	Nicaragua	Latin America & Caribbean	Lower middle income	−0.5605	−0.4723	0.0000	−0.0882	0.0000
36	El Salvador	Latin America & Caribbean	Lower middle income	−0.2680	−0.2256	0.0014	−0.4851	0.4413
37	Bhutan	South Asia	Lower middle income	−0.2602	−0.3890	0.1129	0.0158	0.0000
38	Cyprus	Europe & Central Asia	High income	−0.2584	−0.1735	0.0306	−0.1155	0.0000
39	Niger	Sub-Saharan Africa	Low income	−0.2358	−0.0697	−0.3032	0.0789	0.0582
40	Botswana	Sub-Saharan Africa	Upper middle income	−0.2265	−0.1873	−0.1278	0.0887	0.0000
41	Costa Rica	Latin America & Caribbean	Upper middle income	−0.2165	−0.0333	0.0739	−0.2572	0.0000
42	Uganda	Sub-Saharan Africa	Low income	−0.2021	−0.0681	0.0000	−0.1340	0.0000
43	Lesotho	Sub-Saharan Africa	Lower middle income	−0.1856	−0.1092	0.0000	−0.0764	0.0000
44	Suriname	Latin America & Caribbean	Upper middle income	−0.1850	−0.0650	0.0000	−0.1336	0.0136
45	Nepal	South Asia	Lower middle income	−0.1456	−0.2541	0.1171	−0.0086	0.0000
46	Guinea	Sub-Saharan Africa	Low income	−0.1268	−0.1725	0.0047	0.0409	0.0000
47	Papua New Guinea	East Asia & Pacific	Lower middle income	−0.1055	−0.0799	0.0000	−0.3531	0.3276
48	Solomon Islands	East Asia & Pacific	Lower middle income	−0.0829	−0.0025	0.0000	−0.0804	0.0000
49	Guyana	Latin America & Caribbean	Upper middle income	−0.0816	−0.0038	0.0000	−0.0855	0.0078
50	Burundi	Sub-Saharan Africa	Low income	−0.0770	0.0206	0.0051	−0.1028	0.0000
51	Ethiopia	Sub-Saharan Africa	Low income	−0.0669	−0.8579	1.3800	−0.5890	0.0000
52	Trinidad and Tobago	Latin America & Caribbean	High income	−0.0525	0.0318	0.0000	−2.4699	2.3856
53	Sierra Leone	Sub-Saharan Africa	Low income	−0.0496	−0.0420	0.0000	−0.0076	0.0000
54	Mauritania	Sub-Saharan Africa	Lower middle income	−0.0496	−0.0603	−0.0118	0.0225	0.0000
55	Rwanda	Sub-Saharan Africa	Low income	−0.0398	−0.0247	0.0766	−0.2080	0.1164
56	Cape Verde	Sub-Saharan Africa	Lower middle income	−0.0396	−0.0066	0.0000	−0.0330	0.0000
57	Congo-Brazzaville	Sub-Saharan Africa	Lower middle income	−0.0228	0.0293	0.0000	−0.4217	0.3696
58	Tonga	East Asia & Pacific	Upper middle income	−0.0150	−0.0017	0.0000	−0.0133	0.0000
59	Kenya	Sub-Saharan Africa	Lower middle income	−0.0118	−0.2239	1.1727	−0.9606	0.0000
60	Barbados	Latin America & Caribbean	High income	−0.0117	−0.0204	0.0000	0.0023	0.0064
61	Fiji	East Asia & Pacific	Upper middle income	−0.0115	−0.0100	−0.0201	0.0186	0.0000
62	Kiribati	East Asia & Pacific	Lower middle income	−0.0084	−0.0007	0.0000	−0.0078	0.0000
63	Gambia	Sub-Saharan Africa	Low income	−0.0080	−0.0005	0.0000	−0.0075	0.0000
64	Malawi	Sub-Saharan Africa	Low income	−0.0063	0.0589	−0.1764	0.1112	0.0000
65	Samoa	East Asia & Pacific	Lower middle income	−0.0018	−0.0011	0.0000	−0.0007	0.0000
66	Vanuatu	East Asia & Pacific	Lower middle income	0.0038	−0.0021	0.0000	0.0059	0.0000
67	Jamaica	Latin America & Caribbean	Upper middle income	0.0043	−0.0221	0.1468	−1.4221	1.3017
68	Comoros	Sub-Saharan Africa	Lower middle income	0.0112	0.0015	0.0000	0.0097	0.0000
69	Dominica	Latin America & Caribbean	Upper middle income	0.0150	0.0009	0.0000	0.0141	0.0000

(Continued)

Rank	Country	Region	Income group	*ECI*	Clean	Coal	Oil	NaG
70	Antigua and Barbuda	Latin America & Caribbean	High income	0.0173	−0.0037	0.0000	0.0210	0.0000
71	Grenada	Latin America & Caribbean	Upper middle income	0.0280	−0.0006	0.0000	0.0287	0.0000
72	Seychelles	Sub-Saharan Africa	High income	0.0459	−0.0132	0.0000	0.0591	0.0000
73	Zambia	Sub-Saharan Africa	Lower middle income	0.0849	0.1359	−0.3818	0.3309	0.0000
74	Gabon	Sub-Saharan Africa	Upper middle income	0.0937	−0.1452	0.2511	−0.3805	0.3681
75	Chad	Sub-Saharan Africa	Low income	0.1620	−0.0033	0.0000	0.1652	0.0000
76	Algeria	Middle East & North Africa	Lower middle income	0.1753	0.0401	−4.0113	3.8879	0.2586
77	Senegal	Sub-Saharan Africa	Lower middle income	0.1760	−0.3527	1.1340	−0.6970	0.0918
78	Mali	Sub-Saharan Africa	Low income	0.2339	0.0589	0.0003	0.1747	0.0000
79	Togo	Sub-Saharan Africa	Low income	0.3053	0.0402	0.2571	−0.2479	0.2560
80	Benin	Sub-Saharan Africa	Lower middle income	0.3628	0.1801	0.1018	−0.2740	0.3549
81	Bolivia	Latin America & Caribbean	Lower middle income	0.3728	0.1787	0.0243	−0.9744	1.1443
82	Madagascar	Sub-Saharan Africa	Low income	0.3884	−0.0154	0.8028	−0.3990	0.0000
83	Malta	Middle East & North Africa	High income	0.4016	−0.1145	−0.3324	0.0827	0.7658
84	Jordan	Middle East & North Africa	Upper middle income	0.4799	−0.8130	1.1238	−6.7119	6.8809
85	New Zealand	East Asia & Pacific	High income	0.6100	−1.1972	−0.1248	4.8287	−2.8966
86	Cameroon	Sub-Saharan Africa	Lower middle income	0.6406	0.1188	0.0000	−1.1987	1.7206
87	Mozambique	Sub-Saharan Africa	Low income	0.7305	−0.7131	0.0591	−1.4119	2.7964
88	Cote d'Ivoire	Sub-Saharan Africa	Lower middle income	0.7961	0.0585	0.0008	−4.2049	4.9416
89	Brunei	East Asia & Pacific	High income	0.9454	−0.0003	1.4186	0.0915	−0.5644
90	Morocco	Middle East & North Africa	Lower middle income	0.9999	−0.7979	7.6014	−5.8205	0.0169
91	Myanmar	East Asia & Pacific	Lower middle income	1.2277	−0.2493	0.7427	3.2667	−2.5323
92	Equatorial Guinea	Sub-Saharan Africa	Upper middle income	2.3526	−0.0172	0.0000	−0.5816	2.9514
93	Singapore	East Asia & Pacific	High income	2.5288	−0.5891	1.5237	−25.3288	26.9230
94	Sri Lanka	South Asia	Lower middle income	2.6842	0.2104	4.6632	−2.1894	0.0000
95	Dominican Republic	Latin America & Caribbean	Upper middle income	2.9737	0.0861	3.5023	−5.4023	4.7876
96	Pakistan	South Asia	Lower middle income	3.1417	−6.0721	30.0588	−19.8377	−1.0074
97	Bangladesh	South Asia	Lower middle income	3.3540	−0.5165	8.2706	−6.5574	2.1572
98	Ghana	Sub-Saharan Africa	Lower middle income	6.5644	2.6106	0.1724	−3.8937	7.6751
99	Laos	East Asia & Pacific	Lower middle income	15.9761	1.1551	16.4992	−1.6782	0.0000
100	Philippines	East Asia & Pacific	Lower middle income	17.7287	1.8443	38.7718	−27.2529	4.3655
101	Malaysia	East Asia & Pacific	Upper middle income	21.7426	−1.9722	49.4631	−27.7354	1.9871
102	Indonesia	East Asia & Pacific	Lower middle income	92.2690	−10.4839	206.9578	−71.0501	−33.1548

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Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

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