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RESEARCH ARTICLE

Towards a greener future: examining carbon emission dynamics in Asia amid gross domestic product, energy consumption, and trade openness

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Abstract

The purpose of this study is to examine the impact of gross domestic product, energy consumption, and trade openness on carbon emission in Asia. Among the 48 countries in Asia, 42 were included in the analysis, spanning a period of 20 years. Given that Asia is the predominant contributor, accounting for 53% of global emissions as of 2019, a comprehensive examination at both continental and individual country levels becomes imperative. Such an approach aligns with local, regional, and global development agendas, contributing directly and indirectly to climate change mitigation. The analytical techniques employed in this study encompassed panel regression and multiple linear regression, illuminating the specific contributions of each country to the study variables and their impact on carbon emissions. The findings suggest that gross domestic product (13 out of 42 countries), energy consumption (21 out of 42 countries), and trade openness (eight out of 42 countries) have a highly significant impact ($p < 0.01$) on carbon emissions in Asia. Energy consumption plays a vital role in increasing carbon emissions in Asia, driven by rising populations, urbanisation, and oil and gas production. Policymakers can take several actions such as adopting a carbon pricing system, using sustainable transportation, renewable energy development, and international cooperation within Asia to reach the goal of being carbon neutral by 2050.

Keywords Asia · Carbon emission · Energy consumption · Environmental sustainability · Gross domestic product · Trade openness

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Introduction

Carbon emissions (CE) constitute a fundamental driver of climate change, emerging as the predominant contributor to severe environmental pollution (Li et al. 2021). It is not only harmful for health and environment but also impact negatively on sustainable economic growth (Nosheen et al. 2021). The Asian region is recognised as the leading contributor to carbon emissions, comprising 53% of the global total (Ritchie 2019). In 2019, 8.4 billion metric tons of carbon dioxide (CO_2) emissions from power and heat sources were released in Asia (Kameke 2022). Moreover, Asia significantly contributes to the worldwide emissions of black carbon, stemming from open combustion during forest and land clearing fires, as well as the incineration of agricultural wastes (United States Agency for International Development 2010). Furthermore, Asia hosts some of the world's foremost CO_2 emitters, including but not limited to China, India, and Japan (Blokhin 2022; Fominova 2022). Additionally, certain Asian nations have declared their climate commitments, outlining plans to reach the peak of CO_2 emissions by 2030 and achieve carbon neutrality by 2050 (Lee 2021). There are some main factors that influence the CO_2 emission in each country, and it leads to the increase in total emissions in the continent.

Gross domestic product (GDP) is the market value of the goods and services produced within an economy's borders during a specified period (Asian Development Bank 2023). In the coming 2 years, by improving its position as the largest and fastest-growing economy, the GDP is expected to rise faster in Asia compared to America and Europe (Ahya 2022). Numerous socioeconomic factors, including population growth, the development of the infrastructure and financial sector development, corruption free society, good governance and policy, and many others have an impact on economic growth (EG) (Rahman et al. 2020). At various times, countries like China, India, Japan, and South Korea have been the main drivers of EG. After World War II, South Korea took over the region's economic leadership, replacing Japan as the region's economic powerhouse. South Korea's policies, which included an increase in production and exports, helped the region's economies achieve success (BRINK Asia Editorial Staff 2017). According to data from 2017, Nepal had an annual GDP growth rate of 7.9%, placing it first in the area. Bangladesh came in second with a growth rate of 7.28%, India came in third with a growth rate of 6.68%, and Pakistan came as fourth with a growth rate of 5.70%. The region's lowest GDP growth percentage was 3.30% in Sri Lanka (The World Bank Group 2023a). In Asia, the largest percentage rises in greenhouse gas emissions (GHG) per capita between 2000 and 2012 were observed in Cambodia (142.4%), China (118.7%), and Vietnam (87.5%), while Singapore experienced the largest percentage decreases (−64.7%) (BRINK Asia Editorial Staff 2017). Moreover, in recent decades, China showed a rapid economic growth, Its GDP had risen to 17.39% in 2019. Also, China is now the world's biggest emitter of CO_2 as a result of its development being largely dependent on fossil fuels (coal and oil), which produce carbon emissions (Gregg et al. 2008).

Another main factor that substantially contributes to CE is energy consumption (EC). Energy is a significant component of the production process and the foundation of the industrial sector. Without the use of energy resources, it is impossible to accomplish the goals of EG, and when the EG rises, the level of energy use increases as well and those two trends move together in parallel (Mughal et al. 2022). Primary energies mainly come from fossil fuels, specifically, petroleum products, natural gas, and coal (Mughal et al. 2022). In order to achieve maximum EG, countries are increasing EC and other natural resources, which increases GHG (Adebayo et al. 2020). In China, primary energy is dominated by coal and the proportion of EC by power generation is low. More than 85% of renewable energy is used to generate electricity in Japan and South Korea (Zhang et al. 2019). The use of non-renewable sources for combustion impacts the environment which increases the level of CE (Mughal et al. 2022). Moreover, India's industrial and power sectors produce high levels of CO_2 emissions, and India rely on conventional energy sources such as coal and oil (Misra 2019). Likewise, Pakistan's EC heavily depends on imported oil for energy production (Rehman and Rehman 2022).

The other factor which contributes to CE is trade openness (TO). TO identify as the outward or inward orientation of a given country (ESCWA 2020). International trade between China, Japan, and South Korea has been significantly boosted by TO, which has resulted in enormous EC and increased CO_2 emissions (Dou et al. 2021). Since it accelerates the production of commodities and increases EC, TO promotes CO_2 emissions (Ahmed et al. 2017). Moreover, in Chinese cities, trade exposure causes a significant reduction in air quality and an increase in health issues in areas that have a comparative advantage in a manufacturing sector that emits significant amounts of pollutants, highlighting the noteworthy regional differences on the impacts of trade on pollution (Bombardini and Li 2020). As outlined earlier, GDP, EC, and TO have a direct impact on CE and thereby contributing to the notable escalation of total emissions in the Asian region. Nevertheless, the literature lacks comprehensive insights into the specific and predominant effects of these variables on CE in Asia.

Therefore, the purpose of this study is to investigate the impact of GDP, EC, and TO on CE in Asia for the years 2000 to 2019 and in 42 countries of the region. The contributions

of this study stand out from past research in four different ways. Firstly, it addresses a critical knowledge gap by delving into the simultaneous influence of GDP, EC, and TO as independent variables, providing a nuanced understanding of their collective impact on CE in the Asian context. Secondly, the research employs multiple linear regression, offering a robust methodological contribution and conducting a rigorous statistical analysis for selected Asian countries, which prominently feature among the world's top emitters. Thirdly, graphical representations are employed to elucidate the nuanced linear trends, illustrating how each of the four variables individually influences selected Asian countries. Lastly, the study furnishes a range of policy implications, guiding countries towards emission reduction strategies with the overarching goal of achieving carbon neutrality by 2050.

The subsequent sections of this study are structured as follows: the theoretical framework, literature review encompasses findings from previous studies, followed by the presentation of data and methodology, results and discussion, and, finally, the conclusion, policy implications along with limitations and opportunities for future research.

Theoretical framework

The relationship between CE, GDP, EC, and TO is explained by three theoretical frameworks namely, (1) environmental Kuznets curve (EKC), (2) 3Ps framework of sustainability, and (3) Porter hypothesis. EKC is a hypothesised relationship between environmental degradation and per capita income. According to the EKC, environmental degradation increases when economic development occurs initially, but at a certain point, the society starts to better its relationship with the environment, and environmental degradation levels decline. The EKC is often represented as an inverted "U" shape (Hanif 2018).

The sustainability 3Ps framework, commonly known as the triple bottom line, encompasses three key dimensions: people, profit, and planet. In the "people" dimension, there is a focal point on the social aspect of sustainability, highlighting the impacts of business activities on various stakeholders, including employees, communities, and other relevant parties. The emphasis is on ensuring that business practices consider and positively contribute to social wellbeing. The "profit" dimension concentrates on the economic viability of actions, underscoring the importance of generating profits to sustain the organisation economically. However, this economic sustainability is pursued without compromising the well-being of people and the health of the planet. The goal is to achieve profitability while maintaining ethical and socially responsible business practices. The third dimension, "planet," emphasises the environmental impacts of actions. This aspect of the framework involves efforts to minimise harm to the environment and actively promote practices that contribute to environmental wellbeing. The aim is to ensure that business activities are conducted with a keen awareness of ecological considerations, fostering practices that are environmentally responsible and sustainable.

Beyond the delineation of the 3Ps framework, the "people" component within the framework directs attention to the societal implications of key variables. This involves a nuanced examination of how factors such as escalating GDP and EC can enhance living standards, yet concurrently contribute to CE, thereby adversely affecting public health and overall quality of life. The "profit" component of the framework is centred on the financial consequences, carefully considering how these elements support EG and profitability, while also recognising their potential association with heightened CE. Conversely, the "planet" component necessitates a thorough evaluation of the environmental ramifications of these variables, particularly in relation to CE. It advocates for strategic interventions that can curtail emissions, such as the adoption of renewable energy sources and the implementation of laws promoting sustainable trade practices. It is evident that maintaining equilibrium across these three dimensions is imperative for attaining sustainability within the Asian region (Nurgazina et al. 2021; Dissanayake et al. 2023).

The Porter hypothesis suggest that strict environmental regulations can induce efficiency and encourage innovations that help improve commercial competitiveness and EG. This theory states that strict environmental laws lead to the development and deployment of greener technology and environmental innovations, which increase the efficiency of manufacturing processes and final goods in terms of minimising the CE (Guan et al. 2023). Environmental laws can also boost the EG by enhancing the quality of life of the people by reducing the health related issues (Dissanayake et al. 2023). The present study examined the estimation outcomes within the framework of established theories to demonstrate the correlation between EC, GDP and TO on CE.

Literature review

Asia's CE are significantly affected by a variety of critical factors, including GDP, EC, and TO. EC, which is commonly estimated by a country's national GDP, refers to the rise in the production and consumption of goods and services through time. TO is the extent to which a country engages in international trade, whereas EC is the quantity of energy consumed by a nation to generate products and services. Since most energy sources used in manufacturing emit CO_2 and other greenhouse gases (GHGs). CE rise along with EG and EC. This is undoubtedly true in Asia's developing nations, where industrialisation and EG are expanding

rapidly. Nonetheless, TO can affect carbon emissions both positively and negatively. One way that trade potentially impact emissions is by increasing production and consumption. On the other hand, trade can also result in the transfer of eco-friendly technologies and productive techniques that help reduce emissions (Dou et al. 2021; Hanif et al. 2019; Arshad et al. 2020). About half of global CE are produced in Asia, which is home to five of the biggest emitters of GHGs (Lamb et al. 2021). Due to the region's significant proportion of current emissions and anticipated growth in emissions in the future, the policies of major CO_2 emitters like China and India are essential to the global effort to reduce emissions (Era Dabla-Norris et al. 2021).

Moreover, almost all the Asian countries are heavily dependent on the tourism sector since Asia is one of the most popular tourist destinations in the world because of the countries like Sri Lanka, Indonesia, Singapore, United Arab Emirates, and Malayasia. Simply, tourism help to slow down the natural degradation of environment and CE increases as the result of population growth, energy use, economic development, and urbanisation (Voumik et al. 2023; Saqib 2022). Also, due to the development of tourism sector, environmental pollution is significantly influenced by the factors such as population density, TO, and EG (Jiaqi et al. 2022; Nosheen et al. 2021).

The challenge of excessive CE and related environmental impact has emerged as a prominent global concern, particularly in the context of Asia. The region's rapid EG and industrialisation have led to a significant surge in CE levels in recent years. Consequently, there is a heightened interest in comprehending the association between GDP and CE within Asian countries. Numerous studies have endeavoured to investigate the correlation between GDP and CE in Asia, with the consensus pointing to the unique context of Asia, characterised by a prevalence of developing nations rather than developed ones. The developing nations in Asia are actively addressing the adverse effects of GHG emissions, including CE, by prioritising industrialisation to accelerate economic growth. Additionally, to bolster GDP, these developing nations are placing increased emphasis on urbanisation, contributing to environmental degradation, and giving rise to various health challenges within Asian countries.

Furthermore, the workforce, globalisation, and participation in educational institutions significantly contribute to both CO_2 emissions and EG (Rani et al. 2022; Anwar et al. 2020). Additionally, empirical evidence suggests that EC and GDP exhibit a positive and significant association with CE in the short term, but show a negative correlation and lack statistical significance in the long term (Choudhury et al. 2023).

Moreover, the economic development, as measured by GDP, has contributed to an increase in global warming and climate change, presenting significant global challenges. While urbanisation and green economic recovery positively impact GDP in developed nations, the effect is less favourable in Asian developing nations. This underscores the importance of prioritising natural resources while promoting economic growth in the Asian region (Chen et al. 2023). In recent years, the Asian region has undergone rapid economic growth driven by extensive industrialisation and economic activities, with insufficient consideration of the adverse impacts of CE.

In emerging Asian nations, CO_2 emissions are rapidly increasing due to increased EC (Saqib and Dincă 2023). According to the energy intensity theory, the efficiency of energy consumption plays a pivotal role in determining the amount of carbon emissions produced per unit of energy consumed. Countries with more efficient energy utilisation or lower energy intensities tend to exhibit lower CE per unit of energy consumed. Long-term trends suggest that carbon intensity increases with industrialisation and energy intensity, while urbanisation and the adoption of renewable energy sources contribute to a decrease in carbon intensity. Additionally, the short-term relationship between carbon intensity and energy intensity shows a positive association (Rahman et al. 2022). Furthermore, substantial investments in non-renewable energy for electricity production and other necessities incur high costs, leading to a reduction in the GDP of countries. Given the abundance of renewable energy resources in many Asian countries, redirecting investments towards renewable sources is deemed essential for enhancing energy efficiency while preserving GDP (Rahman and Alam 2022; Lu 2018). In addition to that, economic development and EC positively impacted ecological pollution and natural resources' rent was found to promote environmental pollution across the Asian continent (Bosah et al. 2023). Also, empirical findings proved that EG and non-renewable EC raise the environmental degradation, but the renewable consumption mitigates the adverse effect on the environment over time in Asian emerging countries like China, India, Bangladesh, Iran, and Sri Lanka (Saqib 2022). Throughout the past two decades, the Asian region has consistently and significantly contributed to the rise of the world's energy demand, with China and India being at the forefront. The continued expansion of the economies and urbanisation in the region are going to continue for the foreseeable future.

Moreover, TO exhibits a positive impact on CE (Dauda et al. 2021) in developing countries, particularly in Asia, home to some of the world's largest economies and significant carbon emitters. However, recent research indicates a more nuanced and complex relationship between TO and CE (Wang and Wang 2021), while several studies yielding conflicting results. Past research findings suggest that in the short run, trade openness contributed to a reduction

in carbon emissions, yet over time, this effect diminished. These results imply that developing nations adapted by embracing greener technologies and enhancing their energy efficiency.

Additionally, some studies found out that long-term TO reduced CE, and this effect was clearly reflected in nations with greater levels of EG. Overall, these studies suggest that the relationship between TO and CE in Asia is more complicated than previously believed and is influenced by a variety of factors including economic development, technological innovation, and governmental policies. However, this relationship between TO and CE in Asia is still a matter of debate (Dou et al. 2021; Wang and Zhang 2021; Fang et al. 2018; Shahbaz et al. 2017). Throughout the past two decades, the Asian region has typically become more open to trade because China and India lead the TO due to trade policies (Foo et al. 2020). In addition to that, negative shocks in economic complexity, foreign direct investment (FDI), environmental technology, and renewable energy elevated the pollution levels in the long run while adverse shocks in economic complexity and FDI cause increased pollution in the long run (Saqib and Dincă 2023). On the other hand, there are both positive and negative effects of foreign TO on CE. TO encourages countries which promotes CE in economic sectors with lower CE intensity but for industries with high carbon emission intensity, it also partially restricts it. Also, the number of employees, technological innovation, GDP, and economic activity intensity influence the CE in the industrial sectors in countries like India (Derindag et al. 2023).

A limited number of studies have explored the intricate relationship between CE, GDP, EC, and TO in the Asian region. Furthermore, no study has comprehensively examined these variables simultaneously, encompassing the entire region and presenting them in robust statistical models. Limited studies have employed graphical techniques to illustrate the collective impact of CE across the entire region. Drawing insights from the gaps in previous research, there is a compelling need for a more in-depth analysis of the Asian region considering CE, GDP, EC, and TO collectively. Such an analysis would contribute significantly to the understanding of the interplay between GDP, EC, and TO, essential for achieving the overarching goal of reducing carbon emissions.

Data and methodology

In order to conduct a comprehensive examination, this study employed a panel dataset comprising 42 Asian countries over the period from 2000 to 2019. The selection of this timeframe was primarily driven by data availability constraints for the considered variables. The data utilised for the analysis was sourced from Our World in Data (refer Table 1). Metric tons per capita is used as the unit of measure for CE. For GDP, this study used GDP per capita, and for EC, this study used per capita jilowatt hours. Percentage of GDP is used as the unit of measure for TO.

This study gathered data for all the countries and got average values for each of the variables for each year to design line graphs. The line graphs will help readers to understand the overall variation of each variable during the considered period. Next, this study derived the descriptive statistics by utilising STATA software. Further, the study used maps of Asia to represent the descriptive statistics graphically. Averages were calculated for each country for the considered period.

Analytical models

To perform a statistical analysis examining the interplay of EC, GDP, TO, and CE in the Asian region, this study systematically conducted a comprehensive analysis, taking into account the gathered secondary data.

Panel regression model analysis

Results of panel regression model according to the Eq. 2 is presented in the Table 2. The findings of probability F test and LM test rejected the null hypothesis for the Asian

Table 1 Data sources and variables

Variable	Measure	Data source
Carbon emission	Metric ton per capita	Our World in Data https://ourworldindata.org/grapher/co-emissions-per capita
Gross domestic product	GDP per capita	Our World in Data https://ourworldindata.org/grapher/gdp-per-capita-worldbank
Energy consumption	Per capita kilowatt hours	Our World in Data https://ourworldindata.org/grapher/per-capita-energy-use
Trade openness	Percentage of GDP	Our World in Data https://ourworldindata.org/grapher/trade-as-share-of-gdp

Source: Authors' illustration based on Our World in Data (Our World in Data 2023)

Table 2 Specification test results for panel data models

Asia	F test	LM test	Hausman test
	H_0: POLS	H_0: PLOS	H_0: Random effect
	H_1: Fixed effect	H_1: Random effect	H_1: Fixed effect
	0.7346***	2134.70***	134.93***

The symbols *** represent 1% significance level

region. That means Pool OLS (POLS) approach is unsuitable for the current study. Therefore, the Hausman test is carried out to find out the suitable approach between the random effect model (RE) and fixed effect model (FE). The Hausman test results for the Asian region also rejected the null hypothesis indicating that the estimations of FE model are more accurate than the estimations of RE model. Thus, this study suggested to use the FE model for the Asian region as the most suitable statistical approach for this study.

After conducting all the relevant tests for panel regression, the study realised that the specific outcomes for individual Asian countries were not explicitly disclosed. Consequently, the study opted to employ multiple linear regression (MLR) estimates as an alternative approach to discern the unique conditions prevailing in each respective Asian country.

Multiple linear regression (MLR) model analysis

In Eq. 1, an in-depth understanding of the relationship between the variables considered in each country is provided by the single-country analysis using multiple linear regression (MLR) model.

$$CE_t = \alpha_0 + \propto_1 GDP_t + \propto_2 EC_t + \propto_3 TO_t + \varepsilon_t \quad (1)$$

In the equation, t shows the year taken into consideration. ε_t shows the standard error. This study analyses the significant levels of each Asian country towards the considered variables using MLR model. In the meantime, to get an idea about the overall impact in the Asian region, this study conducted a region wise analysis using panel regression model by using the following equation.

$$CE_{it} = \beta_0 + \beta_1 GDP_{it} + \beta_2 EC_{it} + \beta_3 TO_{it} + \varepsilon_{it} \quad (2)$$

In the equation, i denotes the relevant region, and t shows the year taken into consideration. ε_{it} shows the standard error. By utilising Eq. 2, this study conducted the panel regression model specification test to find out the most suitable model between fixed effects model (FE) and random effects model (RM).

Subsequently, this study designed a scatter plot with linear fit lines employing MLR estimates to elucidate the correlation between actual values and the fitted values. These scatter plots serve as visual aids for comprehending the diverse impacts of each variable across different Asian countries and whether these impacts are on the rise or decline within the specified time frame. Ultimately, countries exhibiting positive trendlines in the scatter plots were selected for in-depth discussion.

Results and discussion

The current study is examining the impact of GDP, EC, and TO on CE in Asia. CE is the producing through burning of fossil fuels and natural gas mainly through the human activities (National Geographic Society 2024). It includes various greenhouse gases like CO_2, methene, and nitrous oxide (N_2O) (Ritchie et al. 2024). This study selected CE as the dependent variable by measuring it using metric ton per capita. EC calculates based on a nation's overall energy demand. It includes the energy sector's own consumption as well as losses incurred in the distribution and conversion of energy (and the ultimate consumption by end users and this study measured EC using per capita kilowatt hours as the unit of measure (Statistics 2024). GDP calculates the monetary value of finished goods and services, or those purchased by the end user, produced in a nation within a specific time frame, such as a quarter or a year. It includes all output produced inside a nation's boundaries (Callen 2024). GDP is measured using the GDP per capita in this study. Finally, TO means the ratio of imports plus exports over GDP and it is measured using the percentage of GDP (Alotaibi and Mishra 2014). In order to present how each variable performed in the considered time period, the study designed Fig. 1 using the variable wise average values from 2000 to 2019.

According to Fig. 1A, CE shows a rapid increase during the considered time period. The region's increased CO_2 emissions are primarily caused by industrialisation as Asia consists of many developing countries. In order to increase the GDP, negative effects of CE are mostly ignored (Odonkor 2020). In 2012, CE shows a drastic increase, while GDP shows an upward trend. The reason behind that is the EG, increased EC, population growth, and lack of regulations in the Asian continent. Moreover, data from the Global Carbon Atlas (Global Carbon Atlas 2021) show that Asia has experienced an increase in CO_2 emissions over the past 20 years. By 2019, Asia's proportion of global CO_2 emissions has climbed to almost 47% from its 2000 level of about 37%. This indicates that throughout the time, the region has contributed to an increasing percentage of the world's CE.

In Asia, GDP shows an increasing trend from 2009 to 2019 in Fig. 1B. The main forces behind Asia's rapid EG are new technology, globalisation, and market-oriented change (Kuroda 2013). Continuing EG is the main reason behind the

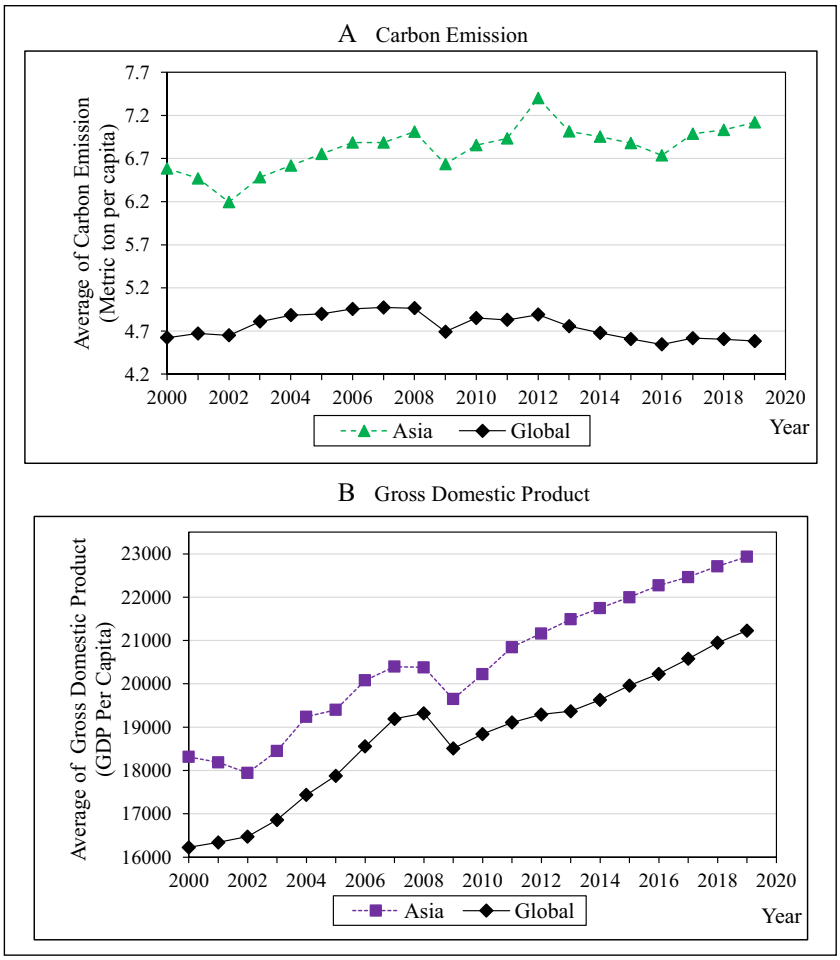

Fig. 1 Average of CE and GDP for Asia and global from 2000 to 2019. Source: Authors' illustrations based on Our World in Data (Our World in Data 2023)

increase in EC. Moreover, Asia's economies grew significantly between 2000 and 2019, with many nations becoming major players in the world economy. China, India, Vietnam, and Bangladesh are some of the region's economies that are fast. Increased foreign investment, rising middle income class, and supportive government policies all significantly contributed to EG. According to data from the World Bank, the average annual GDP growth rate for Asia was 5.5% during this period, while the global average was 2.9% (The World Bank Group 2023d). China and India are the largely expanding economies significantly contributed to the continent rating top among other continents in the world. Figure 2 shows the average of EC and TO for Asia and Global, 2000–2019.

In Fig. 2A, EC has a positive growth from 2009 to 2019 as most of the Asian countries are relying on renewable and non- renewable energies for the purpose of generating electricity (The Economist Intelligence Unit Limited 2022). Asia consumed more than 40% of the world's energy in 2019, according to the International Energy Agency (IEA) (IEA 2023c), and between 2000 and 2019, the region's energy consumption increased by an average of 3.3% annually. Its rise was mostly caused by the region's rapid EG, which has increased industrial production and increased demand for transportation and electricity.

Due to the currency fluctuations, local political tension, local legal system, and increased local competition, Asia shows a downward trend in TO in Fig. 2B (GoGlobal 2023). According to the World Trade Organisation (WTO) (World Trade Organization 2023), the average trade-to-GDP ratio in Asia is still less than the global average due to the high trade restrictions in Asian countries. The WTO also pointed out that the growth of the region's services industry is reflected in the fact that trade in services has increased more faster in Asia than trade in goods.

To better analyse the dataset, descriptive statistics, such as the number of observations, mean value, standard deviation, and minimum and maximum values for CE, GDP, EC, and TO, have been provided in S2 Appendix. According to the S2 Appendix, it is clear that countries with the highest earnings, such as Qatar, Oman, Saudi Arabia, South Korea, UAE, Kuwait, Japan, and China, show the highest mean values for CE associated with other considered independent variables. Additionally, to present the descriptive

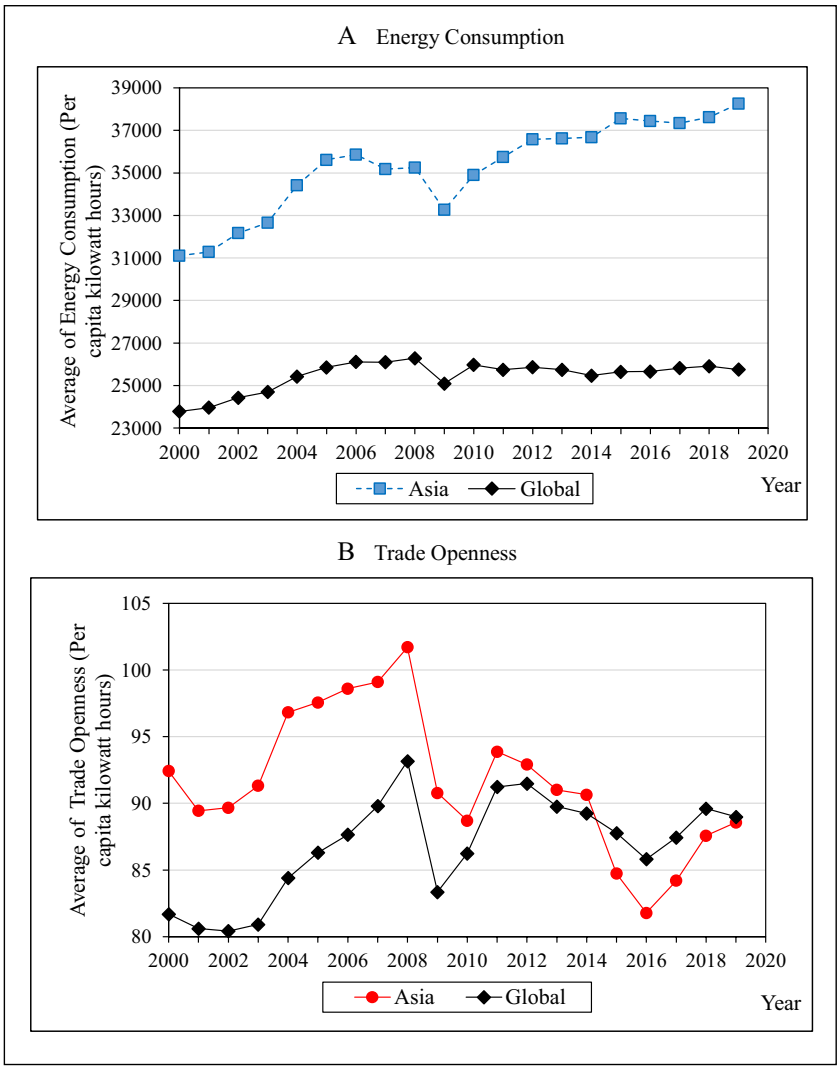

Fig. 2 Average of EC and TO for Asia and Global from 2000 to 2019. Source: Authors' illustrations based on Our World in Data (Our World in Data 2023)

statistics of this study in a more comprehensible manner, world maps were used in Fig. 3 as a new method for graphical representation.

According to the Fig. 3 A and B, Qatar appeared as the highest carbon emitter in both 2000–2005 and 2015–2019 time periods than other countries in Asia because Qatar has one of the smallest populations and is the world's largest liquefied natural gas (LNG) producer compared to other nations in the region (Al-Asmakh and Al-Awainati 2018). During the considered period Qatar witnessed a boom in LNG sector and the energy-intensive processes of LNG liquefaction and processing burn a large quantity of natural gas and produce GHGEs (Meza and Koç 2021; Ashkanani and Kerbache 2023). Compared to 2000–2005 time period, Kazakhstan shows high CE in 2015–2019 in Fig. 3B period due to their dependency on mineral sector to fast track their economy (The World Bank Group and Asian Development Bank 2021).

Saudi Arabia is another country that contributed more to the increase of CE. Lack of diversification in energy sources, transportation, industrial activities, and limited environmental regulations, Saudi Arabia experienced large increases in CE during the considered time period (Song and Zhang 2019). External factors like changes in global oil prices, global economic trends, and the effects of climate change have an impact on Oman's CE throughout the time period (Fig. 3B). Bahrain is also showing an increase in CE when they reached the time period 2015–2019 in Fig. 3B. Bahrain's heavy usage of fossil fuels for energy production contributed highly to the increase of CE in the country. In addition, Bahrain's population is expanding, which could have resulted in a rise in the country's CE from increased energy use for transportation, industry, and household reasons. Turkmenistan and Brunei are also showing an increase in CE during the considered time period. Turkmenistan is a major exporter and producer of natural gases and due to

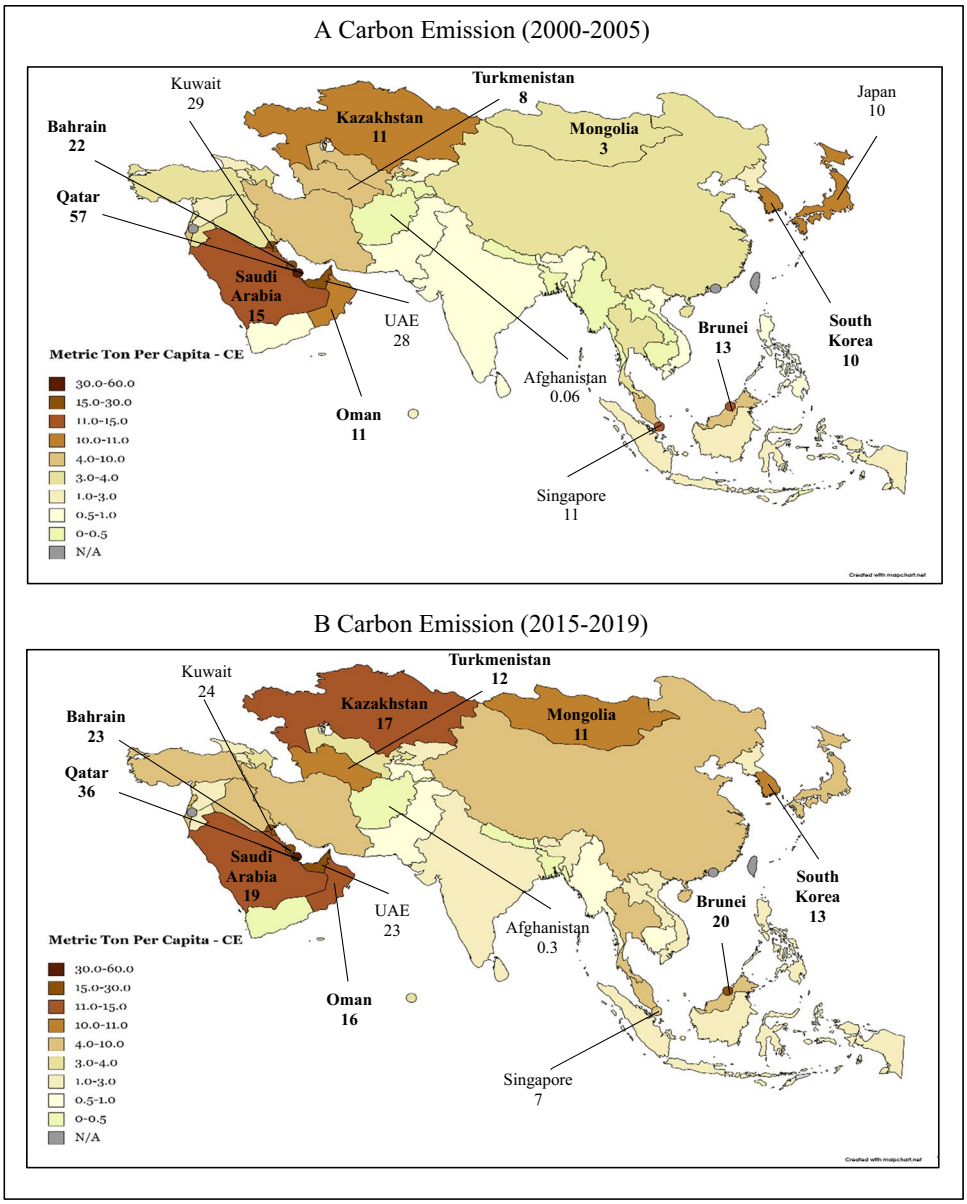

Fig. 3 Carbon emission variation in Asian countries in 2000–2005 and 2015–2019. Source: Authors' illustrations based on Our World in Data (Our World in Data 2023)

their domestic EC, the CE level went up. Brunei has invested in various industrial projects, which are mainly based on oil and gas sectors. These industries are energy intensive and emits high level of CE. When compared to the period of 2000–2005, Oman shows an increase in CE for the period of 2015–2019. Oman's CE grew between 2015 and 2019 due to a variety of reasons, including population growth, increasingEG, and higher EC (Ministry of Energy and Minerals 2023). The International Energy Agency (IEA) reports that Oman's energy-related CO_2 emissions grew by 16% between 2015 and 2019, from 80.4 million metric tons to 93.3 million metric tons. Also, Mongolia shows an increase in CE during 2015—2019.

With a sharp rise in registered automobiles in recent years, Mongolia's transportation industry has been expanding rapidly. Consequently, road transport emissions have increased, particularly in urban areas, leading to an increase in carbon emissions (CE). However, in contrast, Singapore exhibits a decrease in CE, as shown in Fig. 3B.

In Fig. 4A, Qatar displays the highest GDP in both time periods. The Qatari economy is among one of the quickest expanding in the Middle East and, in fact, the entire globe. The high price of hydrocarbons on the international commodity markets has allowed for high development rates to continue. While Qatar's gas exports are expected to increase, these prices seem to be reasonably stable (Ashghal 2023). Also, Oman shows a higher GDP in 2000—2005 and show comparatively low GDP in 2015–2019 in Fig. 4B. It was a result of the sharp fall in crude oil prices in international markets and the government's fiscal policy which was

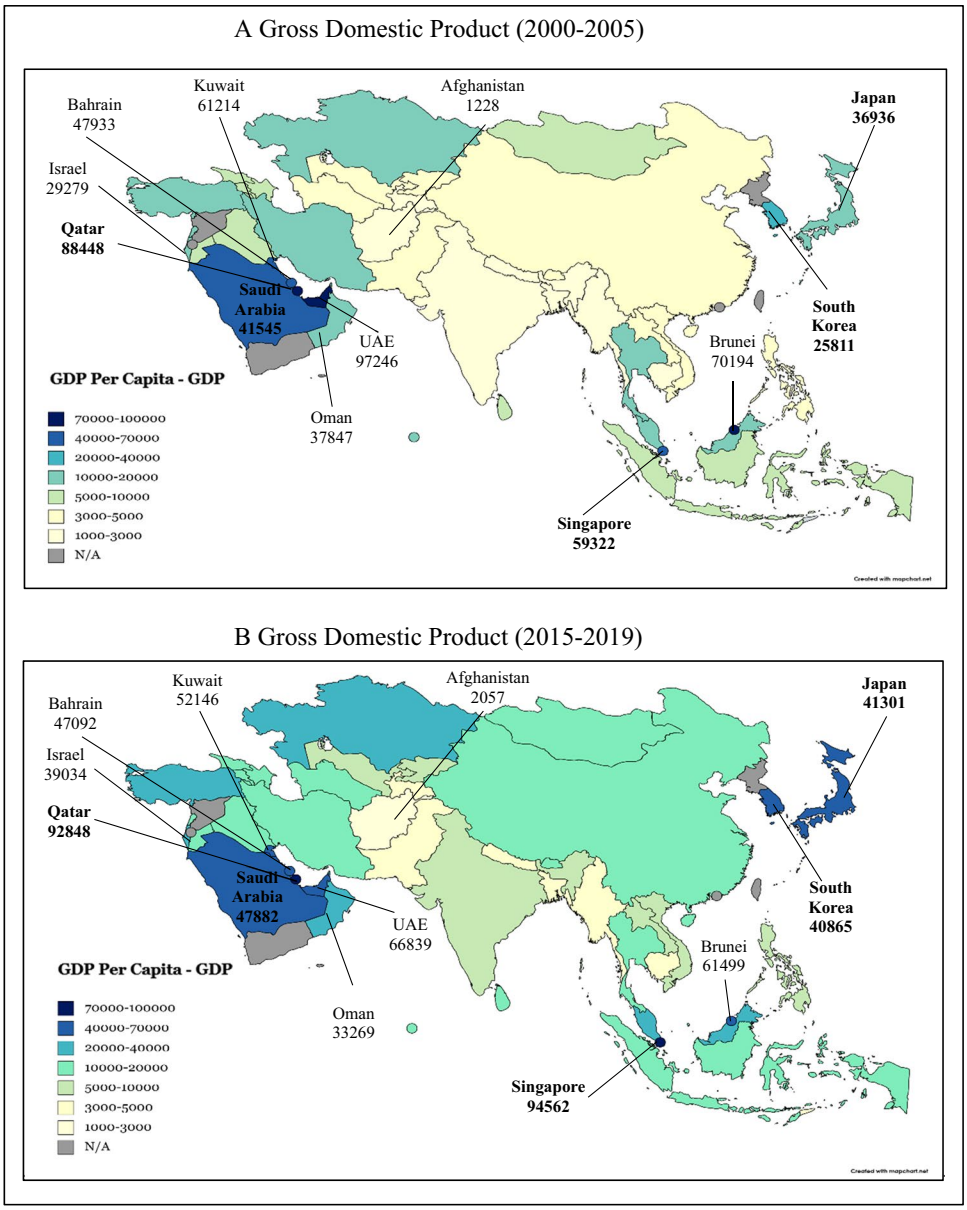

Fig. 4 Gross domestic product variation in Asian countries in 2000–2005 and 2015–2019. Source: Authors' illustrations based on Our World in Data (Our World in Data 2023)

implemented in 2015 (Muscat Media Group 2016). Singapore shows a considerable increase in GDP in Fig. 4B than Fig. 4A. Due to the diversification of the economy, pro-business policies, infrastructure development, and political stability, Singapore shows an increase in GDP.

Japan is also showing an increase in GDP, as depicted in Fig. 4B, during the period between 2015 and 2019. Several factors have influenced Japan's economic growth (EG). These include increased domestic demand for goods and services, a low unemployment rate, Abenomics, and technological innovation, which have been the main driving forces behind Japan's successful EG. In addition to Japan, Saudi Arabia is another country that exhibits an increase in GDP during the same period. The main pillars contributing to the growth of Saudi Arabia's EG include low interest rates, increased foreign investments, youth empowerment, and strong public–private relationships.

Qatar appeared as the highest EC country in Asian region in Fig. 5E and F for the period of 2000–2005 and 2015–2019 because Qatar is a significant worldwide aviation centre and a major supplier of petrochemicals, fertilisers, natural gas, and oil. With renewable energy making up only a small portion of Qatar's overall primary energy consumption, natural gas, and oil dominate the energy mix (US Energy Information Administration 2023). In 2000–2005, Oman shows an increase in EC in Fig. 5E but in 2015–2019 period, EC is relatively low in Fig. 5F. The reason behind that is the use of clean cooking fuels and technologies, such as non-solid fuels like natural gas, ethanol, or even electric technologies,

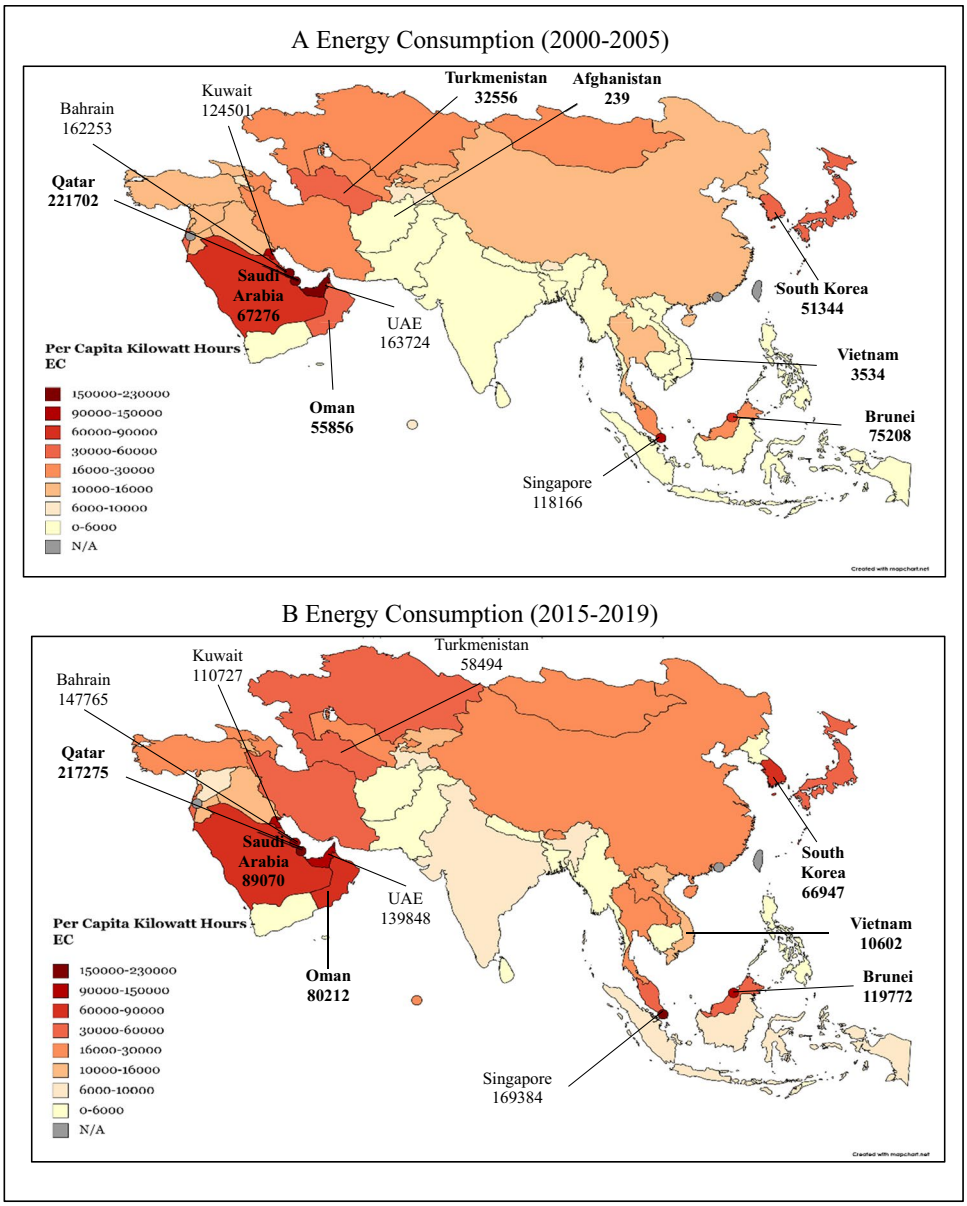

Fig. 5 Energy consumption variation in Asian countries in 2000–2005 and 2015–2019. Source: Authors' illustrations based on Our World in Data (Our World in Data 2023)

and it improves process efficiency and reduces time and EC (Ritchie and Roser 2023).

Saudi Arabia exhibits a significant increase in energy consumption (EC) between 2015 and 2019, as shown in Fig. 5F when compared to Fig. 5E. The growth of EC in the country can be attributed to factors such as population growth, subsidised energy prices, transportation needs, and economic growth. Vietnam and South Korea also demonstrate an increase in EC during the same period. Another country with notable EC is Turkmenistan, as depicted in Fig. 5F. Turkmenistan has made significant investments in the construction of new buildings, roads, and infrastructure, resulting in an increased need for energy to operate transportation systems, buildings, and other infrastructure. South Korea also experiences high EC in Fig. 5F. Similarly, Brunei demonstrates an increase in EC between 2015 and 2019. The oil and gas industry, which serves as the backbone of Brunei's economy, plays a predominant role in the country's energy consumption. Brunei's energy consumption has risen during this period due to factors such as population growth, economic progress, and increasing energy demand.

According to Fig. 6 A and B, Singapore exhibits the highest TO in both time periods, while the UAE demonstrates significant growth in TO, as shown in Fig. 2F. In comparison to other nations in the region, Vietnam has relatively high TO, which has been consistently increasing in recent years. Vietnam's TO experienced growth between 2015 and 2019 due to various factors, including economic reforms, trade agreements, and the development of an export-oriented manufacturing sector. Over the past few decades, the Vietnamese

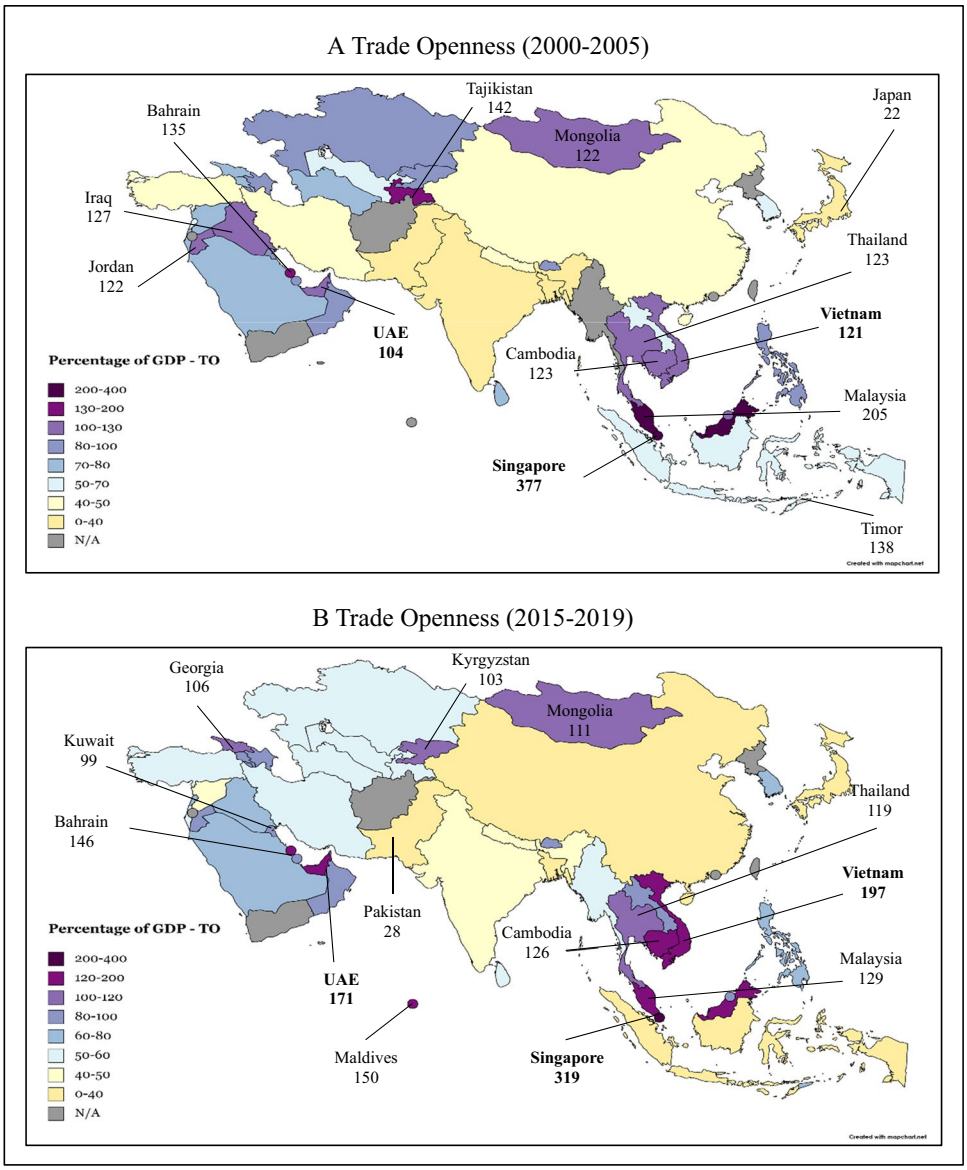

Fig. 6 Energy consumption variation in Asian countries in 2000–2005 and 2015–2019. Source: Authors' illustrations based on Our World in Data (Our World in Data 2023)

government has implemented several economic changes, such as the liberalisation of trade and investment regulations. These changes have facilitated Vietnam's economic integration, attracted international investment, and stimulated the growth of export-focused sectors. When compared to the world maps for other considered variables, TO shows the lowest average values in both time periods, as many Asian countries primarily focus on imports. Furthermore, Asia comprises many developing nations, which contributes to lower TO performance.

This study conducted the single country analysis using MLR in S3 Appendix. Armenia, Bhutan, Georgia, Kazakhstan, Kyrgyzstan Republic, Laos, Maldives, Mongolia, Myanmar, Nepal, Tajikistan, and Turkmenistan show positive significance for GDP towards CE. All are developing nations, and as mentioned earlier, these nations are trying to fast track the economies through various activities which emit high level of CO_2. Moreover, Azerbaijan, Brunei Darussalam, Cambodia, China, India, Israel, Jordan, Qatar, South Korea, and Thailand shows negative significance for GDP. All the countries which are significant for EC are showing positive significance towards CE. Compared to other countries, Mongolia shows the highest positive significance for EC towards CE. The mining sector has been a significant contributor to Mongolia's GDP growth since 2010, which the World Bank (The World Bank Group 2023b) estimates to have been around 7% annually. Consequently, there is now a greater need for energy to run industrial processes, construction projects, and transportation. Furthermore, urbanisation, extreme climate (World Meteorological Organization 2022), and lack of infrastructure lead to the highest positive significance towards CE in Mongolia. Bangladesh, Brunei

Darussalam, Cambodia, Jordan, Nepal, Oman, Turkmenistan, and Uzbekistan show positive significance for TO in S3 Appendix. Brunei Darussalam shows the highest positive significance among all the countries which are positively significant. The economy of Brunei Darussalam is heavily reliant on exports, particularly those of natural gas and oil. The nation has a strong positive significance for TO as a result. Abundance of natural resources, small domestic market, export oriented economic strategy, and regional integration are the main reasons behind the Brunei Darussalam's positive significance for TO (CIA 2023). As implied in S3 Appendix, this study supports readers to understand the positive or negative relationship between each variable towards the CE in each Asian country.

Most research papers consider the variance inflation factor (VIF) and tolerance as indicators of multicollinearity issues. In the current study, VIF is calculated for each of the considered Asian countries, as presented in S4 Appendix, to effectively demonstrate the correlation among the variables. Scatter plots were designed in the same appendix to visually depict the relationship between actual values and fitted values, providing a clear representation of the data. In the discussion, this study primarily focuses on the top carbon emitters and compares the trendline presented in Fig. 3. By analysing the trendline, we can gain insights into the relationship between the variables and observe any notable patterns or trends. The inclusion of these analyses and visual representations in S4 Appendix and Fig. 3 enhances the understanding of the research findings and contributes to the overall clarity and robustness of the study.

Asia's reliance on coal and other fossil fuels, in contrast to Europe or North America, results in high per capita emissions, but the region's varied developmental stages produce a complex situation with carbon. While historical shifts in nations such as South Korea show how to successfully decouple growth from emissions through efficiency measures and investments in renewable energy, other nations exhibit what is known as the "environmental curve," rising simultaneously at first before plateauing or even declining as income levels rise (Goswami et al. 2023; Choudhury et al. 2023). Because of their outdated infrastructure and reliance on antiquated technologies, Asian countries release more carbon per GDP unit than do developed economies. On the other hand, decoupling is possible due to rapid advancement and technology adoption, as demonstrated by Japan's shift from coal to cleaner sources (Fragkos et al. 2021). A further layer of complexity is introduced by trade: although openness-induced technical transfer can lower emissions, greater output for export frequently raises them. This is a result of the different degrees of production methods and environmental laws across trading partners (Sun et al. 2019; Wenlong et al. 2023). Tailored solutions for emissions reduction are necessary because of this complex interplay, which is specific to the economies of many Asian countries. To effectively develop regional and global climate action, it is imperative to comprehend these particular circumstances. With the help of these and further study, we can better understand the complex relationships between trade openness, GDP, energy consumption, and carbon emissions in Asia, opening the door to a cleaner future for both the continent and the entire planet.

According to the MLR estimates results in S3 Appendix, there are many countries that show positive significance for GDP towards CE. As this study identified top carbon emitting countries in Fig. 7, Armenia, Mongolia, and Turkmenistan are the only countries which shows positive trendline for CE from countries which show positive significance in MLR estimates. Between 2000 and 2019, Armenia's economy grew significantly which increased CE as a result of industrialisation. In Mongolia, they experienced the same situation as Armenia, but Mongolia's success of EG depends on their mineral resource sector. The World Bank estimates that Mongolia's GDP per capita increased from US$ 400 in 2000 to US$ 4001 in 2019 (The World Bank Group 2023c). Furthermore, Turkmenistan experienced higher EG during the considered period which is mainly driven by their natural gas sector. Accordingly, those three countries are mainly focusing on developing their economies through industrialisation leading to higher levels of CE and created both environmental and health issues. In S3 Appendix, China and India shows a negative significance for GDP, but in Fig. 7, these show a positive trendline for GDP since both the countries are focusing more on their EG. China is home to a considerable share of the world's manufacturing industries, and over the past 20 years, the industrial sector of the nation has expanded substantially. With an average GDP growth rate of about 7% annually, India has seen substantial economic progress over the last two decades.

Moreover, in S3 Appendix, no country is showing a negative significance for EC towards CE; i.e., all the countries are heavily dependent on renewable energies rather than utilising non-renewable energies. As shown in Fig. 7, Armenia, Bangladesh, China, India, Iran, Malayasia, Mongolia, Oman, Saudi Arabia, and South Korea show upward growth for EC. For the production of energy and the heating of buildings during the winter, Armenia mainly relies on fossil fuels, particularly natural gas. This reliance on fossil fuels may result in higher CE. Also, Bangladesh heavily relies on fossil fuels to provide electricity and to supply power to its industries, particularly natural gas, and coal. Bangladesh relies heavily on imports to meet its energy needs because it has limited domestic energy resources. This results in more CE (IEA 2023a). Coal is frequently used in industrial processes, which require a lot of energy and thus can enhance CE in Bangladesh (Feng et al. 2023).

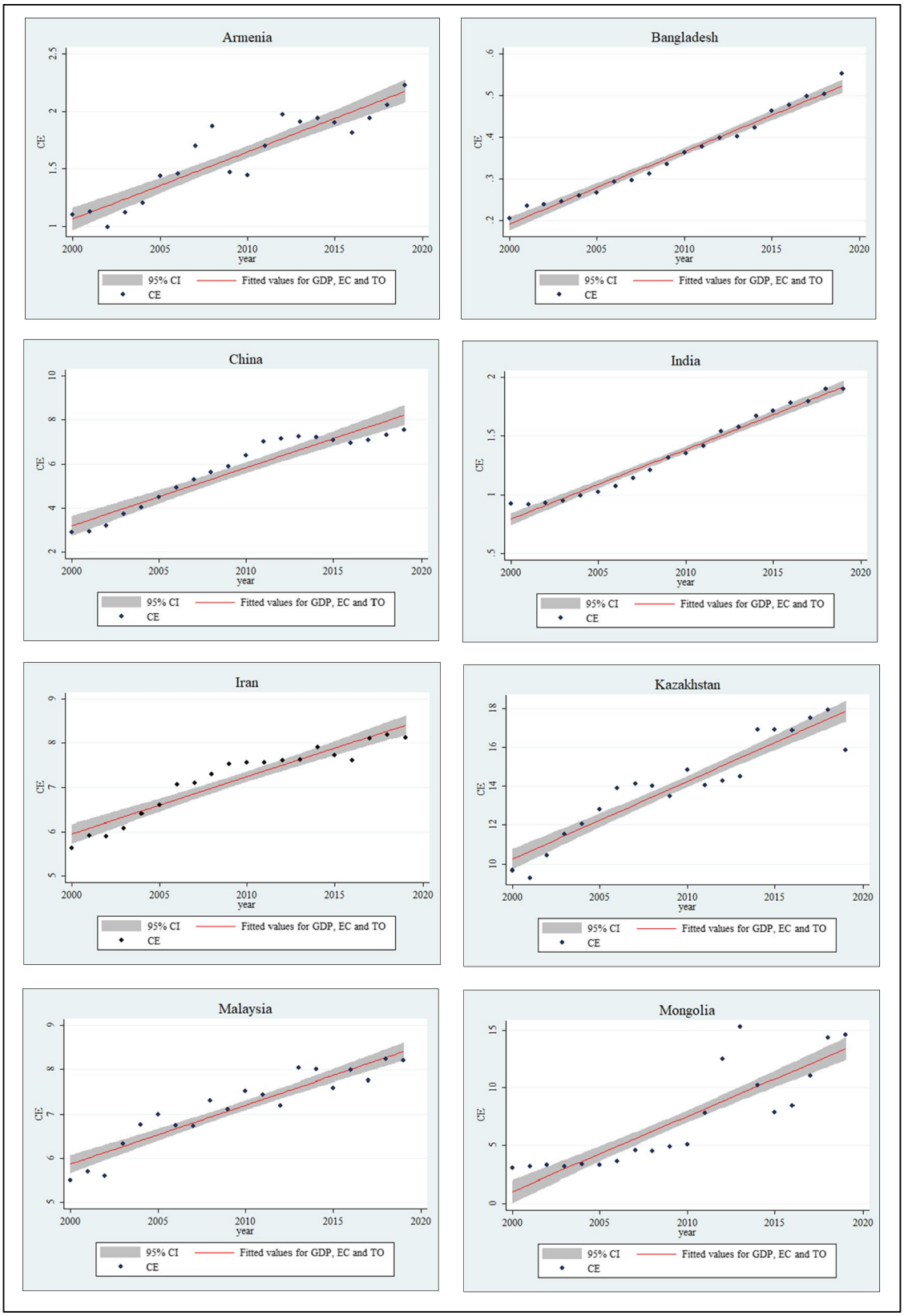

Fig. 7 Linear fit scatter plot graphs for high carbon emitting countries in Asia. Source: Authors' illustrations based on Our World in Data (Our World in Data 2023)

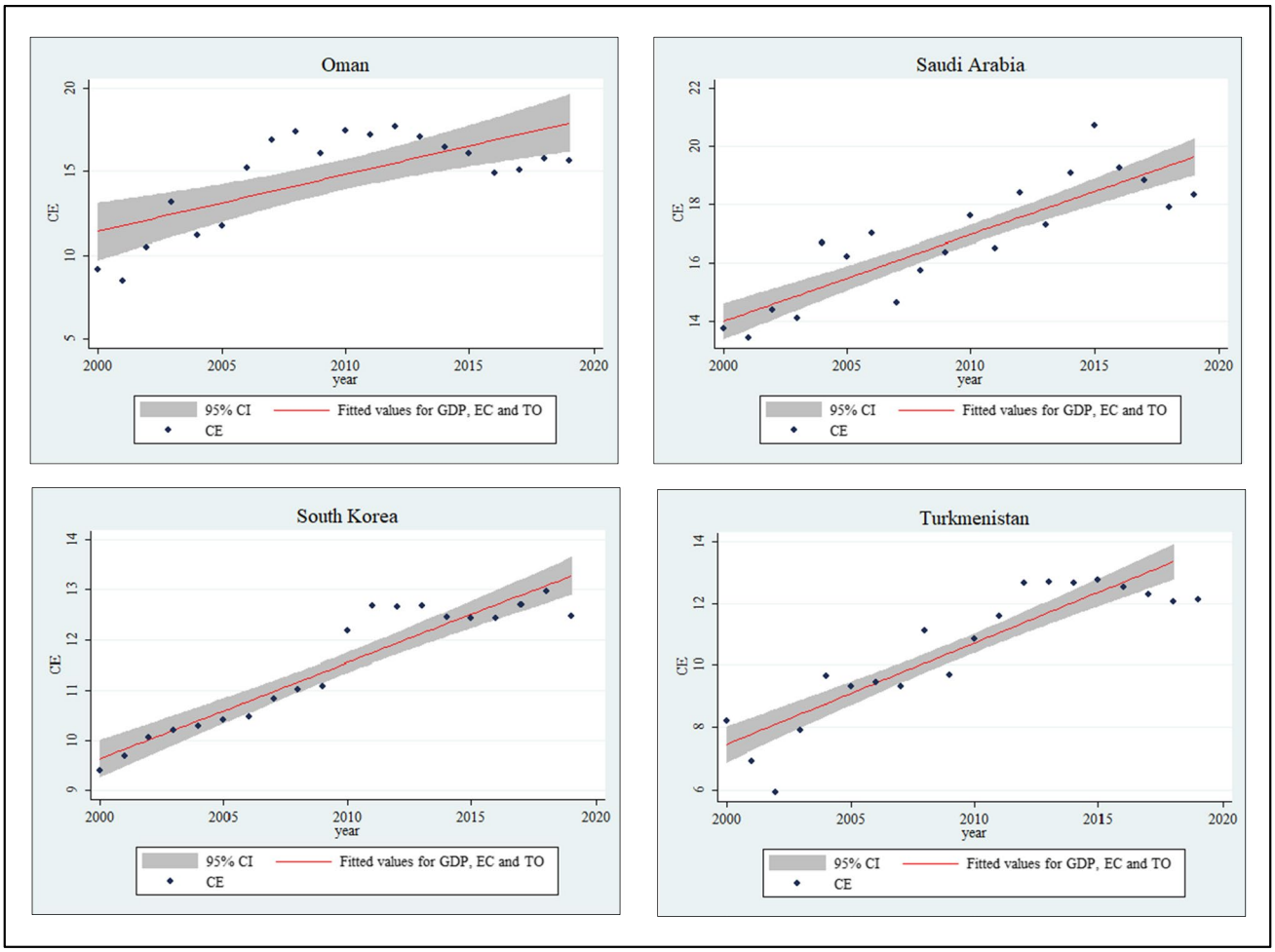

Fig. 7 (continued)

Additionally, the most populated nation in the world, China, has had steady population growth over the past 20 years. Due to that, there is currently a stronger demand for EC and other resources, which increase CE (IEA 2023b; National Bureau of Statistics of China 2012). As a result of increased population, there is currently a greater need for energy and other resources, which raise CE in India. India has been rapidly industrialising, particularly in the manufacturing and construction industries, which result in increased EC and CE. Furthermore, Iran possesses an inefficient energy infrastructure, resulting in elevated EC and consequently increased CE. Additionally, Iran heavily depends on fossil fuels, specifically oil and natural gas reserves, to meet its energy requirements, directly influencing the levels of CE. This reliance on fossil fuels has contributed to various climate and health challenges in Iran. Similarly, Malaysia has witnessed a simultaneous increase in energy consumption in line with its economic growth. Malayasia's main energy sources are fossil fuels like coal and natural gas, and the consumption has greatly increased the nation's CE. Mongolia shows an increasing trendline in Fig. 7 for CE. The nation's dependence on coal as its main source of energy is one of the main causes. Due to the abundance of coal resources in Mongolia, coal-fired power plants have been built and the usage of coal for heating has expanded, especially during the winter. Air pollution and greenhouse gas emission (GHGE) in Mongolia are largely caused by the burning of coal. In addition, the growth of the mining industry in Mongolia is another factor causing an increase in CE. With growing outputs of coal, copper, and other minerals, Mongolia's mining sector has expanded rapidly in the past few years. That has increased the need for EC and transportation, which has raised emissions (Guo et al. 2020). Oman has had considerable EG and development over the considered period, which has increased EC. This includes an increase in the industrial sector's scale as well as the EC of transportation and housing in Oman. As a result, there is a greater need for fossil fuels like oil and gas, which raises CE. Oil and gas production and extraction, however, consume a large amount of energy, increasing CE

in Oman. In addition to that, Oman's hot and dry weather is another factor that has contributed to a growth in the use of cooling systems. The high energy usage of equipment results in increased CE. Oman possesses a considerable migrant workforce despite its relatively small population. A rise in EC and CE has been brought on by the increasing demand for housing, transportation, and services from their workforce (Charabi et al. 2020). The population of Saudi Arabia has been gradually increasing, which has resulted in a rise of EC for domestic purposes like air conditioning and transportation. With considerable investments made in the industrial and construction sectors, EC raised fast and leads to high level of CE. Further, Saudi Arabia's comparatively low cost of fossil fuels has led to an overdependence and lack of incentives for the adoption of renewable energy sources in the country (Mahmood et al. 2020; Worldometer 2023a). However, in South Korea, the primary source of CE comes from its heavy reliance on coal for the purpose of generating electricity. With the industrialisation, South Korea is manufacturing steel and petrochemicals and it leads to an increase in CE through EC (Worldometer 2023b). Also, Turkmenistan has large natural gas reserves that uses for its own energy requirements as well as exports to its neighbouring countries. Due to that, the amount of GHG released by burning fossil fuels has increased and leads to high level of CE.

Not only the GDP and EC, TO also creates a considerable increase of CE level. From the selected high carbon emitting countries in Fig. 7, Bangladesh, Oman, and Turkmenistan show a positive significance for TO in S3 Appendix and as well as upward trend in scatter plot diagrams. There are several reasons behind the positive trend for TO in abovementioned countries. As a developing nation, Bangladesh mainly focuses on international trade to fast track their economy. With a sharp rise in trade and foreign investment, Bangladesh's economic integration with the world economy has accelerated. Energy use and economic activity have both increased as a result, which has also increased CE. Oman mainly exports oil and gas to various countries across the globe, resulting in oil and gas extraction and other activities released high level of CE to its atmosphere. The free trade agreements that Oman was signed with USA, Singapore, and European Union for the export purpose of oil and gas. As a result of high-income export sector, Oman has experienced a trade surplus during the considered period but due to the price cut in oil sector and increasing imports, trade surplus has dropped down. Moreover, Turkmenistan's TO is relatively low during 2000–2019 period but it has a significant impact on CE because Turkmenistan's exports are mainly dependent on the natural gas. However, China shows a negative significance for TO during the considered time period, but it has shown an upward trend in Fig. 7. As China is having an export-oriented economy, an increase in CE is a result of increased production and transportation of goods while manufacturing sector became the largest carbon emitter in China. So, as mentioned above, this study clearly identified how the TO create an impact on CE.

Asia's CE are soaring, mostly due to industrial activities and fuel burning. China alone accounts for over 60% of the region's total emissions and 31% of the global burden (Statista Inc 2024a).This increase contributes to climate change and creates extreme weather conditions like droughts and floods that severely impact people who are already vulnerable throughout the region (The United States Institute of Peace 2024). However, in the recent past China has taken several initiatives to mitigate carbon emission for contributing to sustainable development (Abbas et al. 2024; Li et al. 2023). Precisely estimating CE throughout Asia is crucial. Effective climate mitigation efforts are guided by this data, which also facilitates tailored adaptation measures to shield vulnerable populations from threats posed by climate change and directs investments towards clean energy options. Driven by fast growth in GDP and urbanisation, Asia will have the largest EC in the world in 2022 (nearly 277 exajoules), but at a significant social and environmental cost. Its reliance on fossil fuels like coal and oil has a negative influence on millions of people's health and way of life by greatly increasing GHGEs and air pollution (Statista Inc 2024b; International Renewable Energy Agency 2024).

In order to ensure sustainable growth, it is imperative to evaluate energy use throughout the diverse Asian atmosphere. The entire monetary worth of finished goods and services produced inside a nation's boundaries in a given year is measured by the GDP. Although GDP has increased as a result of Asia's rapid EG, especially in countries like India, CE has significantly increased contributing to global climate change (Khan et al. 2022). To decouple the EG from environmental degradation, understanding the dynamics in increased CE through rapid EG is crucial to make relevant policies (International Monetary Fund 2024; World Bank Group and ClimateWorks Foundation 2024). TO, as determined by indicators such as import and export ratios to GDP, describes how much a nation trades internationally. TO and CE have a complicated and multifaceted relationship in the Asian territory. While some studies point to the possibility of negative effects from air pollutants and increased EC from export-oriented industries, others highlight how factors like technology transfer and cleaner production processes can result in lower CE when trade is more open (Wang et al. 2023). As per the aforementioned, conducting a study based on the considered variables are important to understand and to analyse the increase and decrease of CE in different Asian countries. Therefore, this research study will support to fill that research gap between impact of GDP, EC, and TO on CE for the whole Asian continent which is a necessity to reach the carbon neutrality goal by 2050.

Conclusion

The Asian region, representing over 50% of global emissions and housing more than 60% of the global population, serves as a focal point in this study, aiming to comprehensively investigate the simultaneous impact of GDP, EC, and TO on CE. This research significantly contributes to the existing body of knowledge by delving into the collective and individual effects of these variables on CE in the Asian region, a facet that has been relatively underexplored in previous studies.

Furthermore, the findings underscore a noteworthy positive significance of the Asian region concerning EC based on the results of MLR. The MLR outcomes highlight a prevalent positive significance towards GDP across most countries in the region. This inclination can be attributed to the prevalence of developing countries in Asia, actively pursuing rapid economic growth through industrialisation. Consequently, this economic expansion requires a rise in EC, resulting in a notable positive impact on EC.

It is essential to note that six countries were excluded from the single-country analysis due to data limitations, and the study excluded the period from 2020 to 2022 due to data unavailability during the study period. The reliance on database information alone, coupled with the lack of easily accessible data sources for related variables impacting CE, introduces limitations that future researchers should address and build upon.

This research not only contributes to deciphering the policies required to achieve the UN's goal of carbon neutrality by 2050 but also serves as a foundational analysis that opens avenues for future researchers to explore various dimensions of the impact of GDP, EC, and TO on CE, thereby advancing our understanding of these complex relationships.

Policy implications

Based on the findings of this study, it elucidates the impact of GDP, EC, and TO on CE within each examined Asian country. A significant revelation is that EC exerts a substantial influence, contributing notably to the increase in CE across the Asian region compared to other variables. Consequently, tailored regulations and laws could be implemented in each Asian country, considering their unique income levels, available resources, and technological capabilities.

Given the pronounced impact of EC on escalating CE, it is imperative to prioritise the development of renewable energy sources in each country, aiming to reduce dependence on fossil fuels. Governments are urged to actively support the growth and implementation of renewable energy technologies, encompassing solar, wind, and hydropower. In instances where the requisite technology may be lacking or adaptation is constrained by limited income, seeking support from developed countries becomes a strategic investment to curtail CE levels.

Additionally, governments should institute carbon pricing mechanisms, such as carbon taxes or cap-and-trade programs, particularly in high carbon-emitting countries like China, India, and Japan, as a means to incentivise companies and individuals to mitigate CE. International cooperation, especially through agreements like the Paris Agreement and support through Nationally Determined Contributions (NDCs), should be underscored for a collective and coordinated effort to address CE on a global scale.

Governments are encouraged to promote environmentally friendly modes of transportation, such as public transportation, biking, and walking, to significantly reduce reliance on fossil fuels and minimise CE. These eco-friendly transportation measures can be tailored to suit the context of each Asian country, considering the availability of public transportation services.

Investing in low-carbon technology is deemed essential for CE reduction. Governments are recommended to allocate funds for research and development initiatives focused on low-carbon technologies, including advancements in carbon capture and storage. This strategic investment can play a pivotal role in achieving substantial reductions in CE over time.

Limitations and opportunities for future research

There are several avenues for future research expansion regarding the interplay between EC, GDP, TO, and CE in the Asian region. One avenue is to introduce additional variables, such as population density, industrialisation level, and the rate of urbanisation, as these factors may significantly influence CE. Expanding the study to include more countries based on data availability is another avenue for enhancing the current research scope.

Furthermore, evaluating the effectiveness of existing CE reduction measures could be beneficial. Future research could explore the impacts of emission trading schemes, carbon levies, and renewable energy policies in the context of increasing GDP, TO, and EC. Understanding how these measures contribute to or hinder carbon emission reduction efforts in the Asian region would be valuable.

Finally, investigating the role of technological advancements in reducing CE could be crucial. This involves exploring how advancements in energy efficiency and renewable energy technology contribute to lowering CE in Asia. A

comprehensive understanding of these aspects can guide the development of effective strategies for the region's CE reduction.

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Author contribution All authors contributed to the conception and design of the project. RJ, ND, NR, and TD composed the writing of the manuscript. SE and VG carried out a significant share of tasks on statistical work in the manuscript. RJ, DM, and CW provided critical knowledge in drafting the paper and supervised the entire study. The authors have read and approved the final manuscript.

Data availability All data generated or analysed during this study are included in this published article and its supplementary information files.

Declarations

Ethics approval This study was approved by the Ethics Review Committee of Sri Lanka Institute of Information Technology, Sri Lanka (PVC/RI/EC/2023/05).

Consent to participate Not applicable.

Consent for publication Not applicable.

Conflict of interest The authors declare no competing interests.

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