



OPEN Enhancing environmental quality and economic growth through potential effects of energy efficiency and renewable energy in Asian economies

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This study examines the potential impacts of energy efficiency and renewable energy on economic growth proxies by gross domestic product and environmental quality proxies by carbon dioxide emissions across eight selected Asian countries from 2000 to 2020. This study contributes by calculating green total factor productivity and carbon total factor productivity based on the famous Solow's residual via employing a modified extensive growth accounting model that internalized ignored factors such as energy efficiency and renewable energy. The employed panel cointegration techniques confirm that all variables are co-integrated with carbon dioxide emissions and economic growth. The pooled mean group/autoregressive distributed lag model analysis results indicate that energy efficiency is positively associated with both environmental quality and economic growth. Renewable energy hurts economic growth but has a positive effect on environmental quality which suggests the necessity of implementing an effective strategy for renewable energy alongside energy efficiency measures to enhance economic growth and environmental quality in the selected Asian countries. The findings from the fully modified ordinary least squares estimator are consistent with the environmental quality model. The average growth rate of green total factor productivity is positive despite negative contributions from energy efficiency and renewable energy. Similarly, the average growth rate of carbon total factor productivity is negative despite positive contributions from labor and capital. This discrepancy may be attributed to the beneficial effects of labor and capital as input productivity-driven. Embracing renewable energy sources can take significant steps toward improving environmental quality for future generations. Focusing on green technologies that enhance energy efficiency can substantially promote environmental quality and stimulate sustainable economic growth through innovation and climate change integration to achieve Sustainable Development Goals.

Keywords Energy efficiency, Renewable energy, Green total factor productivity, Carbon total factor productivity, Environmental quality, Asian economies

Environmental issues like climate change, air pollution, and resource depletion can be addressed by energy efficiency improvements combined with a greater reliance on renewable energy sources. The advancement of these initiatives to create a cleaner, healthier, and more sustainable environment for future generations involves the cooperation of governments, businesses, and individuals. The improvement of environmental quality has challenged the entire world's countries and the industrialized countries in particular. The industrial expansion that has been experienced in the former century, such as the unaccountable behavior of human beings relates to the rise in carbon dioxide (CO₂) emissions which escalated remarkably across the globe and become the reason for environmental degradation¹. The fast-growing economies have relied on extensive energy use from different resources in the industrial process. However, a considerable part of energy comes from unclear resources, which release more carbon emissions. Because of the fast industrial uprising and growth in various economies, fossil fuel demand has increased worldwide².

The advancement of the economy hastens industrialization, which in turn increases the value of extracted natural resources, the atmosphere can be impacted by the extensive utilization of these resources, along with

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total reserves, financial progress, and the adoption of renewable energy (RE)³. To maximize the potential for renewable energy in BRICS nations, it is recommended that the industrial sector take the lead in responding to enhancing economic complexity and increasing investments in sources of renewable and clean energy⁴. CO₂ emissions are the main contributors that worsening air quality and global warming. Additionally, clean energy leads to reduced air pollution which would be a path to avoid environmental pollution¹. About 75% of the greenhouse gases (GHGs) released into the atmosphere worldwide are from carbon dioxide emissions³.

Energy efficiency (EE) potentially increases economic growth and reduces greenhouse gas emissions, nevertheless, it is currently advancing at a slower rate than it once did, which has significant negative effects on businesses, consumers, and the environment⁵. “Green growth” has gained rapid attention recently because environmental degradation is often the result of the global pursuit of economic prosperity⁶. The efficiency of energy and green energy are foreseen as key factors in climate change strategy that can be used to relieve the issue of climate change⁷. The service sector with EE and service sector and RE sources act as alternative drivers that mitigate greenhouse gas emissions with a decreasing substitution marginal rate⁸. RE and EE are regarded as two essential strategies for managing greenhouse gas emissions⁹. An established long-run growth development objectives for reducing CO₂ emissions and improving energy efficiency. By supplying affordable, long-term energy, sustainable development seeks to quadruple the global rate of increased energy efficiency by 2030¹⁰. One important strategic goal that can promote economic growth is to concentrate on technology that can improve energy efficiency¹¹. Energy efficiency, using energy prudently and avoiding waste, and generating the most output per unit used, are essential for economic growth¹². Zeraibi¹³ suggests that the chosen Southeast Asian nations will have to address environmental challenges in future years by improving their ability to generate electricity from renewable sources, investing more in technology development, greening the financial sector, and implementing environmentally friendly growth strategies. An essential consideration while talking about environmental issues is the role of both renewable and non-renewable energy sources. Renewable sources of energy, such as hydroelectricity, wind, and solar power, are becoming progressively more common. Since renewable energy sources do not contribute to climate change by releasing carbon dioxide throughout the atmosphere, they are more economical and environmentally beneficial compared to non-renewable ones including gas and oil¹⁴.

According to the International Energy Agency¹⁵, in comparison to the essential prediction, the rapid growth scenario demonstrates that if nations handle policy, regulation, allowing, and financing obstacles, worldwide renewable capacity could increase by an additional 25%. Implementation is difficult in most developed economies, particularly when it comes to expanding grid infrastructure and obtaining permits. Uncertainties in policy and regulations continue to be significant obstacles to a quicker expansion of renewable energy in emerging economies. Finally, in developing nations, inadequate grid infrastructure and a dearth of reasonably priced funding prevent projects from being completed on schedule.

Developing nations are eagerly using resources to achieve industrialization and economic growth without considering the negative impacts of their consumption. As they try to accelerate growth, developing nations rely heavily on non-renewable fossil fuels, which deplete limited resources and produce harmful gases like carbon dioxide, nitrous oxide, and methane¹⁶. Over the past 20 years, Southeast Asia's energy demand has grown by about 3% annually. Although the countries in the region are at different stages of development, most of their economies since 2000 have doubled. The COVID-19 pandemic temporarily impacted these trends, but economic growth is expected to recover, with the region's economy projected to grow by an average of 5% annually until 2030, before slowing down to an average of 3% between 2030 and 2050. Fossil fuels are used to meet Three-quarters of the Stated Policies Scenario (STEPS) projected increasing energy demand by 2030, which results in an almost 35% increase in CO₂ emissions. Southeast Asia's ability to access energy has increased recently. Approximately 95% of households have access to electricity today, and 70% have improved cookstoves and liquefied petroleum gas as clean cooking options¹⁷.

According to British Petroleum¹⁸, China, South Korea, and Malaysia have the highest annual renewable energy consumption growth rate in 2021 with values of 33.1%, 29.6%, and 22.8%, respectively. Furthermore, in India, Indonesia, and Japan the annual renewable energy consumption growth rates were 13.2%, 11.2%, and 9.9%, respectively. However, the Philippines demonstrated a negative annual renewable energy consumption growth rate of -4.0%. On the other hand, the annual primary energy consumption growth rate in 2021 was high for India with a value of 10.4%, the Philippines has shared the same growth rate with China with a value of 7.1%. Asian countries need to fast-track the transition path to efficiency of energy measures and renewable energy to address the environmental challenges accompanying economic development. It is anticipated that the efficiency of energy and green energy will be crucial policy measures for climate change that might mitigate the issue of climate change⁷. South Asian economies have been investing heavily in technological innovations to address environmental issues. Considerable effort has been made to boost renewable energy sources, develop waste management practices, and reduce GHG emission reduction¹⁹.

Several studies have explored the effects of energy efficiency, renewable energy, economic growth, and nuclear energy on environmental quality (CO₂ emissions)^{20,21}. Additionally, other research has delved into the relationship between energy efficiency, RE, and CO₂ emissions, considering factors like economic growth, fossil fuels, trade openness, and property rights^{1,22}. Conversely, limited attention has been given to the potential impacts of EE and RE on economic growth see Refs.^{11,12}. Some studies have specifically examined the connection between RE and economic growth^{23–26}. The Kapital, Labor, Energy, Materials, and Services (KLEMS) approach develops output, input, and productivity datasets at the industrial level. The definition of productivity is output divided by per unit whole inputs. The two nations' productivity gaps are defined by the variations in their respective productivity levels. To quantify these variations, purchasing parities for inputs and outputs are used to relate each nation's productivity levels²⁷. This study aims to investigate the potential effects of EE and RE on environmental quality and economic growth simultaneously as different from previous empirical implementations, such as Ahmed & Elfaki²⁸, and fill the gap in the existing literature. Additionally, it calculates the contributions of energy efficiency

and renewable energy toward environmental quality (CO₂ emissions) and economic growth to elucidate how these factors can promote environmental quality and stimulate growth. Therefore, this study contributes to two aspects. Firstly, it concentrates on investigating the potential effects of EE and RE on environmental quality and economic growth simultaneously in eight selected Asian countries, utilizing fresh data spanning from 2000 to 2020, to unveil the potential of energy efficiency and RE adoption as crucial elements in mitigating CO₂ emissions and enhancing environmental quality while promoting sustained economic growth. Secondly, unlike (KLEMS) approach, this study used the growth accounting theory “Solow residual” as the base to build models for carbon total factor productivity (CTFP) and green growth total factor productivity (GTFP) by modifying Kaya & Yokobori’s²⁹ carbon productivity and Ahmed & Abdul Rahim’s³⁰ Total Pollutant Emissions (TPE) concepts to calculate carbon total factor productivity, and Ahmed’s³¹ model to calculate green growth total factor productivity. Kaya & Yokobori²⁹ proposed the concept of carbon productivity, which measures the economic advantage per unit of carbon emissions to evaluate countries’ efforts in combating climate change while maintaining economic growth. At higher-intensity carbon emissions economic growth is unsustainable, while low-carbon activity is useless in the absence of economic growth. Thus, as a result, the foundation of low-carbon economic research is the idea of advantageous economic growth³². Carbon productivity is considered the main idea in the low-carbon development assessment model³³. GTFP is the term used when referring to the Solow residual and is a measure of productivity growth brought about by technological innovation. To achieve the objectives of this study, the first step is to estimate the long-term coefficients explanatory variables regarding economic growth and environmental quality models using the Pooled Mean Group/Autoregressive Distributed Lag Model (PMG/ARDL). The second step is calculating carbon factor productivity and green total factor productivity by substituting the estimated parameters into the growth accounting equation (Solow residual).

The remaining sections of the current study are as follows. Section “Literature review” shows the literature review. Data description, model specification, and empirical techniques are provided in Sect. “Model specification and estimation procedures”. Section “Results and discussion” discusses the findings results and interpretation. Part 5 accomplishes the study and provides policy recommendations for policymakers.

Literature review

Many studies have contributed to the literature that examines the influence of energy efficiency and renewable energy on economic growth or environmental quality in individual cases. However, limited attention has been given to the potential impacts of energy efficiency and renewable energy on economic growth and environmental quality simultaneously. This research aims to examine the potential impacts of energy efficiency and renewable energy on economic growth proxies by gross domestic product and environmental quality proxies by carbon dioxide emissions across eight selected Asian countries.

Combining energy efficiency measures with growing the usage of renewable energy aids in tackling environmental issues like climate change, air pollution, and resource depletion. There is a significant role that can be played by the efficiency of energy measures and energy from renewable sources in declining CO₂ emissions improving environmental quality and boosting economic growth. Very few studies were conducted to discover the potential role of efficiency of energy, RE, nuclear energy, and economic growth (GDP) on CO₂ emissions^{20,21}. Other studies considered the role of efficiency of energy, renewable energy, and economic growth^{1,22}. On the other side, limited studies have considered the possible influences of energy efficiency and renewable energy on economic growth (for example Refs.^{11,12}). Some studies investigated the connection between renewable energy and economic growth^{23–26}. Using data from MINT countries spanning 1990 to 2014, Akram et al.²⁰ assessed the role of economic growth, EE, RE, and nuclear energy on CO₂ emissions. The empirical results from the nonlinear panel ARDL elucidate that EE and RE effectively contribute to reducing CO₂ emissions. Economic growth has been found to lead to rising CO₂ emissions in the MINT nations. Nuclear energy has an insignificant influence on CO₂ emissions. Ponce & Khan¹ employed fully modified ordinary least squares (FMOLS) in developed countries and ascertained that the efficiency of energy and RE are negatively interrelated to CO₂. However, GDP shows a positive connection with CO₂ emissions. The efficiency of energy lowers the energy intensity of the manufacturing process and lowers CO₂ emissions¹. Akram et al.²¹ employed nonlinear panel ARDL on data spanning from 1990 to 2014 from BRICS countries to discover the asymmetric influence of RE and EE on CO₂ emissions. The outcomes reveal that EE shows a significant influence in mitigating CO₂ emissions. Additionally, RE displays a negative correlation with CO₂ emissions. On the other side, GDP contributes to intensifying CO₂ emissions in BRICS countries.

Irfan et al.²² employed panel data related to countries from South Asia for the years 1990 to 2014 to study the effects of RE and EE on CO₂ emissions by utilizing the pooled mean group method. The outcomes disclose that the coefficient of EE holds a significant positive effect on CO₂ emissions. The calculated coefficient of renewable energy elucidates a statistically significant negative connection with CO₂ emissions. Moreover, economic growth illustrates an insignificant impact on CO₂ emissions. Usman et al.³⁴ investigated the factors that influence both economic growth and ecological footprint in 15 countries that emit the most from 1990 to 2017. The findings from the augmented mean group reveal that renewable energy, amongst other factors, greatly helps mitigate environmental degradation. Reversely, non-renewable energy deteriorates environmental degradation. For the growth model, both renewable energy and nonrenewable are strongly support economic growth.

Regarding studies focused on the influences of energy efficiency and renewable energy on economic growth. Bayar & Gavriltea¹¹ found that in the long run, energy efficiency has a favorable impact on economic growth, whereas renewable energy has no significant influence on economic growth in emerging economies. Kadir et al.¹² discovered that labor, capital, carbon emissions, renewable energy, and energy efficiency are positively linked with the growth of GDP in emergency seven economies. Marinaş et al.²³ highlight that an increase in renewable energy consumption leads to increases in GDP in the CEE countries. A study by Xie et al.²⁶ on Next-11 economies validates the hypothesis of renewable energy-led growth.

Many other studies have considered the consequences of EE and RE on CO₂ emissions together and individually. Tariq et al.⁷ found the efficiency of energy is inversely associated with GHG in South Asia. They mentioned that energy efficiency among other factors is a decisive component of the implementation of climate change legislation. Bargaoui³⁵ found energy efficiency promotes environmental Quality in the Middle Eastern and North African countries. However, renewable energy exhibits an insignificant statistical consequence on environmental quality. A study by Gyimah et al.³⁶ displays that RE leads to a surge in carbon emissions in Ghana. GDP has a statistically insignificant impact on CO₂ emissions. Saqib & Usman⁶ applied the quantile autoregressive distributed lag (ARDL) method data from China and the United States and found that renewable energy contributes to lowering CO₂ emissions in the United States and China. By employing panel ordinary least squares (POLS) along with panel quantile regression methods in BRICS countries, Cheng et al.³⁷ point out that RE has played a role in reducing per capita CO₂ emissions. On the other side, GDP per capita contributes to escalating CO₂ emissions per capita. Usman & Makhdom³⁸ discovered that with other variables renewable energy contributes to the decline of the ecological footprint in BRICS-T, while non-renewable energy surges the ecological footprint. Using global panel data, Liobikienė & Butkus⁸ findings elucidate that EE and RE are negatively linked to GHG Emissions. By employing fixed-effect panel quantile regression (PQR) and panel ordinary least squares in data from 1990 to 2014 in 66 developing countries, Akram et al.³⁹ incorporated EE and RE in the EKC hypothesis and found that energy efficiency mitigates CO₂. RE also supports declining CO₂ emissions. Reversely, GDP leads to escalating CO₂ emissions. Likewise, under the EKC framework, Dong et al.⁴⁰ found that RE among other factors is the essential factor contributing to CO₂ emissions alleviation in China using data from 1993 to 2016. Table 1 provides a brief of the relevant literature on the relationship between the independent variables and both CO₂ emissions and economic growth.

In conclusion of this part, most of the previous studies concerning environmental quality side conducted in MINT countries²⁰, nine developed countries¹, BRICS countries²¹, South Asian countries²², and MENA Countries³⁵. Studies concerning economic growth implemented in CEE countries²³, Next-11 economies²⁶, emerging economies¹¹, and in emergency seven economies¹². Accordingly, this study contributes by concentrating on studying the potential effect of EE and RE on both GDP growth and environmental quality in 8 selected Asian countries using new data covering the period 2000 to 2020. Furthermore, the most significant contribution is by calculating carbon total factor productivity and green growth total factor productivity using the growth accounting theory “Solow residual” on modified versions of Kaya & Yokobori’s²⁹ concept and Ahmed’s³¹ framework. This study included energy efficiency and renewable energy that were overlooked by Ahmed & Elfaki’s²⁸ empirical implementation. Additionally, the contributions of environmental quality (CO₂

Author	Methodology	Estimation results
Akram et al. ²¹	Nonlinear panel ARDL	EE shows a significant influence in mitigating CO ₂ emissions. RE displays a negative correlation with CO ₂ emissions. GDP contributes to intensifying CO ₂ emissions in BRICS countries.
Akram et al. ³⁹	Fixed-effect panel quantile regression (PQR) and panel ordinary least squares	Energy efficiency mitigates CO ₂ emissions. RE supports declining CO ₂ emissions. GDP leads to escalating CO ₂ emissions.
Akram et al. ²⁰	Nonlinear panel ARDL	EE and RE effectively contribute to reducing CO ₂ emissions. Economic growth leads to a rise in CO ₂ emissions. Nuclear energy insignificantly influences CO ₂ emissions.
Ponce & Khan ¹	FMOLS	EE and RE are negatively interconnected to CO ₂ emissions. GDP shows a positive connection with CO ₂ .
Irfan et al. ²²	PMG	EE holds a significant positive effect on CO ₂ emissions. Renewable energy elucidates a statistically significant negative connection with CO ₂ emissions and economic growth illustrating an insignificant impact on CO ₂ emissions.
Cheng et al. ³⁷	POLS and panel quantile regression methods	RE played a role in reducing per capita CO ₂ emissions.
Bargaoui ³⁵	Generalized method of moments (GMM)	EE promotes environmental Quality renewable energy displays an insignificant statistical consequence on environmental quality.
Saqib & Usman ⁶	Quantile ARDL	Renewable energy contributes to lowering CO ₂ emissions
Gyimah et al. ³⁶	Two-stage least squares	RE leads to a surge in carbon emissions. GDP has a statistically insignificant impact on CO ₂ emissions.
Usman et al. ³⁴	Augmented mean group (AMG)	Renewable energy helps mitigate environmental degradation. Non-renewable energy deteriorates environmental degradation. Renewable energy and nonrenewable are strongly support economic growth.
Bayar & Gavrilletea ¹¹	AMG	Energy efficiency has a favorable impact on economic growth. Renewable energy has no significant influence on economic growth.
Kadir et al. ¹²	Quantile ARDL	Labor, capital, carbon emissions, renewable energy, and energy efficiency are positively linked with the growth of GDP.
Marinaş et al. ²³	PMG	An increase in renewable energy consumption leads to increases in GDP.
Tariq et al. ⁷	FMOLS and panel dynamic ordinary least square (DOLS)	Efficiency of energy is inversely associated with greenhouse gas (GHG).
Xie et al. ²⁶	Method of moments quantile regression	Renewable energy boosts growth

Table 1. Summary of relevant literature on the relationship between independent variables and both CO₂ emissions and economic growth.

emissions), economic growth, energy efficiency, and renewable energy were calculated to explain the dynamics of how energy efficiency and renewable energy could promote environmental quality and boost growth. This study applies PMG/ARDL to test the influence of EE and RE on GDP growth and environmental quality in the short run and long run. Next to the above-reviewed literature and contribution development, the following points serve as the groundwork for the establishment of the hypotheses in this study as follows.

H₁ Energy efficiency and renewable energy enhance environmental quality (lower CO₂ emissions).

H₂ Energy efficiency and renewable energy boost growth.

Model specification and estimation procedures

The focal intention of this study is to inspect the influence of energy efficiency and renewable energy on both the growth of GDP on environmental quality and to develop a framework and model to calculate carbon total factor productivity and green growth total factor productivity by integrating energy efficiency and renewable energy implications on both the growth of GDP and environmental quality and internalizing energy efficiency and renewable energy in Cobb–Douglas function as essential exogenous input. It is worth noting that energy efficiency and renewable energy are essential channels that promote environmental quality and enhance economic growth. The seminal work of Solow⁴¹ introduced exogenous technological progress and became a foundation for the total factor productivity concept. Thus, Unlike the previous works by Ahmed & Elfaki²⁸ and Ahmed⁴², this study integrated energy efficiency and renewable energy to calculate GTFP or green technological progress. The capital, labor, energy, materials, and services (KLEMS) approach's goal is to develop output, input, and productivity datasets at the industrial level. The definition of productivity is output divided by per unit whole inputs. The two nations' productivity gaps are defined by the variations in their respective productivity levels. To quantify these variations, purchasing parities for inputs and outputs are used to link each nation's productivity levels²⁷. This study differs from previous empirical implementations, such as that of Ahmed & Elfaki²⁸, by including energy efficiency, renewable energy, and CO₂ emissions. Unlike the KLEMS approach, this study used the growth accounting theory "Solow residual" as the base to build models for carbon total factor productivity and green growth total factor productivity by modifying Kaya & Yokobori's²⁹ and Ahmed & Abdul Rahim's³⁰ TPE concepts to calculate carbon total factor productivity, and Ahmed³¹ model to calculate green growth total factor productivity. Therefore, this study fills the gap in these studies by integrating energy efficiency and renewable energy jointly in the Cobb–Douglas function. Following the models used by Bayar & Gavriltea¹¹ and Kadir et al.¹², the general form of growth of GDP is presented below:

$$GDP_t = F(L_{ti}, K_{ti}, CO_{2ti}, EE_{ti}, RE_{ti}, \mu_{ti}), \quad (1)$$

For analysis purposes, Eq. (1) was transformed into natural logarithm form as in Eq. (2). The data was converted to their natural logarithm to avoid the possibility of the presence of heteroscedasticity⁴³.

$$\ln GDP_{ti} = \beta_0 + \beta_1 \ln L_{ti} + \beta_2 \ln K_{ti} + \beta_3 \ln CO_{2ti} + \beta_4 \ln EE_{ti} + \beta_5 \ln RE_{ti} + \mu_{ti}, \quad (2)$$

where \ln represents natural logarithm, i describes units of cross-sectional, t refers to time, GDP denotes economic growth; L signifies labor; K represents physical capital; CO₂ denotes carbon emissions (environmental quality), EE denotes energy efficiency, RE denotes renewable energy, and μ_{ti} stands for the standard error term or residual (The residual term used as a proxy for the growth of total factor productivity, which considered as an economy technological progress through input quality terms) in this study is used as a proxy for GTFP.

To calculate GTFP and contributions of productivity growth indicators, the constant has not been used anymore³¹. Therefore, the following stage is to compute the growth rates of productivity indicators by changing Eq. (2) into the basic growth accounting extended model as follows:

$$\Delta \ln GTFP_{ti} = \Delta \ln GDP_{ti} - [\beta_1 \cdot \Delta \ln L_{ti} + \beta_2 \cdot \Delta \ln K_{ti} + \beta_3 \cdot \Delta \ln CO_{2ti} + \beta_4 \cdot \Delta \ln EE_{ti} + \beta_5 \cdot \Delta \ln RE_{ti}], \quad (3)$$

where the shares of the average value provided by the weight; as $\Delta \ln GTFP_{ti}$ total factor productivity. $\Delta \ln GDP_{ti}$ denotes the total GDP output per capita; $\beta_1 \cdot \Delta \ln L_{ti}$ is the total labor contribution; $\beta_2 \cdot \Delta \ln K_{ti}$ is the aggregate physical capital contribution; $\beta_3 \cdot \Delta \ln CO_{2ti}$ is the contribution of aggregate CO₂; $\beta_4 \cdot \Delta \ln EE_{ti}$ is the total contribution of energy efficiency. $\beta_5 \cdot \Delta \ln RE_{ti}$ is the contribution of aggregate renewable energy.

Regarding environmental quality, this study extended the models used by Ponce & Khan¹ and Akram et al.²⁰ to scrutinize the influence of energy efficiency and renewable energy on environmental quality as presented below:

$$CO_{2ti} = F(L_{ti}, K_{ti}, GDP_{ti}, EE_{ti}, RE_{ti}, \mu_{ti}) \quad (4)$$

For examination purposes Eq. (4) transformed into natural logarithm form as follows:

$$\ln CO_{2ti} = \alpha_0 + \alpha_1 \ln L_{ti} + \alpha_2 \ln K_{ti} + \alpha_3 \ln GDP_{ti} + \alpha_4 \ln EE_{ti} + \alpha_5 \ln RE_{ti} + \mu_{ti} \quad (5)$$

The error term or residual in Eq. (5) is used as a proxy for CTFP following Kaya & Yokobori's²⁹ concept and Ahmed's³¹ framework. In this respect, Ahmed & Abdul Rahim³⁰ introduced the concept of TPE as a counterpart of TFP that expresses the degree of environmental degradation calculated based on pollutant emissions qualities. Meanwhile, the TFP is a combined contribution of the quality of inputs as an indicator of technological progress.

To calculate CTFP and the contributions of each indicator, Eq. (5) was reformulated into the basic growth accounting extended model as in Eq. (6).

$$\Delta \ln CTFP_{ti} = \Delta \ln CO_{2ti} - [\alpha_1 \Delta \ln L_{ti} + \alpha_2 \Delta \ln K_{ti} + \alpha_3 \Delta \ln GDP_{ti} + \alpha_4 \Delta \ln EE_{ti} + \alpha_5 \Delta \ln RE_{ti}], \quad (6)$$

where $\Delta \ln CTFP_{ti}$ is the combined contribution of the total pollutants' emissions as a residual counterpart to GTFP as an indicator of green technological progress. $\Delta \ln CO_{2ti}$ denotes the aggregate CO₂ emissions; $\alpha_1 \Delta \ln L_{ti}$ is the total labor contribution; $\alpha_2 \Delta \ln K_{ti}$ is the aggregate physical capital contribution; $\alpha_3 \Delta \ln GDP_{ti}$ signifies the aggregate GDP contribution; $\alpha_4 \Delta \ln EE_{ti}$ is the total contribution of energy efficiency; $\alpha_5 \Delta \ln RE_{ti}$ is the contribution of aggregate renewable energy.

This study used a varied quantitative analysis, building on the previous work of Ahmed⁴² to examine the effects of renewable energy and energy efficiency on long-term green growth progress and environmental quality, as well as to compute GTFP and carbon factor productivity. Growth accounting and the parametric econometric technique are combined in the methods used to develop the enhanced extensive growth theory. This process has been developed into two stages: first, the models for environmental quality and economic growth are estimated using an econometric technique, and the productivity indicators are calculated for both models in the second step as indicated in Ahmed⁴². Though this study contributes by calculating CTFP and GTFP as counterpart residuals using a modified extensive growth accounting model that internalized ignored factors such as energy efficiency and renewable energy.

Definition of variables and data sources

Enhancement of efficiency of energy and generating energy from different renewable sources will contribute to improving environmental quality and boost economic growth. Referring to studies by Refs.^{1,20–22,35} concerning the environmental quality side and studies by Refs.^{11,12,23,26} regarding the economic growth side, this study contributes by concentration to analyze the potential effect of EE and RE on both GDP growth and environmental quality in 8 selected Asian economies (Malaysia, Philippines, Indonesia, Thailand, South Korea, China, India, and Japan) using balanced panel data spanning from 2000 to 2020 based availability of data. Labor factor captured by the labor force. Gross fixed capital formation is used to capture physical capital. Consumption of RE is measured as the percentage of aggregate final energy consumption. Primary energy consumption (primary energy comprised of commercially traded fuels) is used as a gauge of EE. GDP per capita at 2015 US dollar constant divided by population used as a gauge for economic growth. Per capita metric tons of carbon dioxide emissions are used to measure environmental quality (CO₂ emissions). All variables dataset collected from the World Bank⁴⁴. However, primary energy consumption data was collected from British Petroleum⁴⁵. Time and countries have been chosen with the availability of data on EE and RE. More details about data and sources are available in Table A1 of the appendix.

Preliminary cointegration analysis tests

To scrutinize the impact of EE and RE on GDP growth and environmental quality, this study conducted the cross-sectional dependence (CS) test to specify the suitable unit root tests. If all variables exhibit CS, the unit root first-generation tests could yield inaccurate outcomes⁴⁶. Therefore, this study conducted the second-generation panel unit root test of cross-sectional augmented IPS (CIPS) and Cross-sectional (CADF) by Pesaran⁴⁷ to determine the stationarity of the variables. Furthermore, to avoid spurious regression analysis, cointegration panel tests by Kao⁴⁸, Pedroni⁴⁹, and new simple Westerlund⁵⁰ are utilized.

Estimation techniques

To analyze the long-run elasticities of EE and RE on GDP growth and environmental quality, this study employed the PMG/ARDL. The PMG estimator makes it possible to estimate this common long-run coefficient by avoiding the less reasonable assumption that the dynamics in every nation are the same⁵¹. Additionally, the FMOLS estimator is used to test the robustness of estimated long-run elasticities. Furthermore, the panel causality test by Dumitrescu Hurlin is used to investigate the causality direction among energy efficiency, RE, GDP, and environmental quality. Due to its superior handling of panel data with cross-sectional dependency and heterogeneity²⁰, Dumitrescu-Hurlin (DH) panel causality is used.

Results and discussion

This study utilized some descriptive statistics and correlation as shown in Table 2. The means of labor, economic growth, capital, and renewable energy values were more volatile than the others with values of 18.16444, 8.679974, 3.304960, and 2.456362, respectively.

The Jarque–Bera test reveals that GDP, L, CO₂, EE, and RE are normally distributed as indicated by Probability. Moreover, the test of skewness displays that environmental quality has a negative skewness value of -0.243409 well as renewable energy with a value of -0.713450. In contrast, L, EE, K, and GDP show a positive skewness value of 0.50471, 0.349823, 0.31306, and 0.243029, respectively.

As shown in the lower part of Table 2, the environmental quality indicator shows a highly positive correlation with economic growth, indicating that as long as a country's economic growth increases environmental quality deteriorates by CO₂ emissions rise. Additionally, capital displays a high positive correlation with EE, meaning that the inflow of capital enhances energy efficiency. RE shows a negative correlation with GDP meaning that a country's renewable energy consumption displayed an insignificant role in boosting GDP growth. On the other side, RE shows a high negative correlation with CO₂ emissions meaning that a country's renewable energy consumption plays a significant role in reducing CO₂ emissions.

	GDP	L	K	CO ₂	EE	RE
Mean	8.679974	18.16444	3.304960	1.274203	2.218576	2.456362
Median	8.539033	17.81103	3.271616	1.330031	2.108701	3.002707
Maximum	10.49511	20.47571	3.795911	2.502784	4.994374	3.852485
Minimum	6.627356	16.05111	2.900406	− 0.237696	0.059646	− 0.371064
Std. dev.	1.099546	1.332676	0.221275	0.892148	1.267277	1.185762
Skewness	0.243029	0.504719	0.313067	− 0.243409	0.349823	− 0.713450
Kurtosis	1.981290	2.047696	2.591123	1.581231	2.534210	2.291643
Jarque-Bera	8.918156	13.48093	3.914575	15.74929	4.945244	17.76471
Probability	0.011573	0.001182	0.141241	0.000380	0.084363	0.000139
	LGDP	LL	LK	LCO ₂	LEE	LRE
GDP	1					
L	− 0.423743	1				
K	0.050337	0.683283	1			
CO ₂	0.911273	− 0.275781	0.280441	1		
EE	0.19905	0.76794	0.829484	0.395728	1	
RE	− 0.833556	0.531957	− 0.069548	− 0.860679	− 0.082159	1

Table 2. Descriptive statistics and correlation.

	GDP	L	K	CO ₂	EE	RE
Test	Statistic					
Breusch-Pagan LM	552.2138 ^a	346.6675 ^a	120.6481 ^a	324.5547 ^a	510.4822 ^a	260.4278 ^a
Pesaran scaled LM	70.05102 ^a	42.58374 ^a	12.38062 ^a	39.62879 ^a	64.47439 ^a	31.05948 ^a
Bias-corrected scaled LM	69.85102 ^a	42.38374 ^a	12.18062 ^a	39.42879 ^a	64.27439 ^a	30.85948 ^a
Pesaran CD	23.48271 ^a	15.66565 ^a	− 1.243612	13.11505 ^a	11.89488 ^a	− 2.672919 ^a

Table 3. Cross-section dependence test. ^aIndicate significance at a 1% level.

Variable	CADF		CIPS	
	Level	First difference	Level	First difference
GDP	− 1.665	− 1.343	− 1.888	− 2.406 ^b
L	− 1.729	− 2.141	− 1.291	− 3.029 ^a
K	− 1.774	− 2.362 ^b	− 1.629	3.316 ^a
CO ₂	− 1.974	− 2.311 ^b	− 1.742	− 3.122 ^a
EE	− 2.209 ^c	− 2.231 ^c	− 1.859	− 3.083 ^a
RE	− 1.747	− 2.214 ^c	− 1.477	3.058 ^a

Table 4. Panel unit root tests. ^{a, b, c}Indicate significance at 1%, 5%, and 10% level respectively.

Based on the no cross-section dependence null hypothesis, the present study employed cross-sectional dependence tests of bias-corrected scaled Pesaran⁵² CD and scaled LM, Baltagi et al.⁵³, and Breusch & Pagan⁵⁴ LM to examine whether the panel data exhibit a cross-sectional dependence which will support to select the applicable panel unit root tests. The results are presented in Table 3.

As revealed in Table 3, the statistical values for all variables are high indicating that the probability is less than 1% level. This result means the no cross-section dependence null hypothesis is rejected in all. These findings indicate that one country's shocks will influence the other countries in the dataset. In the presence of CS, the unit root panel tests second-generation (CIPS) and (CADF) are more appropriate to determine the stationarity of the variables. The CIPS and CADF outcomes are portrayed in Table 4.

Table 4 points out that at the level whole series is not stationary based on the result from CIPS and CADF tests excluding EE under the CADF test. Nevertheless, at the first difference, the findings of CADF made an evident that K, RE, EE, and environmental quality are stationary however GDP and L are not stationary. However, under the CIPS test, all series are stationary at the first difference. Establishing the stationarity of the GDP, L, K, RE,

EE, and CO₂ emissions allows step further testing of the cointegration relationships amid the variables for the two models. To do so, the panel cointegration tests by Pedroni, Kao, and Westerlund were executed to study the cointegration ties amongst L, K, CO₂, RE, EE, and GDP, and amid L, K, GDP, RE, EE, and CO₂. The findings are illustrated in Table 5.

The empirical outcomes from Pedroni, Kao, and Westerlund cointegration tests in Table 5 signalize that most of the statistics are significant, indicating the rejection of the null hypothesis which says no co-integration relationship exists, and accepting the alternative hypothesis, which confirms that L, K, CO₂, RE, and EE, are co-integrated with LGDP, as well as L, K, GDP, EE, and RE are co-integrated with CO₂.

After the establishment of cointegration relationships amid the variables, the PMG/ARDL method is employed to estimate long and short-term coefficients in this study as recorded in Table 6.

As seen from the outcomes in Table 6 in the growth model (GDP dependent variable), the coefficients of energy efficiency and capital are positive at a 1% significance level in connection with the growth of GDP. This indicates a 1% rise in EE and capital support the growth of GDP by 1.373355% and 0.102651% respectively based on PMG/ARDL outcomes. This result is compatible with Bayar & Gavriletea¹¹ and Kadir et al.¹² findings and supports the hypothesis validity suggesting that enhanced energy efficiency can help spur growth of GDP. One important strategic goal that can promote economic growth is to concentrate on technology that can improve energy efficiency¹¹. Energy efficiency, using energy prudently and avoiding waste, and generating the most output per unit used, are essential for economic growth¹². Renewable energy shows an unfavorable and significant influence on GDP growth and does not validate the hypothesis of this study. This outcome contradicts with Xie et al.²⁶ and. This implies that an effective renewable energy use strategy is needed to promote GDP growth as well as have a decisive influence on environmental quality by dwindling emitting greenhouse gases. The negative and statistically significant coefficient of CO₂, in the long term, reveals a rise in CO₂ emissions by 1% decline in GDP growth by 0.241546%. This result matches with Azam et al.⁵⁵ and shows that deterioration in the environmental quality by surging CO₂ emissions affected boosting economic growth in selected Asian countries. Reducing pollution will eventually promote sustainable economic growth and maturity and significantly increase societal welfare⁵⁵. The coefficient of labor displayed a negative relationship with GDP growth and showed that a 1% rise in labor will diminish GDP growth by 1.545345%. This result contradicts with Kadir et al.¹².

Regarding the environmental quality model (CO₂ emissions dependent variable), As realized from the outcomes in Table 6 the coefficient of EE is positive at a 1% significance level in connection with environmental quality (CO₂) and does not support the hypothesis indicating that energy efficiency enhanced environmental quality. This indicates a 1% rise in EE exacerbates environmental quality by 0.665720%. This result contradicts with^{1,7,20,21} and is compatible with Irfan et al.²². This result can be explained by the rebound effect Irfan et al.²². This effect implies that people may use more energy or consume more goods and services when energy-efficient technologies or practices result in lower energy costs. Renewable energy shows a favorable and significant influence on environmental quality and supports the hypothesis signifying that renewable energy enhances environmental quality by lowering CO₂ emissions. This proposes applying an effective renewable energy use strategy to promote environmental quality in chosen Asian countries will have a crucial impact on abating emitting greenhouse gases, mitigating global warming, and reducing climate change consequences. These results agree with Akram et al.^{20,21}. Additionally, this means a 1% increase in RE diminishes CO₂ emissions by -0.089661% based on PMG/ARDL outcomes in the long run. The positive and statistically significant coefficient of GDP, in the long term, reveals a rise in CO₂ emissions by 0.364006% if GDP upsurges by 1%. This shows a deterioration in the environmental quality in selected Asian countries. This result matches with Akram et al.^{21,39}. This finding supported the EKC hypothesis that in the early stage of modern economic growth, environmental degradation tends to get worse. The coefficient of labor showed a negative connection with CO₂ emissions. Physical capital was found insignificantly related to CO₂ emissions. In the short run, the ECT (-1) coefficients are negative but significant in environmental quality model (CO₂ dependent variable), manifesting that the change that takes place in the short run will be adjusted to the long run equilibrium by 0.206422% and 0.264695% annually in both GDP growth and environmental quality models respectively. Furthermore, in the short run, RE is positively correlated with GDP growth. Figure 1 shows the long-run main findings in graphical form that explain the relationships among the independent variables and both CO₂ emissions and economic growth.

Consequently, in this study, the FMOLS estimator is employed to analyze the consistency prediction and the robustness of PMG/ARDL estimates. The findings presented in Table 7 manifest the consistency of L, K, and EE with the outcomes of the PMG/ARDL in the long run in the GDP growth model and full consistency with the environmental quality model. Adjusted R-squared reveals that the variations in the GDP growth and environmental quality are explained by 0.995% and 0.998% of the independent variables in each model, respectively.

The empirical analysis of RE's contribution to the sustainability of the quality of the environment discovers that the consumption of renewable energy ameliorates the quality of the environment in the long run. Based on these outcomes propose that policymakers must focus on alternative energy sources instead of fossil fuels to guarantee sustainable environmental quality. RE consumption is crucial to transitioning to a more sustainable and environmentally friendly future. By embracing renewable energy sources, this can take significant steps toward improving environmental quality and preserving the planet for future generations.

To calculate CTFP and GTFP integrating energy efficiency and renewable energy implications on both the growth of GDP and environmental quality. The second phase involves using the basic growth accounting models' estimated coefficients to calculate the indicators of the factor productivity. In the next step, the estimated paramotors are substituted into the growth accounting Eqs. (3) and (6). The result is presented in Table 8.

Table 8 demonstrates that the average growth rate of GTFP is positive, regardless of the negative contributions from energy efficiency and renewable energy, this could potentially be explained by the beneficial effects from labor, capital, and CO₂ emissions as the average growth rate. The quick development and expansion of

Pedroni residual cointegration test				
$GDP_t = F(L_{t,i}, K_{t,i}, CO_{2t,i}, EE_{t,i}, RE_{t,i}, \mu_{t,i})$	$CO_{2t} = (L_{t,i}, K_{t,i}, GDP_{t,i}, EE_{t,i}, RE_{t,i})$			
	Statistic	Prob.	Statistic	Prob.
Alternative hypothesis: common AR coeffs. (within-dimension)				
Panel γ -statistic	10.25009 ^a	0.0000	0.019136	0.4924
Panel rho-statistic	2.451390	0.9929	1.701239	0.9556
Panel PP-statistic	− 0.809644	0.2091	− 2.449045 ^a	0.0072
Panel ADF-statistic	− 1.936671 ^b	0.0264	− 2.063321 ^b	0.0195
Weighted				
Panel γ -statistic	3.325062 ^a	0.0004	− 0.912124	0.8191
Panel rho-statistic	2.464558	0.9931	1.847004	0.9676
Panel PP-statistic	− 0.751423	0.2262	− 3.398269 ^a	0.0003
Panel ADF-statistic	− 1.969237 ^b	0.0245	− 3.803870 ^a	0.0001
Alternative hypothesis: individual AR coeffs. (between-dimension)				
Group rho-statistic	3.433316	0.9997	2.835025	0.9977
Group PP-statistic	− 2.984838 ^a	0.0014	− 5.935990 ^a	0.0000
Group ADF-statistic	− 1.244367	0.1067	− 4.138066 ^a	0.0000
Kao cointegration test	− 2.160800 ^a	0.0154	− 3.557469 ^a	0.0002
Westerlund test variance ratio	− 1.3810 ^c	0.0836	− 1.4744 ^c	0.0702

Table 5. Panel cointegration tests for 2 models. ^{a, b, c}Indicate significance at 1%, 5%, and 10% level respectively.

Variable	$GDP_t = F(L_{t,i}, K_{t,i}, CO_{2t,i}, EE_{t,i}, RE_{t,i}, \mu_{t,i})$		$CO_{2t} = F(L_{t,i}, K_{t,i}, GDP_{t,i}, EE_{t,i}, RE_{t,i})$	
	Coefficient	t-statistic	Coefficient	t-statistic
Long-run (pooled) coefficients				
L	-1.545345 ^a	-22.35147	-0.664828 ^a	-12.27490
K	0.102651 ^a	2.810470	0.062524	1.090867
CO ₂	-0.241546 ^a	-2.814860	-	-
GDP	-		0.364006 ^a	5.852055
EE	1.373355 ^a	22.41116	0.665720 ^a	9.560166
RE	-0.218844 ^a	-3.426925	-0.089661 ^a	-2.962347
C	34.19677 ^a	25.46062	8.582868 ^a	7.350481
Short-run coefficients				
ECM (-1)	-0.206422	-1.472268	-0.264695 ^b	-1.951430
D(GDP(-1))	0.433115 ^b	2.258054		
D(L)	0.557713 ^a	2.719960	-0.906206 ^a	-3.462407
D(L(-1))	0.024582	0.084080	0.049285	0.077764
D(K)	0.054754	0.750993	-0.107131	-0.832787
D(K(-1))	0.015485	0.353316	-0.036629	-0.357644
D(CO ₂)	0.118948	1.100866		
D(CO ₂ (-1))	-0.133959 ^a	-2.918116		
D(GDP)			0.603520	1.384666
D(GDP(-1))			0.465638	1.092426
D(EE)	0.065753	0.267946	0.460235	1.232972
D(EE(-1))			-0.019031	-0.146318
D(RE)	0.091705 ^b	2.245333	-0.150643	-1.394397
D(RE(-1))			-0.084598	-1.101623

Table 6. PMG/ARDL estimated coefficients for 2 models. ^{a, b, c}Indicate significance at 1%, 5%, and 10% level respectively.

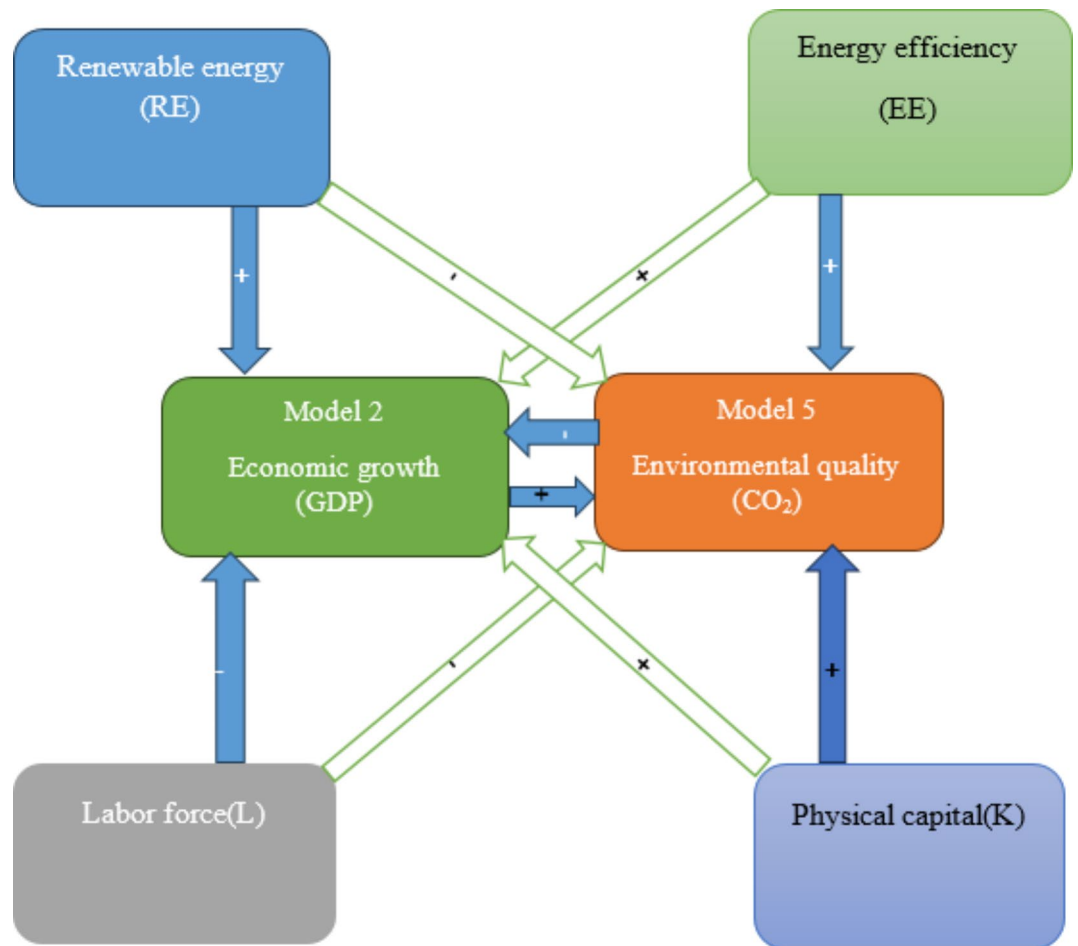


Fig. 1. The long run PMG/ARDL main findings in graphical form.

manufacturing in Asian countries were facilitated by the abundance of labor and capital influx, which is shown in the positive GTFP increase throughout the aforementioned time frame. The positive growth of GDP and positive contributions of labor and capital with negative contributions of EE and RE have a significant role in affecting the average growth of green TFP slightly as indicated by the low GTFP average growth value (0.007886), implying that it is urgently needed for an effective strategy energy efficiency and renewable energy use to reverse the negative effects of EE and RE into positive and to promote GDP growth. One important strategic goal that can promote economic growth is to concentrate on technology that can improve energy efficiency¹¹.

On the other side, the average growth rate of CTFP is negative with a value (-0.00483) irrespective of the positive contributions from CO_2 , L, K, and GDP. This may be due to the high negative contributions of EE and RE. The positive share of GDP to CO_2 emissions might be justified by the environmental Kuznets curve (EKC) hypothesis which means that the country's expansion in earlier economic development and industrialization progress increased environmental stress. Furthermore, this shows that the rise in EE exacerbates environmental quality and also can be justified by the rebound effect²². This effect suggests that people may use more energy or consume more goods and services when energy-efficient technologies or practices result in lower energy costs. At higher intensity carbon emissions economic growth is unsustainable, while low-carbon activity is useless in the absence of economic growth. Thus, as a result, the foundation of low-carbon economic research is the idea of advantageous economic growth³². Therefore, encouraging more expenditure and efficient spending toward the promotion of energy efficiency use and renewable energy generation will contribute significantly to improving environmental quality and fostering economic growth.

Finally, the panel causality test of Dumitrescu Hurlin (DH) is used to investigate the causality path among energy efficiency, RE, and GDP on environmental quality as depicted in Table 9. The null hypothesis indicates each variable does not homogeneously cause other variables.

According to DH panel causality test results in Table 9, a bidirectional causality exists amid economic growth and environmental quality and confirms that economic growth and environmental quality each have a reverse effect on the other. Energy efficiency and GDP growth displayed a mutual causality, this explains that energy efficiency contributes significantly to fostering economic growth, as well as sustainable economic growth enhances energy efficiency use. On the other side, energy efficiency showed a unidirectional relationship to environmental quality. Renewable energy demonstrates causality toward GDP growth which supports the effective role of renewable energy use strategy to promote GDP growth. However, a mutual causality was

Variable	$GDP_t = F(L_{t,i}, K_{t,i}, CO_{2t,i}, EE_{t,i}, RE_{t,i}, \mu_{t,i})$		$CO_{2t} = F(L_{t,i}, K_{t,i}, GDP_{t,i}, EE_{t,i}, RE_{t,i})$	
	Coefficient	t-statistic	Coefficient	t-statistic
L	- 0.162342	- 0.9223935	- 0.368066 ^a	- 3.890830
K	0.175616 ^c	1.631082	0.070866	1.109882
CO ₂	0.526975 ^a	2.590593		
GDP			0.166343 ^b	2.381561
EE	0.709013 ^a	4.004722	0.630744 ^a	7.220662
RE	0.112624 ^a	3.131687	- 0.037807 ^c	- 1.687120
Adjusted R ²	0.995		0.998	

Table 7. Robustness FMOLS estimator. ^{a, b, c}Indicate significance at 1%, 5%, and 10% level, respectively.

$\Delta \ln GTFP_{i,t} = \Delta \ln GDP_{i,t} - [\beta \cdot \Delta \ln L_{i,t} + \gamma \cdot \Delta \ln K_{i,t} + \rho \cdot \Delta \ln CO_{2i,t} + \phi \cdot \Delta \ln EE_{i,t} + \delta \cdot \Delta \ln ER_{i,t}]$ (3)						
LGDP	L	K	CO ₂	EE	RE	GTFP
0.008883	0.153532	0.055021	0.056298	- 0.01734	- 0.01222	0.007886
$\Delta \ln CFP_{i,t} = \Delta \ln CO_{2i,t} - [\beta \cdot \Delta \ln L_{i,t} + \gamma \cdot \Delta \ln K_{i,t} + \rho \cdot \Delta \ln GDP_{i,t} + \phi \cdot \Delta \ln EE_{i,t} + \delta \cdot \Delta \ln ER_{i,t}]$ (6)						
CO ₂	L	K	GDP	EE	RE	CTFP
0.056298	0.153532	0.055021	0.008883	- 0.01734	- 0.01222	- 0.00483

Table 8. GTFP, CTFP, and indicators contributions (%).

Null hypothesis	W-stat.	Zbar-stat.	Prob.	Direction
L → GDP	8.50585	11.7273	0.0000	L ↔ GDP
GDP → L	5.73698	7.32295	2.E-13	
K → GDP	2.48142	2.14438	0.0320	K → GDP
GDP → K	1.67167	0.85633	0.3918	
CO ₂ → GDP	3.04910	3.04739	0.0023	CO ₂ ↔ GDP
GDP → CO ₂	3.56132	3.86216	0.0001	
EE → GDP	6.47531	8.49740	0.0000	EE ↔ GDP
GDP → EE	3.47920	3.73154	0.0002	
RE → GDP	4.95077	6.07233	1.E-09	RE → GDP
GDP → RE	5.75987	7.35937	2.E-13	
K → L	1.10434	-0.04612	0.9632	Rejected
L → K	1.54805	0.65968	0.5095	
CO ₂ → L	2.27038	1.80868	0.0705	CO ₂ ↔ L
LL → CO ₂	4.43859	5.25762	1.E-07	
EE → L	3.73377	4.13648	4.E-05	EE ↔ L
L → EE	2.28467	1.83142	0.0670	
RE → L	5.21759	6.49676	8.E-11	RE ↔ L
L → RE	4.80112	5.83429	5.E-09	
CO ₂ → K	1.66972	0.85322	0.3935	K → CO ₂
K → CO ₂	3.22787	3.33175	0.0009	
EE → K	1.94423	1.28988	0.1971	Rejected
K → EE	2.02686	1.42132	0.1552	
RE → K	2.29718	1.85131	0.0641	RE ↔ K
K → RE	4.07877	4.68526	3.E-06	
EE → CO ₂	3.43035	3.65383	0.0003	EE → CO ₂
CO ₂ → EE	1.03501	-0.15640	0.8757	
RE → CO ₂	2.49340	2.16343	0.0305	RE ↔ CO ₂
CO ₂ → RE	4.48803	5.33627	9.E-08	
RE → EE	1.83763	1.12032	0.2626	EE → RE
EE → RE	4.54560	5.42783	6.E-08	

Table 9. Panel causality of Dumitrescu Hurlin. → indicates unidirectional causality and ↔ means bidirectional causality.

discovered between renewable energy and environmental quality. These results show how using renewable energy can effectively stabilize environmental quality in selected Asian countries by lowering greenhouse gas emissions, lessening the effects of global warming, and minimizing the effects of climate change.

Conclusion

The current study looks at the potential effects of energy efficiency and renewable energy on both GDP and CO₂ emissions using data covering the years 2000 – 2020 in eight chosen Asian countries (Malaysia, Philippines, Indonesia, Thailand, South Korea, China, India, and Japan). Furthermore, this study made a significant contribution by calculating carbon total factor productivity and green growth total factor productivity using the growth accounting theory “Solow residual” on modified versions of Kaya & Yokobori’s²⁹ concept and Ahmed’s³¹ framework. For this purpose, the current study included energy efficiency and renewable energy that were overlooked by Ahmed & Elfaki’s²⁸ empirical implementation. Additionally, the contributions of energy efficiency, labor, capital, and renewable energy indicators to environmental quality (CO₂ emissions) and economic growth were calculated to explain the dynamics of how energy efficiency and renewable energy could promote environmental quality and boost growth. The panel unit root second-generation test of IPS (CIPS) and (CADF) was conducted to determine the stationarity of the series. The panel cointegration approaches by Pedroni, Kao, and the new simple Westerlund are applied to examine the long-term cointegration relationship of the series. The study utilized the PMG/ARDL technique to estimate the parameters in the long term. Furthermore, FMOLS is applied to test the robustness of estimated long-run elasticities. The findings of CIPS and CADF make evident that RE, EE, GDP, and environmental quality are stationary at the first difference. The results from the Pedroni, Kao, and Westerlund cointegration tests reveal the presence of a long-run connectedness among the variables.

The coefficients of EE and capital are positive in connection with the growth of GDP. Renewable energy shows an unfavorable and significant influence on GDP growth, implying that an effective renewable energy use strategy needed to promote GDP growth as well as will have a decisive influence on environmental quality by declining emitting greenhouse gases. The negative and statistically significant coefficient of CO₂ emissions, in the long term, reveals a rise in CO₂ emissions decline in GDP growth. This outcome shows that the deterioration

in the environmental quality by surging CO₂ emissions will affect boosting economic growth in selected Asian countries. The coefficient of labor displayed a negative relationship with GDP growth.

Concerning the environmental quality model (CO₂ emissions dependent variable), the coefficient of energy efficiency is positive in connection with CO₂ emissions. Renewable energy shows a favorable and significant influence on environmental quality, this proposes applying an effective renewable energy use strategy to promote environmental quality in chosen Asian countries will have a crucial impact on abating emitting greenhouse gases, mitigating global warming, and reducing climate change consequences. The positive and statistically significant coefficient of GDP, in the long term, reveals a rise in GDP leads to an upsurge in CO₂ emissions, viewing a deterioration in the environmental quality in selected Asian countries and supporting the EKC hypothesis that in the early stage of modern economic growth, environmental degradation tends to get worse. The coefficient of labor showed a negative connection with CO₂ emissions. Physical capital was found insignificantly related to CO₂ emissions.

In the short run, the ECT (-1) coefficients are negative but significant in environmental quality model (CO₂ emissions dependent variable), manifesting that the change that takes place in the short run will be adjusted to the long run equilibrium by 0.206422% and 0.264695% annually in both GDP growth and environmental quality models respectively. Furthermore, in the short run, RE is positively correlated with GDP growth.

The findings from the FMOLS estimator manifest consistency of L, K, and EE with the outcomes of the PMG/ARDL in the long run in the GDP growth model and full consistency with the environmental quality model.

The average growth rate of GTFP is positive. The positive growth of GDP and positive contributions of labor and capital with negative contributions of EE and RE significantly affect the average growth of green TFP slightly as indicated by the low GTFP average growth value. On the other side, the average growth rate of CTFP is negative regardless of the positive contributions from CO₂, L, K, and GDP. This may be due to the high negative contributions of EE and RE. The positive share of GDP to CO₂ emissions might be justified by the environmental Kuznets curve (EKC) hypothesis which means that the country's expansion in earlier economic development and industrialization progress increased environmental stress.

Policy implications

Based on the empirical findings of this study several policy implications are provided. Energy efficiency significantly enhances economic growth and worsens environmental quality. This finding is in favor of boosting economic growth, however, it does not support improving environmental quality by reducing CO₂ emissions. Accordingly, Asian countries must implement suitable energy policies to boost economic expansion and lower CO₂ emissions (improving the quality of the environment). Asian economies need to put in place the necessary policies to maintain a balance between economic growth and environmental quality. These policies should take the form of implementing long-term energy practices, such as establishing and enforcing laws and regulations about energy efficiency, taking steps to discourage the use of inefficient machinery, offering incentives in the form of tax breaks and financial rewards to businesses and industries that invest in energy-efficient practices and technologies. These measures would support the achieving sustainable development goals (SDGs).

The negative impact of renewable energy on GDP growth implies that to gain advantages from strategies that promote the development of sources of renewable energy and the use of environmentally friendly energy a viable plan for achieving economic growth through the use of renewable energy (solar, wind, and hydro energy), replace nonrenewable energy sources, and implement grants, tax deduction, and rewards for businesses that successfully sustainably use clean energy in place of nonrenewable energy must be implemented. These strategies will correspondingly enhance environmental quality mitigating global warming and reducing climate change consequences by declining emitting greenhouse gases. Encouraging more expenditure and efficient spending toward the promotion of energy efficiency use and renewable energy generation will contribute significantly to improving environmental quality and fostering economic growth in the long run. Asian economies can leverage labor abundance by investing in vocational training to enhance workforce skills and productivity to guarantee efficient use of resources. Capital accumulation supports sustainable infrastructure development such as energy from renewable resources (solar, wind, hydro).

Study limitations and future work

This study has provided insightful contributions in examining the effects of energy efficiency and renewable energy on environmental quality and economic growth in eight Asian economies. However, due to data availability in chosen Asian countries, the study has certain limitations. Future research can develop this study by including institutional quality, green technology innovations, and economic uncertainties impact on environmental quality and economic growth. Additionally, future studies can employ different econometric methods, different sample periods, and a wider range of countries and historical periods such as MENA, OECD, BRICS, and developing, and developed nations.

Data availability

The data used in this study is collected from the World Development Indicators (WDI) and British Petroleum (BP). The data is available to be shared upon request from Khalid Eltayeb Elfaki via abuarabsk@gmail.com.

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Elsadig Musa Ahmed is the project leader, writing, review & editing and Khalid Eltayeb Elfaki design, Data collection, Methodology, Project administration and Writing draft.

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Declarations

Competing interests

The authors declare no competing interests.

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