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Assessing the impact of FDI, CO2 emissions, economic growth, and income inequality on renewable energy consumption in Asia

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A R T I C L E I N F O

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A B S T R A C T

This study analyzes the influence of foreign direct investment (FDI), economic growth (GDP), income inequality (II), and carbon dioxide emissions (CO2E) on renewable energy consumption (REC) in Asia from 1995 to 2020. This study seeks to elucidate the factors influencing renewable energy consumption in various economic and environmental circumstances across Asia. The study employs advanced econometric techniques, such as panel cointegration, cross-sectional dependency tests, quantile regression, and Dumitrescu-Hurlin causality tests, revealing significant relationships between the variables. The findings indicate that increased GDP and FDI promote REC, but income inequality and CO2 emissions have intricated context-sensitive impacts. This research emphasizes the need for specific policy interventions to promote renewable energy adoption, especially in countries with high inequality and CO2 emissions. These findings provide valuable insights for policymakers working towards sustainable energy transition in Asia.

Abbreviations

Abbreviation	Full Form
REC	Renewable Energy Consumption
FDI	Foreign Direct Investment
GDP	Gross Domestic Product
CO2E	Carbon Dioxide Emission
II	Income Inequality
IEA	International Energy Agency
MNE	Multinational Enterprises
WDI	World Database Indicators

1. Introduction

Over several years, there has been a notable increase in both the Gross Domestic Product (GDP) and energy consumption. In addition to the increase in CO2 emissions, there has also been a concurrent increase in environmental pollution. During that period, the primary energy source was fossil fuels; however, over time, there was a decline in the availability of fossil fuels. Policymakers advocate a transition towards green energy to mitigate CO2 emissions and reduce environmental damage. As an essential part of sustainable growth, renewable energy will be beneficial in guiding Asian economies towards a more resilient and eco-friendly future. According to the SDGs, specifically SDG-7, our main concern is to provide clean and affordable energy. The main focus of this study was the dependent variable of renewable energy consumption. Several factors affect the use and adoption of renewable energy sources. The primary way to determine how ready Asian countries are for sustainable energy changes is to look at the amount of renewable energy they use. The world's energy needs are growing because of population growth, technological progress, urbanization, business growth, and economic development. According to the data from the IEA

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(International Energy Agency), between 2019 and 2021, the energy and process CO2 emissions growth rate increased by 6.7 % in the United States, 4.8 % in China, 10.7 % in India, 7.4 % in the European Union, and 5.6 % in rest of the world. The growth rate of greenhouse emissions has increased by 6.2 % in the United States, 4.8 % in China, 10.3 % in India, 7.0 % in the European Union, and 5.3 % in the rest of the world [1]. [2] explained that the renewable energy industry, which is turning into a green market, has a new type of economic growth that can minimize the unfavorable consequences of non-renewable energy consumption to some degree, while encouraging sustainable development techniques. This growth can be addressed or minimized by using green markets. The accelerated expansion of green energy in Asian countries can be attributed to the adoption of various renewable energy sources, such as solar energy, liquid biofuels, wind energy, solar thermal energy, and biogas. The distribution of green energy is as follows: 40.1 %, 16.7 % of another kind, 19.9 %, 5.6 %, and 8 % for the third, fourth, and fifth types, respectively [3]. It will also analyze the energy transition strategies and challenges of Gulf Council countries.

The implementation of renewable energy has become profoundly entangled with a multifaceted network of influencing factors. The analysis of income inequality as an independent variable arises from recognizing its complex influence on the formation of social structures and the availability of resources. This study underscores the relevance of income inequality, a pervasive socioeconomic phenomenon in Asia, in shaping the utilization and distribution of renewable energy resources. In addition, unequal income distribution may affect REC through economic and political channels [4]. From a monetary perspective, inequality affects societal tendencies, such as egoism, short-termism, and mercantilism, affecting green energy use. This affected the amount of green energy consumed. Consequently, the power dynamics between these groups affect the adoption of renewable energy. Without this, institutional structure is a potent stimulus for green energy consumption and environmental sustainability maintenance [5,6].

Asian countries have many different landscapes and economies, and income inequality is a problem that affects the use and distribution of renewable energy supplies. The unequal sharing of resources and income often reflects unequal access to clean, long-lasting energy sources. Some people in society have trouble with money, which could make it more difficult for them to invest in or gain access to green energy technologies. This can make people more dependent on traditional energy sources. Consequently, this difference in energy access adds to the complicated link between Asia's income inequality and the use of green energy. Determining this connection is crucial for reducing the differences and creating policies that encourage people to use renewable energy.

Furthermore, Foreign Direct Investment (FDI), which serves as an external economic influencer, presents itself as an additional significant factor deserving careful consideration. An analysis is needed to understand how the influx of foreign capital affects the adoption of renewable energy technology in Asian countries, and whether it helps or hinders their progress. Some [7–9] agree that Foreign Direct Investment (FDI) can help a country's income and production growth. It encourages the free flow of wealth, which allows trade to grow, but also causes environmental problems, which have become one of the most critical issues in recent years. The idea that attracting FDI can help protect the environment and grow the economy has quickly been blown out worldwide. Multinational companies (MNEs) send knowledge, technologies, and management methods from their home countries to host countries. This is usually considered to be a flow. As competition between countries increases, foreign direct investment (FDI) becomes more critical for a country's economic growth. This is because FDI helps companies in host countries improve their technology through technology transfer [7]. Several studies [10] indicate that foreign direct investment (FDI) is crucial to the economic growth of host nations, especially in developing countries with sophisticated financial markets. FDI can also have a secondary effect on renewable energy, because multinational companies are more likely to use green energy techniques that work well. According to Brunnschweiler and Economics [11,12], the growth of renewable energy requires much more capital and technology, and FDI can help the renewable energy business by providing capital and technology. In addition, there is evidence that some foreign companies and nations also follow high environmental standards. These international enterprises are more likely to use clean energy from natural sources and implement energy-saving measures.

Delving deeper into intricacies, exploration pivots towards the role of Gross Domestic Product (GDP) as an independent variable. Gross Domestic Product (GDP), an indicator of economic growth, encompasses the financial activities that fuel energy consumption. The association between renewable energy consumption and economic development in Asia highlights the interconnected relationship between these two variables. According to Ref. [13], a strong national economy must effectively use the available energy. In addition, many scholarly investigations have concluded that the standard of capital accumulation in a country impacts the rate at which the country's economy expands. Expanding a country's economy is one factor driving energy needs. The increased demand for and consumption of energy has resulted in a significant increase in the release of toxic compounds into the environment. According to research conducted by Refs. [14,15], the energy industry has the same effect on economic development as it does in the environment. The ecological status of the country presents various difficulties to its natural resources, as the level of environmental pollution continues to rise. In this hypothetical situation, it is also possible that all available energy resources will be used. As a result, a significant amount of effort has been invested in sustainably employing energy resources.

The complicated link between CO2 emissions and renewable energy consumption in Asia forms a vital axis in the region's sustainable energy trajectory. Elevated CO2 emissions frequently signal a heavy dependence on fossil fuels and non-renewable energy sources. Consequently, rising environmental awareness and responsibility to combat climate change have underlined the urgency of switching towards renewable energy. The adoption and integration of renewable energy technologies offers a path to decrease CO2 emissions, reduce the carbon footprint, and mitigate the harmful consequences of climate change [16–18]. Understanding this link elucidates the essential significance of renewable energy in diversifying energy sources and minimizing detrimental effects on the environment from CO2 emissions across various Asian economies. Addressing all the relationships between these variables, our study has the following central question:

Research Question: *How do income inequality, CO2 emissions, GDP, and FDI collectively influence the adoption and consumption of renewable energy in Asia?*

The research objectives of this study are as follows.

1. To assess the impact of FDI on REC in Asia.
2. Examining the relationship between economic growth and renewable energy consumption.
3. This study explored the effect of income inequality on renewable energy consumption.
4. To analyze the effect of CO2 emissions on renewable energy consumption.

Renewable energy is essential for fulfilling the global climate objectives and achieving sustainable development. Renewable energy is a growing priority in Asia because the region is facing rapid economic growth, high CO2 emissions, and significant social and environmental challenges. Despite the increasing significance of renewable energy, the determinants of its adoption in Asian countries remain inadequately examined, especially the interplay of economic, social, and environmental variables that affect REC levels across Asia. This study aims to fill a significant gap in the literature by examining the impact of FDI, GDP, income inequality, and CO2 emissions on REC in 36 Asian countries from 1995 to 2020.

The motivation to examine the relationship between income inequality, CO2 emissions, GDP, FDI, and renewable energy consumption in Asia arises from the strong demand for beneficial transformation in the region. Asia, renowned for its abundant variety and rapid economic growth, is a critical juncture for vast opportunities and challenges. Through a comprehensive analysis of these factors within the context of Asia, our objective was to make a meaningful contribution to the region's pursuit of sustainable development. The importance lies not only in the pursuit of knowledge, but also in the potential practical consequences, a possibility to discover valuable information that can shape policies, empower communities, and stimulate a fundamental transformation towards a fairer, more prosperous, and environmentally aware future for the diverse collection of Asian nations. This study aims to utilize knowledge to facilitate significant and impactful changes, guiding Asia towards comprehensive economic development and sustainable advancements in energy technology.

This study makes a significant empirical contribution by thoroughly examining the determinants of renewable energy consumption in 36 Asian countries from 1995 to 2020. This study adopts a comprehensive, multi-country approach, enhancing its generalizability and significance for policymakers across Asia, in contrast to other studies that concentrate on isolated regions or individual countries. The empirical novelty of the study lies in integrating multiple variables–FDI, GDP, Income inequality, and CO2 emissions–to examine the collective impact on REC. This study systematically analyzes these aspects to provide a more thorough understanding of the determinants of REC adoption. This study uncovers the dynamic relationships between variables often missed in traditional analyses by employing advanced econometric techniques, such as quantile regression, panel cointegration tests, cross-sectional dependence, and Dumitrescu-Hurlin panel causality tests. For example, quantile regression facilitates comprehension of how the impacts of these variables fluctuate over varying degrees of renewable energy consumption. This study's emphasis on cross-sectional dependency and causation enhances the research by acknowledging the interdependence of Asian countries, indicating that the links between variables may be multidirectional. This empirical technique contributes to the growing literature on renewable energy adoption in Asia by providing new insights and a refined methodology for future studies.

This study significantly enhances the literature on Rec and its drivers, particularly in the Asian context. Although several studies have examined the economic and environmental determinants of REC, few have integrated the effects of FDI, income inequality, and CO2 emissions into a comprehensive model. By addressing this gap, this study enriches the literature by providing a more holistic understanding of the drivers of REC in regions where renewable energy adoption is particularly crucial for meeting sustainable development goals.

The novelty of the results lies in their ability to reveal nuanced and context-specific insights into the determinants of renewable energy consumption across 36 Asian countries, highlighting both heterogeneity and interdependence within the region. We chose only 36 countries because the remaining countries lacked data on the study's variables. The quantile regression results show that the effects of FDI and income inequality are more pronounced at moderate and lower levels of REC. The results showed a consistent negative relationship between CO2 emissions and REC, indicating a critical need for climate-focused policies. The cross-sectional dependence outcome shows the interconnectedness of Asian countries, offering actionable insights into regional collaboration and tailored policymaking.

The remainder of this paper is organized as follows. Section 2 provides an overview of the recent literature that is important to this topic. Section 3 explains the theoretical basis of the proposed testable model. Section 4 defines the specific methodologies used for econometric analysis. Section 5 presents and analyzes the results of the study. Finally, Section 6 concludes the study by discussing the policy implications, limitations, and future research directions.

2. Literature review

2.1. Renewable energy consumption and income inequality

Limited research exists on the link between income inequality and renewable energy consumption, although the literature on the impact of inequality on environmental quality offers some insights. In this section, we discuss how income inequality may affect renewable energy consumption using the literature on income inequality in the environment. Research indicates that income inequality affects renewable energy consumption through economic and socio-political channels [19]. Income inequality, a pervasive socio-economic factor, has been widely studied in the context of renewable energy adoption, with scholars like [5,16,20–22] highlighting its profound influence on access to and distribution of clean energy resources. Income inequality and rate of technological advancement are both controllable variables. According to Refs. [23,24]empirical data computed using the nonlinear autoregressive distributed lag (NARDL) approach, the rising trend in exports and technical innovation contributed to increased carbon pollution.

Studies by Refs. [25–27] found that income inequality impacts renewable energy usage by influencing social norms, including individualism, consumerism, and short-termism. Distrust and income inequality limit group action and promote individualism. Inequality-driven civilizations lack environmental sensitivity, rent seeking, and the widespread use of non-renewable ecological resources to meet personal needs. These groups worry little about the long-term implications of consumption. They preferred short-term gains. This shortsightedness can affect renewable energy usage and harm the environment. Conspicuous consumption and status competitiveness characterize such civilizations. Renewable energy consumption can be affected by income inequality through its influence on power dynamics and institutional quality among various social groups. Institutions are crucial for shaping environmental policies, income distribution, and energy consumption [28–30]. [26] Income inequality indicates that poor institutions discourage efficient investment and weaken environmental policies. Elite groups engage in ecologically harmful behaviors in weak institutions. Limited investment in renewable energy negatively impacts the uptake of sustainable energy. Income inequality causes power disparities, which influence environmental policies. Power disparities impact renewable energy use and institutional function by providing elite groups that profit from traditional energy sources environmental policymaking power [31]. Rent-seeking profit seeking hinders the benefits of renewable energy consumption in underprivileged populations. Another option is for high-income elites to care more about their environment. The Environmental Kuznets Curve (EKC) hypothesis suggests that individuals adopt post-materialist principles, such as environmentalism, after meeting short-term needs [19,25,32–34]. Based on the literature, the following hypothesis was formulated.

H1. *Higher income inequality is associated with higher levels of renewable energy consumption.*

2.2. Renewable energy consumption and gross domestic product (GDP)

After the 1973 and 1979 oil shocks, renewable and environmentally friendly alternative energy sources became necessary, leading to numerous theoretical and empirical investigations. Sustainable development, "green recovery," and "green economy" have propelled the switch to renewable energy in recent years [29,35]. Many studies have examined renewable energy use and economic growth [36–40].

They found that energy consumption drives the economy's short- and long-term growth [41]. empirically tested the ARDL and Toda-Yamamoto causality tests in Turkey. Their findings supported the conservation theory and suggested that the REC hurts economic growth. The authors found a one-way relationship between economic growth and renewable energy consumption [42,43]. used dynamic ordinary least squares (DOLS) to study the impact of renewable energy on economic growth in 15 West African nations from 1995 to 2014. However, the authors advised using clean energy sources, such as solar, wind, and hydroelectric power, that do not harm humans or the environment. Using a threshold model [44], examined the correlation between renewable energy use and economic growth in 103 countries, from 1995 to 2015. Renewable energy consumption affects this relationship, particularly in emerging countries. REC significantly affects economic growth, but only if poor countries exceed a certain point. Developing countries must exceed a particular renewable energy consumption threshold to obtain positive economic growth from renewable energy investments. Renewable energy consumption below a specific threshold negatively impacts economic growth in developing countries. Countries that use renewable energy below the threshold (lnREC $<$9.6054) negatively impact economic growth [45,46]. studied energy consumption and economic growth in 42 developing countries from 2002 to 2011. The generalized moment method (GMM) showed that long-term renewable energy boosts economic growth. From 2007 to 2016 [47], examined 25 EU member states and found a link between economic growth and the use of green and other types of energy.

The nexus between economic growth, as measured by Gross Domestic Product (GDP), and the utilization of renewable energy sources has been explored in depth by researchers, such as [16,48–54], demonstrating that renewable energy has a positive and statistically significant effect on economic growth under varying control and policy conditions. In the long run, research conducted in 25 OECD nations found that economic development fosters REC (Renewable energy consumption). In contrast, in the short term, economic growth harms the REC. Researchers have examined how economic growth affects global CO2 emissions pollution around the world. Several researchers who examined how economic growth affects the environment have pointed out that it affects CO2 emissions at different times of growth. EKC is the amount of pollution that increases as a country's income increases, but starts to decrease after a certain point [44,55]. [56,57] discovered that from 1980 to 2005, there was a positive correlation between real GDP per capita and renewable energy consumption in G7 countries. Based on the literature, the following hypothesis was formulated.

H2. *Higher GDP positively correlates with higher levels of renewable energy consumption.*

2.3. Renewable energy consumption and foreign direct investment (FDI)

The impact of Foreign Direct Investment (FDI) on renewable energy consumption has garnered scholarly attention, with studies [58–61] emphasizing the significance of external investments in shaping a country's energy landscape. This is because they use clean energy sources, and the technology has improved. FDI leads to better technology, making the world cleaner [62–64]. found that FDI reduces environmental damage and equipment, and China's industrial constitution lessens environmental pollution [43,52]. supports the pollution halo hypothesis that foreign direct investment may boost green growth in Southeast Asia. Green bonds temporarily reduce energy intensity; according to Ref. [53], per capita income, economic integration, FDI, and renewable energy sources may also affect energy intensity, while ASEAN modernization may have the opposite effect [65]. identified a bidirectional causal association between FDI inflows and economic growth in MENA nations from to1990-2022 using the generalized method of moments (GMM). A similar relationship was found between energy consumption and economic development. Energy consumption causes FDI inflows. The study by Ref. [66] provides solid proof of the link between FDI at the sector level and energy use. Between 1998 and 2003, most of Jiangsu Province's foreign direct investment (FDI) went to industry, primarily extractives and manufacturing. However, the share of FDI in the service sector is growing. During the same period, Jiangsu Province's energy output decreased. The authors explain this effect by stating that it had a scale effect on income, a composition effect that caused people to leave dirty industries, and a technology effect caused by stricter control of dirty industries that saved energy and the environment [67]. examine the correlation between renewable energy consumption, foreign direct investment, and GDP in 31 Chinese provinces from to 2000–2015. The empirical data shows a long-term equilibrium link between GDP per capita, FDI per capita, and renewable energy consumption per capita. A slight slowdown in gross domestic product growth, with an emphasis on foreign direct investment, would promote renewable energy in China in the long run but not in the short run [7,68]. found a correlation between FDI and energy consumption, indicating a favorable impact on the adoption of renewable energy. Max analyses the correlation between renewable and non-renewable energy consumption, foreign direct investment, economic growth, and carbon emissions in nine countries (CCPI 2018 report: Denmark, Finland, France, India, Italy, Morocco, Norway, Portugal, and Sweden). The newly developed bootstrap autoregressive distributed lag (ARDL) approach shows how renewable energy consumption and foreign direct investment affect CO2 emissions in nations with high CCPI ratings. This study indicates a long-term association between FDI and renewable energy consumption [69,70]. found that FDI contributes to Saudi Arabia's environmental degradation, but reduces it in Asian nations. Click or tap here to enter text.

H3. *Higher FDI leads to increased renewable energy consumption.*

2.4. Renewable energy consumption and CO2 emissions

Multiple studies have linked fossil fuel usage with increased carbon emissions in industrialized and developing nations over the last 20 years. Various authorities and governments have recognized the significance of green energy in changing carbon emissions and fulfilling energy requirements. Thus, many studies have examined carbon emissions and REC dynamics. Many researchers, like [50,72–80], have found a negative relationship between renewable energy consumption and CO2 emissions. Furthermore [81,82], discovered a one-way causation between the REC and CO2 emissions. He also found two-way causation between China and India [36,83]. establishes that imports per capita, urbanization, exports per capita, and carbon emissions are all significant elements that influence regional renewable energy consumption in different areas of China [84]. conducted a study in China to forecast carbon emissions and determine the energy consumption goals until 2030.

In the United States [85,86], discovered that while there was no direct relationship between renewable energy consumption and CO2 emissions, there was a one-way relationship between CO2 emissions and renewable energy consumption between 1960 and 2007 [87]. examined the link between CO2 emissions and the use of green energy, while considering income and oil costs. Long-term dynamic OLS and fully modified OLS data show that in China, Brazil, India, and Indonesia, the use of green energy is driven by CO2 and income. Renewable energy consumption and short-term CO2 emissions were bidirectional in these countries [88,89]. analyzed data from 1982 to 2016 in China, India, Iran, Indonesia, and South Africa, the top developing countries regarding greenhouse gas emissions from fuel consumption [70,90]. They confirmed the pollution haven theory and indicated that energy consumption considerably increases greenhouse gas emissions in emerging countries [91,92]. examine the variables that impact renewable energy consumption (REC) in sixty-four economies. Their research revealed a positive correlation between CO2 emissions and REC. Based on the literature, the following hypothesis is formulated.

H4. *Higher CO2 emissions are associated with lower renewable energy consumption.*

We also outline some of the literature based on our study in Table 1, while Shows the Flow of variables in different Asian countries from 1990

Table 1
Literature review of this study.

Author	Variables	Country	Methods	Results
Xiaotian et al. (2022) [16]	Renewable energy consumption, trade openness, CO2 emissions, Income inequality, economic growth	20 OECD nations	AMG assessor	Trade openness, REC, and income inequality have one-way relationships with CO2 emissions.
Weiyang Fan, YU Hao (2020) [67]	REC, economic growth, FDI	China	Vector error correction model, impulse response function analysis, granger causality test	Long-term relationship between GDP, REC, and FDI.
Janusz et al. (2021) [93]	REC, economic growth, FDI	Kazakhstan and Uzbekistan	granger causality test	Two-way link between FDI and REC
Lamia et al. (2018) [94]	REC and FDI	Bangladesh	Vector error correction model	Two-way link between REC and FDI
Aviral Kumar (2011) [95]	REC, GDP, CO2 emissions	India	Structural Vector Autoregressive	a positive shock on the REC increases GDP and decreases CO2 emissions.
Bakhsh et al. (2017) [17]	GDP, CO2 emissions, Renewable waste, FDI	Pakistan	Simultaneous equation model	↑in GDP, more CO2 emissions↑. FDI also increases pollution.
Bekhet and Othman (2018) [96]	CO2, GDP, Renewable Energy, waste resources	Malaysian	VECM, Granger causality, CUSUM, CUSUMSQ	RE reduces CO2
Dong et al. (2018) [97]	CO2, GDP, Nuclear energy, Fossil consumption, renewable energy	China	ARDL, cointegration, FMOLS, DOLS, VECM	NE, RE reduces CO2.
Cheng et al. (2019) [71]	CO2, renewable energy, environmental development, related technologies, GDP, exports, FDI, domestic credit to private sector	BRICS countries	Panel Quantile, OLS regression	FDI, RE reduces CO2. Exports increase CO2.
Nosheen et al. (2021) [98]	Degradation, GDP, GDP square, Tourism, FD, trade liberalization, Urbanization	Asia	FMOLS, DOLS	TU, TL, and URB increase DG
Ibrahim et al. (2024) [99]	Democracy, FDI, Sustainable development	BRICS-TM Countries	Kónya's causality test, Cointegration test with multiple structural breaks	democratic development with macroeconomic indicators positively impacts foreign direct capital inflows.
Macro et al. (2021)	Climate change, economic growth, renewable energy resources	Brazilian Economy	LSTM model	Greater use of renewables may sustain the economic growth recovery.
Farzana et al. (2024) [100]	Green finance, carbon neutrality, renewable energy investment, geopolitical risk, economic performance	G20 nations	Continuously updated fully modified and continuously updated bias-corrected estimators.	The negative relationship between renewable energy investments, green finance, and carbon neutrality.
Amir et al. (2023) [9]	Co2 emissions, renewable energy consumption, FDI, exports, economic growth	BRICS countries	ARDL, Pool Mean Group (PMG), Mean group (MG)	All variables have long-term positive impacts on economic growth.
Sefa et al. (2021) [101]	Income inequality, REC	17 nations	Time-varying non-parametric techniques	In a short period, the relationship was negative, but after 2010, it switched to positive.
Yilmaz et al. (2014) [102]	FDI, Domestic Investment, GDP	Turkey	Vector error correction model	Long-run relationship between GDP, FDI, and domestic investment.
Nguyen et al. (2018) [103]	FDI, GDP, Environmental Pollution	Vietnam	ARDL	Inverse U-shape between income per capita and environmental degradation.
Cosimo et al. (2022) [104]	FDI, GDP growth	Malta	Time-series and ANNs model	Causality results show the neutrality hypothesis.

to 2020. (see Fig. 1).

According to the Key Indicator Database, Asian countries are increasingly using energy. The energy use from 2000 to 2020 is shown in Fig. 2. Fig. 3 Shows the CO2 emissions of the Asian countries during the same time frame. Fig. 4 illustrates how various nations' shifts towards greener and more renewable forms of energy help in sustainable development.

3. Theoretical Underpinning

This study's conceptual framework is based on two main theoretical perspectives: Modernization Theory and the Environmental Kuznets Curve (EKC) hypothesis. These theories provide a basis for comprehending the intricate interconnections between FDI, CO2 emissions, GDP, Income inequality, and REC in Asia. This section establishes a robust theoretical foundation for the research by expanding these ideas and examining their integration and conflict.

3.1. Modernization theory and renewable energy transition

Modernization theory posits that economic development, industrialization, and technical progress drive social and structural change. This study posits that modernization theory suggests that when Asian countries undergo economic progress, they allocate resources to advanced technology and infrastructure, such as renewable energy systems, to attain sustainable development. Higher GDP increases renewable energy adoption as countries move towards more efficient systems. When a country's economic growth increases, the government allocates resources for R&D in green technologies and subsidies for renewable energy deployment. FDI also facilitates this theory by transferring knowledge, technology, and capital to the developing economies. FDI allows access to advanced technologies that enhance renewable energy adoption, thereby reducing dependence on fossil fuels. This theory highlights the progress in recognizing the challenges of income inequality. Income inequality may obstruct fair access to renewable energy technology, impeding energy transition in low-income regions.

Renewable Energy Consumption (REC) is the variable that represents the extent to which renewable energy sources are adopted and used. The growing global focus on sustainable development, as defined by sustainability and Environmental Economics Theory, suggests that fluctuations in renewable energy are an environmental requirement and a fundamental element for ensuring long-term economic sustainability. This notion is further supported by Ecological Modernization Theory, which promotes the harmonious integration of economic development and environmental preservation. It posits that breakthroughs in environmentally friendly technologies can stimulate economic expansion, while reducing adverse environmental effects [105,106]. This section provides a concise explanation of the theoretical connections between independent and dependent variables.

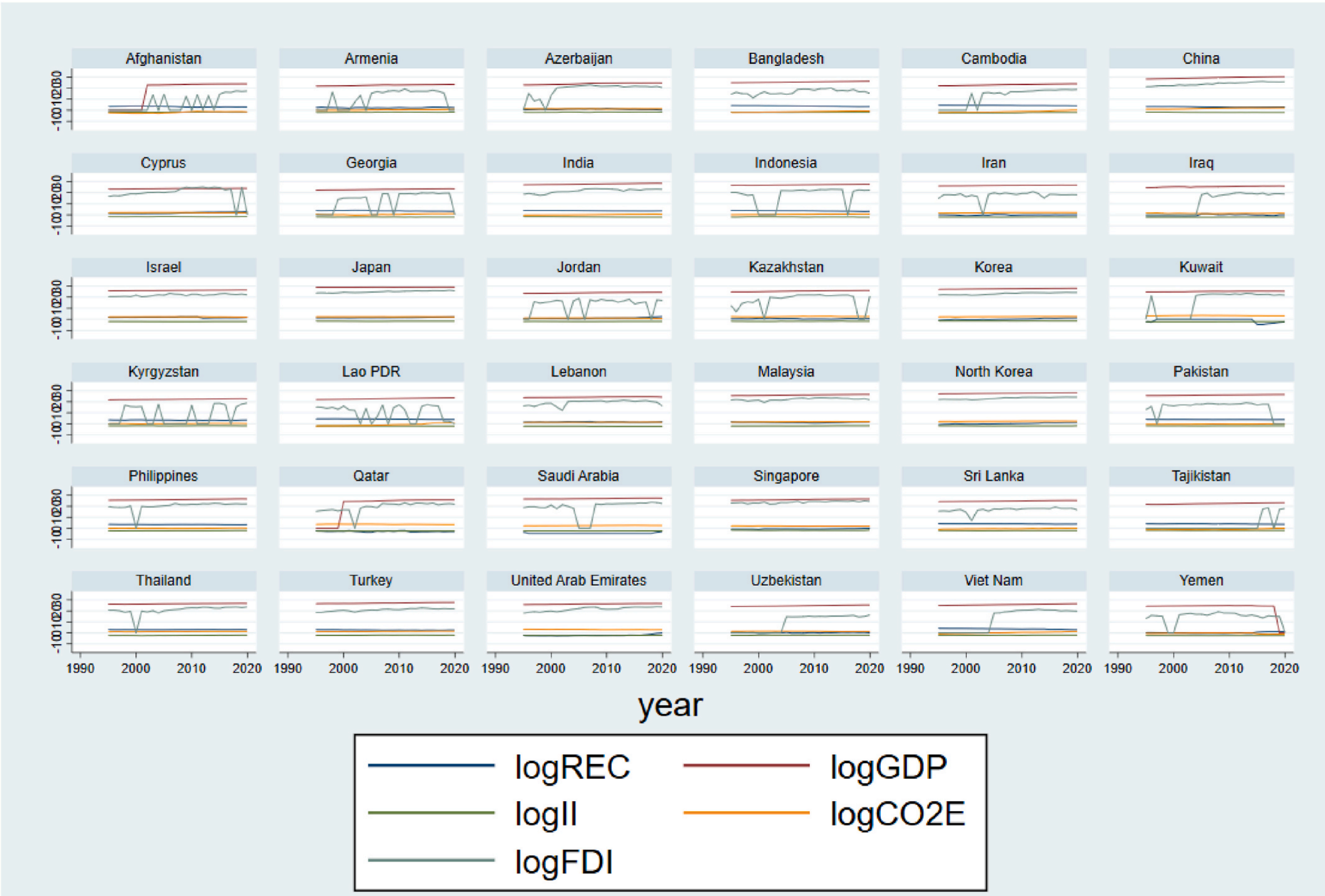

Fig. 1. Shows the Flow of variables in different Asian countries from 1990 to 2020.

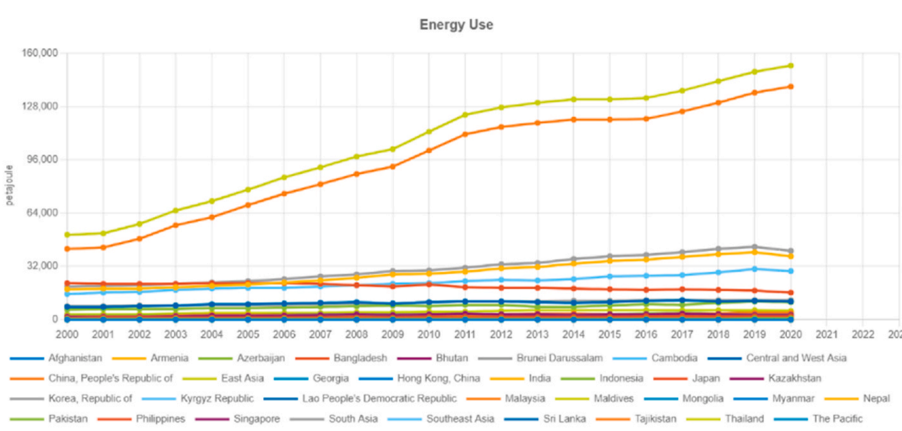

Fig. 2. Energy Consumption of Asian countries from 2000 to 2020, sourced by Key Indicator Database.

3.2. *Environmental Kuznets Curve (EKC) hypothesis*

The Environmental Kuznets Curve (EKC) hypothesis asserts an inverted U-shaped correlation between economic development and environmental degradation [107,108]. During the first phase of economic growth, CO2 emissions often rise as industrialization intensifies. As income levels increase, civilizations want cleaner surroundings, resulting in investment in green technology and renewable energy. According to this theory, CO2 emissions increase with economic growth and decrease when countries adopt cleaner energy sources. This shift corresponds with implementing renewable energy, which lowers emissions while fostering economic development [56,109,110]. Income inequality might impede the decline of the environmental Kuznets curve since disproportionate resource allocation may hinder investments in renewable energy. Affluent portions of the population may prioritize consumption over ecological conservation, whereas economically disadvantaged areas cannot advocate clean energy alternatives [63,111].

In addition, the study investigates Gross Domestic Product (GDP) as an independent variable, examining GDP's impact on REC through

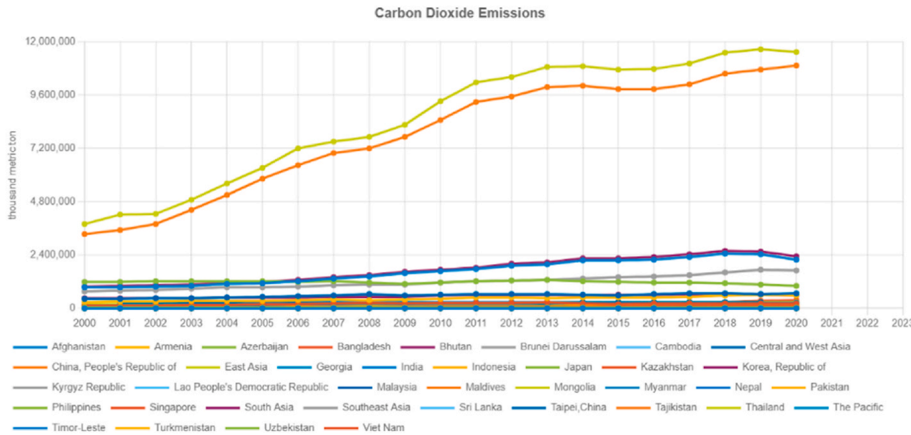

Fig. 3. CO2 Emission of Asian Countries from 200 to 2020, sourced by Key Indicator Database.

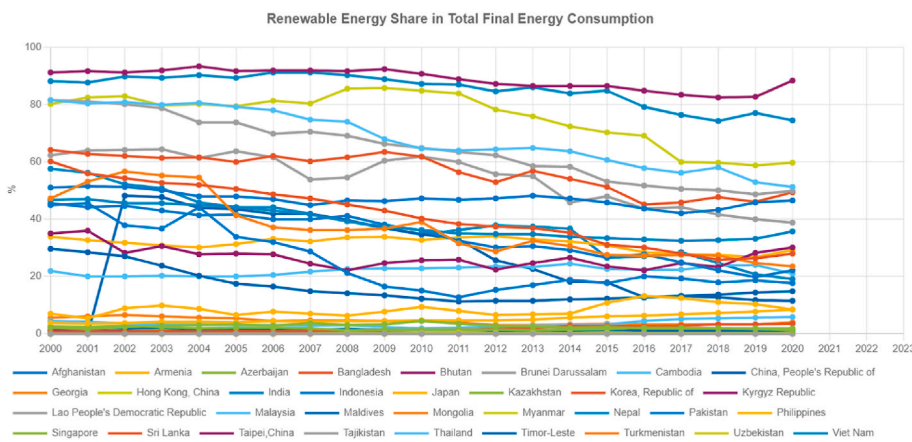

Fig. 4. Renewable Energy share in Total Consumption, sourced by Key Indicator Database.

Economic Development Theory. According to this idea, as a country's economy expands, there is a corresponding increase in its energy consumption. Still, there is also the possibility of moving towards energy sources that are more environmentally friendly. This change is further elaborated by the Energy Transition Theory, which proposes that economic development frequently occurs concurrently with the transition from fossil fuels to renewable energy sources [40,112,113].

In simple words, we can say that (as shown in Fig. 5) If there is an increase in FDI in the country, more investment projects will start, and if they are investing in green technologies, then in this way, the country's GDP or economic growth also increases. If all benefits are distributed equally, economic growth decreases the income inequality. If the benefits are not equally distributed, income inequality increases, thereby increasing energy consumption patterns and CO2 emissions. From the literature, we can see that if there is an increase in CO2 emissions, more energy will be consumed to mitigate climate change (see Fig. 6).

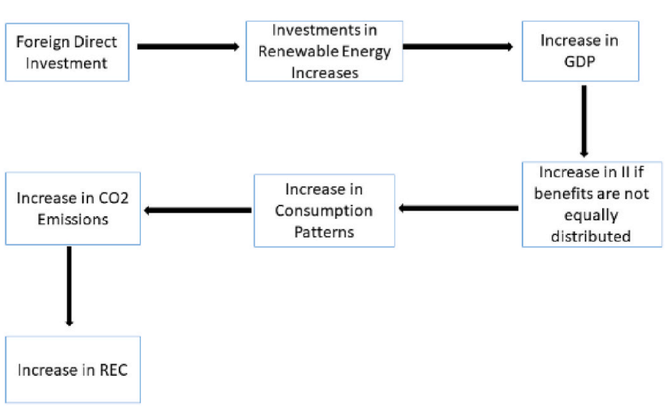

Fig. 5. Theoretical underpinning of variables.

3.3. Conflict and integration between modernization theory and EKC hypothesis

Modernization theory and the EKC hypothesis exhibit conflicts and synergies regarding their implications for adopting renewable energy. The modernization theory regards economic development as a primary driver of technological progress, including renewable energy. EKC theory posits that economic expansion may initially exacerbate environmental deterioration, thereby postponing the use of renewable energy until a higher income level is attained. Modernization theory perceives inequality as a structural challenge that must be rectified to facilitate advancement. However, the EKC hypothesis posits that inequality intensifies environmental damage in the first development phase, extending the EKC's apex. Both views concur that a sustained economic expansion facilitates ecological enhancement. The EKC hypothesis supplements the modernization theory by addressing the steps during which economic expansion alters ecological consequences. Modernization theory offers a comprehensive framework for comprehending how technical progress and foreign direct investment expedite the decline of the environmental Kuznets curve and promote the use of renewable energy.

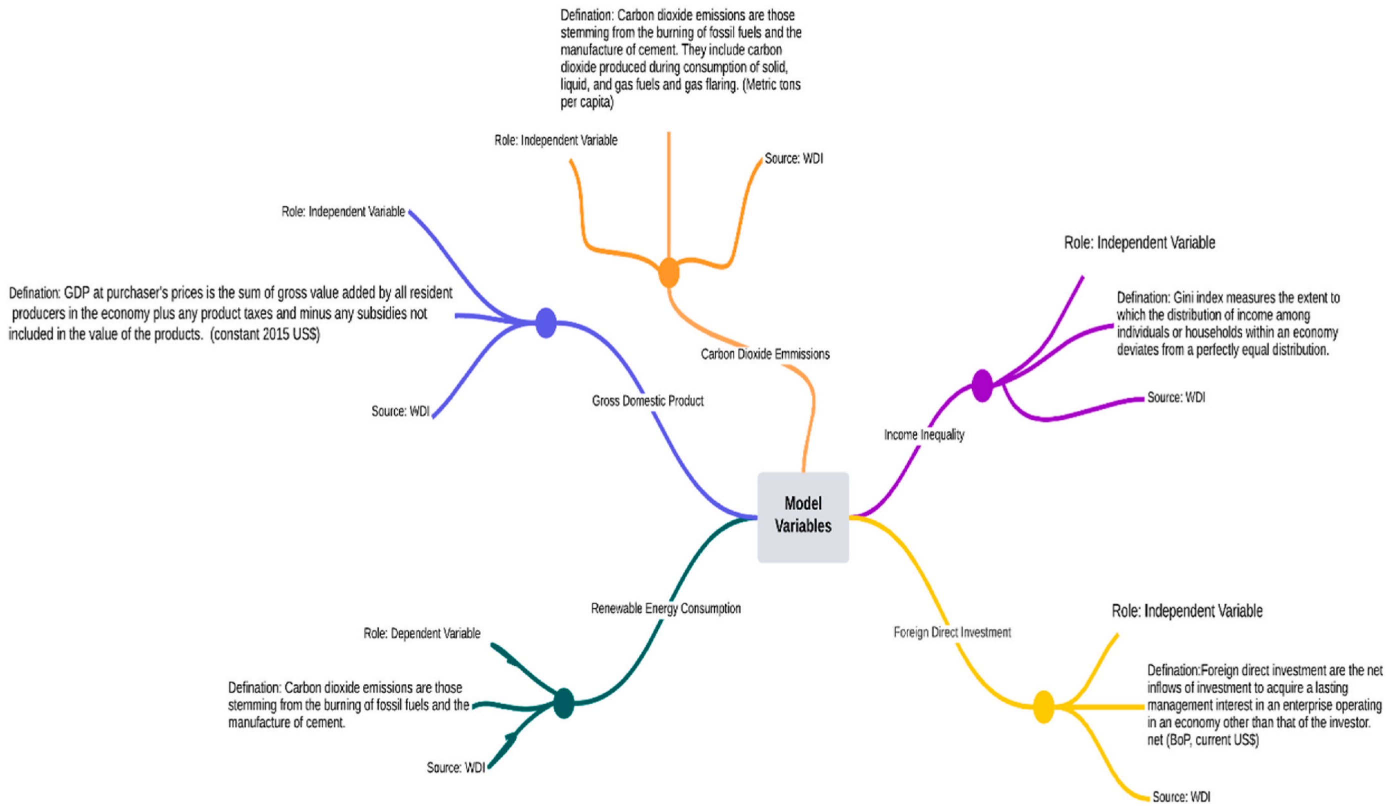

Fig. 6. Shows the model variables, their definitions and source.

3.4. Relevance to the study

The conceptual framework of this study is directly informed by the theoretical basis of modernization theory and the EKC hypothesis. In the context of this study, modernization theory explains the importance of FDI and GDP in encouraging renewable energy adoption and technological improvement in Asia. The EKC hypothesis elucidates the correlation between CO2 emissions, economic growth, and adoption of renewable energy, highlighting the need for policies that accelerate the shift to cleaner energy sources. This study connects modernization theory and the EKC hypothesis by examining how economic growth, technological advancement, and policy measures may mitigate environmental degradation and foster renewable energy development.

4. Methodology and data collection

4.1. Model specifications and conceptual framework

Our research shows the impact of FDI, GDP, income inequality, and CO2 emissions on Renewable energy consumption in 36 Asian countries from to 1995–2020. These countries were selected for analysis based on the availability of pertinent data during the designated period. A comprehensive description of each variable used in this study is presented in Table 2. Guided by modernization theory and the Environmental Kuznets curve hypothesis, the framework combines economic, social, and environmental elements to analyze their collective and individual impacts on REC. The model specification in this study employs panel data econometric techniques, including panel cointegration to capture long-run relationships, cross-sectional dependence (CSD) tests to account for interdependence among countries, and quantile regression to uncover heterogeneous effects across different levels of REC.

Based on a review of the literature and theories, our study uses a primary model that analyzes the relationship between FDI, GDP, II, CO2 emissions, and REC.

$$\mathrm{REC} = \mathrm{f}\ (\mathrm{GDP}, \mathrm{II}, \mathrm{CO2E}, \mathrm{FDI}) \qquad \text{Equation 1}$$

$$\mathrm{logREC}_{it} = \alpha + \beta 1\mathrm{logGDP}_{it} + \beta 2\mathrm{logII}_{it} + \beta 3\mathrm{logCO2E}_{it} + \beta 4\mathrm{logFDI}_{it} + \varepsilon \qquad \text{Equation 2}$$

Here, REC represents renewable energy consumption; GDP is gross domestic product, which is a proxy for economic growth, CO2E carbon dioxide emissions; FDI, foreign direct investment; and II, income inequality. *i* denotes the nation, and *t* signifies time.

This study utilized panel data to analyze all selected variables. Full and short names of variables are mentioned in Table 2, the unit of measurement is also written, and the data source is from where we collected data on countries, as mentioned earlier, for analysis. The basic idea for this study was taken from the work of [16,20,114,115], who used cross-sectional dependence and slope heterogeneity in their study for the first time while researching OECD countries [114]. uses quantile regression to examine the impact of hydropower energy in Malaysia under the EKC hypothesis. The same analysis was performed in our study. Therefore, we use quantile regression to obtain robust results for Asian countries. When we use panel data, the first-generation unit test fails. For this reason, second-generation unit tests were applied. For CSD, three types of tests are used, i.e., Pesaran scaled LM analysis, breach-pagan LM analysis, and Pesaran CD analysis. Cointegration and quantile regression at 0.25,0.50,0.75, and 0.95 are calculated.

4.2. Sample size

The sample size for this study was Asia and sub-divisions of Asia, that is, Southeast Asia, Eastern Asia, Central Asia, Southern Asia, and Western Asia. A list of countries in all these regions is provided in table below. In total, 46 countries were located in all five regions. Initially, we selected 46 Asian countries, but after collecting data, we realized that some countries lacked specified data for our variables, so we concluded

Table 2
Explanation of the variables.

S#	Variables	Type of Variable	Abbreviation	Definition and unit of measure	Source
1	Renewable Energy Consumption	Dependent Variable	REC	Renewable energy consumption is the share of renewable energy in total final energy consumption. (% of total final energy consumption)	WDI
2	Gross Domestic Product	Independent Variable	GDP	GDP at purchaser's prices is the sum of gross value added by all resident producers in the economy plus any product taxes and minus any subsidies not included in the value of the products. (constant 2015 US$)	WDI
3	Carbon dioxide Emissions	Independent Variable	CO2E	Carbon dioxide emissions are those stemming from the burning of fossil fuels and the manufacture of cement. They include carbon dioxide produced during consumption of solid, liquid, and gas fuels and gas flaring. (Metric tons per capita)	WDI
4	Foreign Direct Investment	Independent Variable	FDI	Foreign direct investments are the net inflows of investment to acquire a lasting management interest in an enterprise operating in an economy other than the investor's. Net (BoP, current US$)	WDI
5	Income Inequality	Independent Variable	II	The Gini index measures the extent to which the income distribution among individuals or households within an economy deviates from a perfectly equal distribution.	WDI

with 36 countries from 1995 to 2020. The highlighted nations were excluded from this study. Table 3 presents the names of the sample nations.

4.3. Econometric approaches

4.3.1. Pre-estimation analysis

A comprehensive pre-estimation study was performed to guarantee the robustness and reliability of the findings, focusing on the essential assumptions and features of the panel data. Given that REC and its determinants are affected by many socioeconomic and environmental variables, it is crucial to assess the appropriateness of the data for panel analysis. The growing interconnections across countries require a thorough analysis of cross-sectional dependencies (CSD) in the panel data framework. Such dependencies, often arising from unobserved standard shocks, considerably affect the models' residuals and variables [116]. Owing to interdependencies across 36 Asian countries, it is essential to evaluate cross-sectional connections accurately. This analysis is vital for maintaining the accuracy and objectivity of the results and for facilitating informed decisions for appropriate unit root and cointegration analyses. Neglecting this analysis undermines the reliability of estimates, resulting in predicted errors and production of potentially deceptive data [117].

4.3.2. Cross-sectional dependence

Cross-sectional dependency is a significant issue in panel data estimation, and neglecting it may lead to inaccurate and unreliable results. Three separate analyses were used to assess cross-country dependency within the 36 Asian countries: the Breusch-Pagan Legendre test, Pesaran scaled LM test, bias-corrected scaled LM test, and Pesaran CD test. The Pesaran CD test effectively assesses cross-sectional dependency in panel data when serial correlations and heteroscedasticity coexist.

$$LM = T\sum_{i-1}^{N-1}\sum_{j=i+1}^{N}\widehat{\rho_{ij}^{2}} \qquad \text{Equation 3}$$

Pesaran's scaled LM test is calculated by using Equation (3).

Table 3
Shows a list of countries in our sample.

Southern Asia (09)				
India	Pakistan	Bangladesh	Iran	Afghanistan
Nepal	Sri Lanka	Bhutan	Maldives	
Eastern Asia (04)				
China	Japan	Korea	Mongolia	
South-eastern Asia (11)				
Indonesia	Philippines	Vietnam	Thailand	Myanmar
Malaysia	Cambodia	Laos	Singapore	Timor-Leste
Brunei				
Western Asia (17)				
Turkey	Iraq	Saudi Arabia	Yemen	Syria
Jordan	Azerbaijan	United Arab Emirates	Israel	Cyprus
Lebanon	Oman	Kuwait	Georgia	Armenia
Qatar	Bahrain			
Central Asia (05)				
Uzbekistan	Kazakhstan	Tajikistan	Kyrgyzstan	Turkmenistan

$$CD_{(lm)} = \sqrt{\frac{1}{N(N-1)}}\left(\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\left(T_{\hat{\rho}_{ij}^{2}}-1\right)\right) \quad \text{Equation 4}$$

Equation (4) calculates Pasaran's CD test,

$$CD = \sqrt{\frac{2T}{N(N-1)}}\left(\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\left(\widehat{\rho_{ij}}\right)\right) \quad \text{Equation 5}$$

In Equation (5), T denotes the temporal scope of the study period, while N indicates the number of cross-sectional units under study, namely the chosen 36 countries. where ρ denotes the correlation coefficient. In the CSD test, the null hypothesis states that there is no cross-sectional dependence, whereas the alternative hypothesis indicates the presence of cross-sectional dependence.

4.3.3. Examination of stationarity

Before conducting a cointegration analysis and model estimation, it is essential to determine the variables' stationarity characteristics and integration orders using unit root analysis. Traditional panel unit root statistics, predicted based on cross-sectional independence and homogeneity assumptions, exhibit size bias and control property issues, potentially leading to skewed and inaccurate outcomes. This study employed innovative second-generation stationarity tests, as proposed in Ref. [118], to address this problem. Standard augmented Dickey-Fuller (ADF) regressions enhance prior panel unit root evaluations [118] using cross-sectional averages of lagged values for both explanatory and dependent variables alongside the initial difference of each cross-sectional entity. This innovative approach produces the cross-sectional augmented Dickey-Fuller(CADF) statistic for analytical applications by asymptotically removing the effects of CSD and typical latent dynamics. The following equation presents the statistics concept:

$$\Delta y_{it} = \alpha_i + \beta_i y_{i,t-1} + \theta_i \bar{y}_{t-1} + \gamma_i \Delta\bar{y}_t + \varepsilon_{it} \quad \text{Equation 6}$$

The primary difference estimator is denoted by the symbol Δ, with variable y_{it} being the subject of the study in the panel dataset. The symbol α_i denotes the individual constant and εit denotes the residual component. Additionally, the estimates of the latent variable and the first difference, represented as Δyt and y_{t-1}, respectively, are computed as cross-sectional averages for each unit of analysis. Equation (6) delineates the formulation of the cross-sectionally augmented IPS(CIPS) test developed using the CADF approach.

$$\text{CIPS} = \frac{1}{N}\sum_{i=1}^{N} t_i\,(\text{N},\text{T}) \quad \text{Equation 7}$$

In Equations (6) and (7), the term ti(N, T) represents the test statistic derived from the OLS regression for the ith cross-sectional unit. The null hypotheses for both tests assess the presence of a uniform unit root. By contrast, the alternative hypothesis posits the stationarity of the variables.

4.3.4. Panel cointegration test

Cointegration is assessed using Westerlund's (2007) cointegration test, a specific version of the generic cointegration test. The analysis involves two steps: stationarity and cointegration tests. This technique may help analyze and predict the long-term influence of economic systems owing to its insight into their dynamics. The cointegration tests developed by Ref. [119] rank cointegration based on the number of cointegrating vectors connecting variables.

$$E[y\_t^2] - (1-b)E[y\_t] + C = 0 \quad \text{Equation 8}$$

$$E[y\_t^3] - (2-b)E[y\_t^2] + 3(1-b)E[y\_t] + C = 0 \quad \text{Equation 9}$$

$$E[y\_t^4] - (3-b)E[y\_t^3] + 4(2-b)E[y\_t^2] + 3(1-b)E[y\_t] + C = 0 \quad \text{Equation 10}$$

In the above equations,y_t^2 represents the squared deviation between the observed values and the initial cointegrating relationship, and E[y_t^2] and E[y_t^4] denote expectations and variables, respectively.

4.3.5. Quantile regression

Quantile regression relies on the minimization of weighted absolute deviations, referred to as the L_1 approach, to estimate conditional quantile functions [120,121]. Symmetric weights are used for the median (quantile = 0.50), whereas asymmetric weights are applied for all other quantiles, for example, 0.1–0.9. Conversely, the conventional OLS regression, referred to as the L_2 approach, estimates conditional mean functions. In contrast to OLS, quantile regression is not confined to elucidating the mean of a dependent variable. It can be used to explain the factors influencing the dependent variable at any position within its distribution. Quantile regression enables statistical analysis of how REC is affected by all independent variables in different quantiles.

Quantile regression extends the notion of an unconditional quantile to a quantile that depends on one or more factors. Least squares minimize the aggregate of the squared residuals,

$$min_{\{b_j\}_{j=0}^{k}}\sum_i\left(y_i - \sum_{j=0}^{k} b_j x_{j,i}\right)^2 \quad \text{Equation 11}$$

where y represents the dependent variable at observation i, x denotes the jth regressor variable at observation i, and b_j represents the jth regression coefficient estimate of the model. In contrast, quantile regression minimizes the weighted sum of absolute deviations.

$$min_{\{b_j\}_{j=0}^{k}}\sum_i\left|y_i - \sum_{j=0}^{k} b_j x_{j,i}\right| h_i \quad \text{Equation 12}$$

Where weight hi is defined as

$H_i = 2 - 2q$

Suppose that the residual for the ith observation is non-positive. Variable (0<q < 1) represents the quantile to be estimated or predicted.

4.3.6. Dumitrescu-Hurlin (D-H) panel causality test

The analysis of long-term correlations and probable cointegration among the variables suggests the possibility of causal relationships in at least one direction. Acknowledging that the long-run estimators used in this study do not indicate the directionality of short-term causal links among the variables is essential. To address this restriction, our work uses the non-causality test developed by [122].

This analysis considered both short-run dynamics (CSD) and cross-sectional heterogeneity. It is an advanced methodology for the non-causality hypothesis proposed by Refs. [123,124], and is designed to analyze heterogeneous panels with invariant coefficients. The Dumitrescu and Hurlin test computes statistics by averaging the individual Wald statistics derived from Granger's non-causality test throughout the panel. Their linear model posits a uniform null hypothesis, indicating the absence of causation and presumes no causal relationships among the variables for all entities in the panel.

$$\text{Logy}_{i,t} = \alpha_i + \sum_{k=1}^{k} \lambda i^k\, logy_{i,t-k} + \sum_{k=1}^{k} \beta i^k\, logx_{i,t-k} + \varepsilon_{i,t} \quad \text{Equation 13}$$

where $\beta_i = (\beta_i 1, \beta_i 2, \beta_i k)$ and $\beta_i 1k$ represents the slope coefficient, λi^k which represents the response variable lag parameter. A balanced panel framework assumes constant lag duration k. Additionally, α_i reflects steady individual impacts over time.

5. Empirical results & interpretation

5.1. Descriptive statistics

This descriptive analysis offers the first comprehension of the dataset used to examine the factors influencing REC in Asian countries. Table 4 and Fig. 7 present the logarithmic values of the main variables. The mean REC (1.654) indicates modest adoption levels, ranging from −4.605 to 4.461, highlighting significant disparities in renewable energy consumption across nations. Economic performance, measured by GDP, exhibits considerable diversity, with a mean of 25.045 and values ranging from 0 to 30.313, showing financial inequalities between industrialized and developing countries. FDI has significant variability, with a mean of 16.743 and high standard deviation of 7.959, indicating disparities in investment inflows across countries. Income inequality remained largely steady; nonetheless, its limited range(-2.453 to −1.489) indicates ongoing socioeconomic gaps affecting access to renewable resources. Ultimately, CO2 emissions show significant diversity (mean 1.030, range −2.902 to 3.864), with elevated emissions mostly seen in highly industrialized countries, highlighting the need for focused mitigation strategies.

5.2. Cross-section dependence results

This study used the Breusch-Pagan LM test, Pesaran scaled LM test, bias-corrected scaled LM test, and Pesaran CD test to analyze cross-sectional dependency in the data. Table 5 and Fig. 8 show the CD findings. The results of the cross-sectional dependency tests provide substantial evidence of interdependence among the variables across countries. All variables exhibit significant findings in the Breusch-Pagan LM, Pesaran scaled LM, and Bias-corrected scaled LM tests, suggesting cross-sectional dependency. The Pesaran CD test is statistically significant for all variables, indicating that countries' economic, social, and environmental characteristics are interrelated rather than independent, possibly owing to regional trade, investment flows, and common environmental laws. These findings highlight the need to consider cross-sectional dependency in econometric analyses to prevent biased estimates and enhance the validity of the results.

5.3. Unit root results

Analyzing panel data requires determining whether the variables are stationary or non-stationary. Variable non-stationarity may lead to inaccurate regression findings, statistical inferences, and faulty policy implications. Panel unit root analysis was used to determine the unit roots of the variables.

Table 6 and Fig. 9 show the common augmented Dickey-Fuller (CADF) and cross-sectionally augmented IPS (CIPS) panel unit root test results. The results of the CIPS and CADF tests demonstrate the stationarity of the variables examined in this study. At this level, most variables exhibit nonstationarity because their test statistics fail to surpass the necessary threshold for stationarity. At the first difference, all variables exhibit stationarity, as shown by significant test statistics with $p < 0.05$ or $p < 0.01$, establishing that the variables are integrated of order one, I(1). These results confirm the appropriateness of panel cointegration methods for examining the long-term correlations between the REC and its drivers. The tests confirm that the data satisfies the requisite criteria for rigorous econometric analysis, circumventing spurious regression problems.

Table 4
Descriptive analysis (Author's calculation).

Variable	M	SD	Minimum	Maximum
logREC	1.654097	2.176495	−4.60517	4.461531
logGDP	25.0458	3.59653	0	30.313317
logFDI	16.74329	7.958995	0	26.27733
logII	−1.960196	0.2207659	−2.453408	−1.488549
logCO2E	1.030751	1.404217	−2.902848	3.864029

5.4. Panel cointegration test

This study used Westerlund's cointegration analysis, a statistical method that examines the temporal relationship between two or more variables. It is often used in econometric analysis to ascertain whether two or more variables exhibit a steady relationship with one another. The test determines the presence of evidence of cointegration among variables. The results of Westerlund's test for cointegration provide inconclusive evidence of cointegration among the variables, as shown in Table 7 and Fig. 10. At the group level, the Gt and Ga statistics do not reject the null hypothesis of no cointegration, suggesting little evidence of cointegration among the individual countries. Nonetheless, at the panel level, the Pt statistic is significant ($p = 0.001$), indicating the existence of cointegration when analyzing the panel collectively. Pa statistics are negligible, offering no compelling evidence of global cointegration. As the results are significant, we further examine the log-run relationships using quantile and robustness regressions.

5.5. Quantile regression

Next, we need to perform further estimations of the long-term associations between variables. For this, we applied quantile regression to our dataset. Quantile regression facilitates the examination of how the association between independent variables and the dependent variable fluctuates throughout various quantiles of the distribution of the dependent variable. This study used quantile regression at the 0.25, 0.50, 0.75 and 0.95 quantiles to analyze the factors influencing REC across different levels of energy utilization.

The findings indicate that GDP continuously positively and statistically significantly influences REC across all quantiles. However, the effect diminishes at higher quantiles, from 0.0864 at 0.25 0.0653 0.95. This suggests that economic development significantly affects renewable energy adoption in countries with less renewable energy use. Income inequality exerts a substantial positive influence at the lower quantiles. However, it becomes negligible at higher quantiles, indicating that inequality may promote renewable energy adoption in lower consumption scenarios, but not in advanced phases of renewable energy transitions. CO2 emissions exert a consistently negative and substantial influence across all quantiles, indicating that increased emissions deter renewable energy usage, irrespective of the consumption level. Ultimately, FDI is positively significant at the 0.50 and 0.75 quantiles while negligible at the 0.25 and 0.50 quantiles, indicating that FDI has a more pronounced impact on enhancing renewable energy consumption in middle-tier countries.

These results (Table 8 and Fig. 11) highlight the variability in the factors influencing renewable energy consumption, with the impacts of GDP, income inequality, CO2 emissions, and FDI differing markedly across the various levels of renewable energy consumption. This underscores the need for customized policies that consider different countries with varied economic and environmental circumstances.

5.6. Robustness regression

We also performed a robustness regression to confirm the results of the quantile regression. The findings of this analysis (Table 9 and Fig. 12) reveal a strong correlation between REC and its determinants. The coefficient for GDP (0.0901433, $p = 0.000$) indicates a positive and statistically significant influence of economic growth on REC. comparable to the quantile regression findings, which similarly demonstrated uniformly positive impacts across all quantiles. Likewise. II(1.081247) has a substantial beneficial influence, notably corroborating the quantile regression results at lower quantiles, where II has a large impact. The

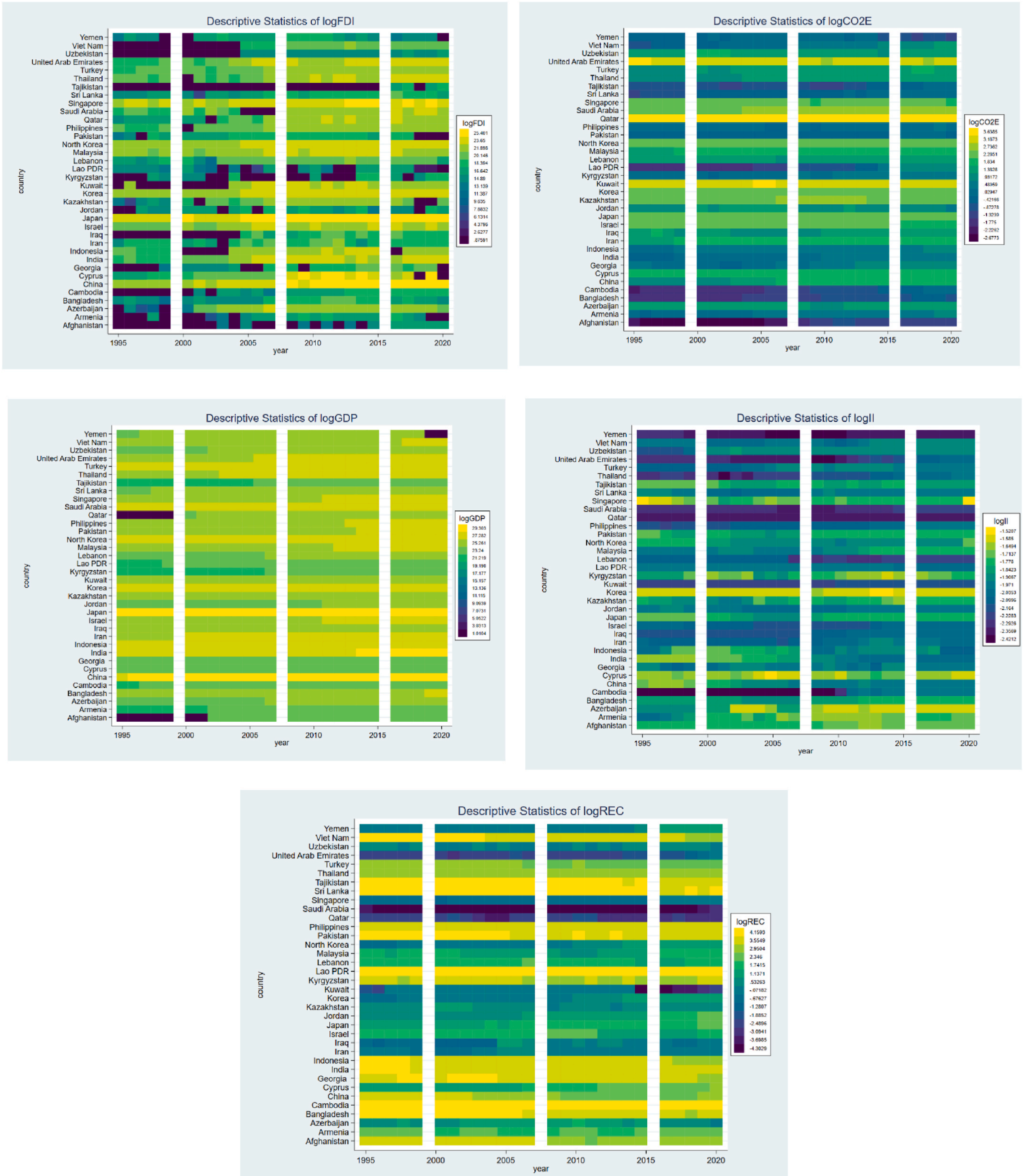

Fig. 7. Heatmap of descriptive statistics of all variables (Author's calculation).

correlation of CO2E is negative and highly significant, indicating that increased CO2E correlates with decreased renewable energy uptake. This conclusion supports the quantile regression findings, consistently demonstrating a negative connection across all the quantiles. Finally, the coefficient for FDI indicates a favorable influence of FDI on REC, supporting the quantile regression findings for the median quantiles (0.50, 0.75) when FDI exhibited substantial impacts.

Table 5
Cross-section dependence test (Author's calculation).

	logREC		logGDP		logFDI		logII		logCO2E	
	Statistic	Prob.	Statistic	Prob.	Statistic	Prob.	Statistic	Prob.	Statistic	Prob.
Breusch-Pagan LM	5382.346	0.0000	13998.54	0.0000	3910.735	0.0000	4536.548	0.0000	7586.586	0.0000
Pesaran scaled LM	133.8822	0.0000	376.6160	0.0000	92.42424	0.0000	110.0545	0.0000	195.9796	0.0000
Bias-corrected scaled LM	133.1622	0.0000	375.8960	0.0000	91.70424	0.0000	109.3345	0.0000	195.2596	0.0000
Pesaran CD	2.002616	0.0452	111.4971	0.0000	46.90416	0.0000	13.08031	0.0000	18.80570	0.0000

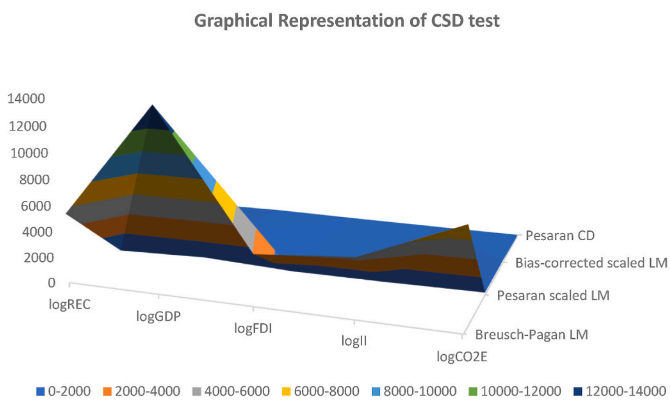

Fig. 8. Shows the graphical representation of CSD tests.

Table 6
Shows results of CIPS and CADF unit root analysis (Author's calculation).

	CIPS		CADF	
	Level	Difference	Level	Difference
logREC	−0.872*	−4.248*	−1.000	−2.861*
logGDP	−2.851	−3.261*	−1.887	−2.678*
logII	−1.421***	−3.540*	−1.667	−2.980*
logCO2E	−1.991***	−4.314*	−1.891	−2.913*
logFDI	−3.479*	−5.577*	−2.890*	−4.502*

Note: H_0 is the unit root, and *,**, and *** indicate P-values at 0.1, 0.05, and 0.01, respectively.

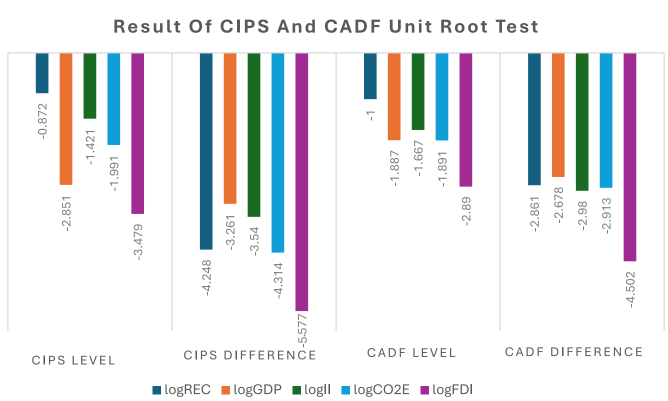

Fig. 9. Graphical representation of unit root test results.

5.7. Dumitrescu-Hurlin (D-H) panel causality test results

The Dumitrescu-Hurlin (D-H) panel causality test was used to investigate the directional relationships between the variables. This test evaluates the predictive capacity of one variable over another. The findings in Table 10 demonstrate bidirectional causation between REC and GDP, suggesting that REC and GDP mutually enhance each other. Fig. 13 shows a graphical representation of the causality relationships between the variables. The dotted line indicates a bidirectional relationship, whereas the straight line indicates a unidirectional relationship.

Table 7
Westerlund's cointegration analysis (Author's calculation).

Statistic	Value	Z-value	P-value	Robust P-value
Gt	−1.465	2.996	0.999	0.450
Ga	−1.023	7.472	1.000	1.000
Pt	−13.890	−3.307	0.001	0.080
Pa	−1.598	3.706	1.000	0.380

Note: H_o denotes cointegration.

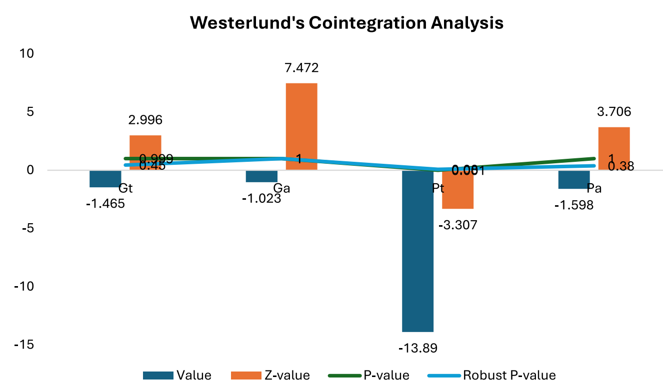

Fig. 10. Graphical representation of Westerlund's cointegration analysis.

6. Discussion and conclusion

6.1. Discussion

The findings validate H1, which asserts that increased income inequality correlates with elevated REC, especially in countries with low-to-moderate REC levels [35]. At elevated REC levels, income inequity diminishes or becomes negative, indicating that fair access to renewable energy is necessary for an advanced energy transition [125]. Similarly, H2 is robustly sustained because economic development exhibits a persistent positive correlation with REC, underscoring the significance of financial capability in fostering investments in renewable energy infrastructure [10,126]. The bidirectional causation between GDP and REC underscores the reciprocal advantages of adopting renewable energy, promoting economic development, and highlighting green growth dynamics.

The results corroborate H3, demonstrating that FDI substantially enhances REC, especially in countries with moderate energy adoption levels, where foreign investments are pivotal in facilitating knowledge transfer and financing clean energy initiatives [94]. The bidirectional correlation between FDI and REC indicates that renewable energy markets draw further investment and establish a self-reinforcing loop. Additionally, the findings for H4 correspond with the predictions, suggesting that increased CO2 emissions adversely affect REC, highlighting the significance of renewable energy in alleviating environmental

Table 8
Quantile regression results at 0.25, 0.50, 0.75, and 0.95 (Author's calculation).

Variable	0.25		0.50		0.75		0.95	
	coefficient	P value	coefficient	P value	coefficient	P value	coefficient	P value
logGDP	0.0864	0.000	0.1136	0.000	0.0987	0.000	0.0653	0.000
logII	1.7930	0.000	1.2615	0.000	0.1979	0.303	−0.21976	0.166
logCO2E	−1.2837	0.000	−1.2879	0.000	−1.0820	0.000	−0.8980	0.000
logFDI	0.00453	0.656	0.0240	0.003	0.01342	0.031	−0.002670	0.602

Note: LogREC is the dependent variable.

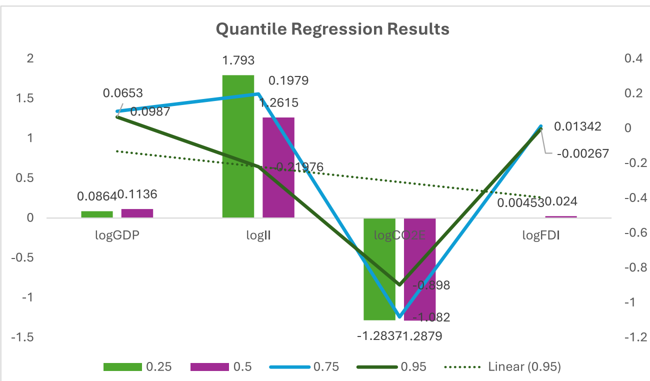

Fig. 11. Graphical representation of quantile regression result with a 0.95 % trendline.

Table 9
Results of robustness regression (Author's calculation).

Variables	Coefficient	Std.Error	T value	P > ItI
logGDP	0.0901433	0.0123501	7.30	0.000
logII	1.081247	0.1830688	5.91	0.000
logCO2E	−1.242448	0.0325221	−38.20	0.000
logFDI	0.0227208	0.0059048	3.85	0.000

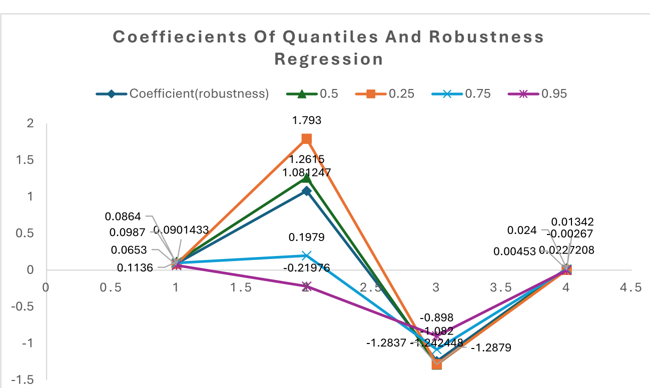

Fig. 12. Graphical representation of coefficients of all variables of quantile and robustness regression.

deterioration [85]. The existence of bidirectional causation between REC and CO2E underscores a feedback loop in which renewable energy mitigates emissions, whereas elevated emissions stimulate governmental incentives for adopting renewable sources.

The results are reinforced by panel cointegration tests, which validate the long-term correlations across variables, and quantile regression, which emphasizes the diverse impacts across REC levels. These findings provide a strong empirical validation for the hypotheses and emphasize the need for customized policies that consider each country's economic,

Table 10
Dumitrescu-Hurlin (D-H) panel causality test results.

Variables	logREC	logGDP	logII	logFDI	logCO2E
logREC	–	2.7644	4.2956	1.7111	3.2560
		7.4859	13.9821	3.0168	9.5714
		0.000	0.0000	0.0026	0.0000
logGDP	3.4836	–	3.4034	3.9484	5.0126
	10.5372		10.1966	12.5089	17.0239
	0.0000		0.0000	0.0000	0.0000
logII	3.3233	3.8680	–	1.7088	4.6193
	9.8568	12.1677		3.0071	15.3554
	0.0000	0.0000		0.0026	0.0000
logFDI	1.6555	1.3528	4.0117	–	1.8096
	2.7810	1.4967	12.7775		3.4349
	0.0054	0.1345	0.0000		0.0006
logCO2E	2.5719	3.6695	3.6542	2.6740	–
	6.6690	11.3257	11.2609	7.1023	
	0.0000	0.0000	0.0000	0.0000	

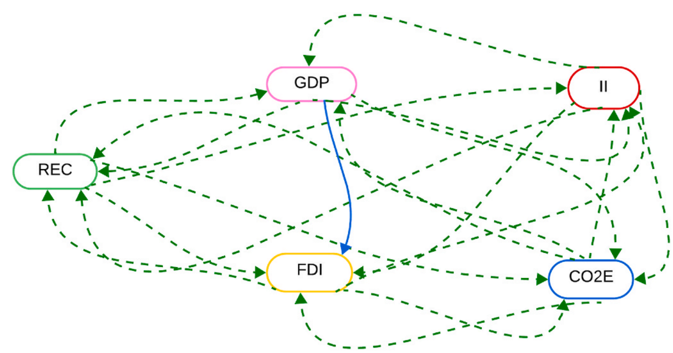

Fig. 13. Causal relationship between variables.

social, and environmental characteristics while fostering regional cooperation.

6.2. Conclusion

This study examined the impact of GDP, income inequality, FDI, and CO2 emissions on renewable energy consumption in 36 Asian countries from 1995 to 2020. According to the environmental Kuznets curve hypothesis and modernization theory, the results indicate that economic development positively affects renewable energy consumption, reinforcing the notion that as countries advance, they invest more in cleaner energy sources. Research indicates that FDI is a crucial catalyst for renewable energy transitions, emphasizing the significance of globalization and technology transfer in facilitating energy transitions in underdeveloped and emerging countries. The EKC theory is further substantiated by the inverse correlation between CO2 emissions and REC, suggesting that increased emissions prompt policy transitions towards renewable energy, while using renewable energy actively mitigates emissions. These results corroborate modernization theory by illustrating that economic progress and foreign investments stimulate technical innovation, facilitating greener energy use.

This research underscores the complex interplay between income inequality and REC. This indicates that inequality may promote renewable energy adoption in low-consumption scenarios, while obstructing it at elevated levels when fair energy access is essential. This discovery incorporates a social aspect of modernization theory by demonstrating how socioeconomic inequalities affect energy transitions. The validation of bidirectional relations between REC and their primary causes highlights the interdependence of economic, environmental, and social factors, stressing the reciprocal enhancement of renewable energy adoption and sustainable development. The enduring co-integration across variables confirms the theoretical framework, indicating that persistent investments in renewable energy may yield lasting economic and environmental advantages. These findings require customized, region-specific policies corresponding to sustainable development goals, especially SDG7 (affordable and clean energy) and SDG 13 (climate action), to expedite energy transitions across Asia.

6.3. Policy implications

This study has considerable implications for policymaking, practice, research, and sustainable development goals regarding renewable energy transition in 36 Asian countries. The results underscore the need for customized policies that foster economic development, attract foreign direct investment, diminish CO2 emissions, and mitigate income inequality to expedite the implementation of renewable energy. Governments may use these findings to formulate region-specific actions including providing subsidies for clean energy technology, implementing carbon pricing systems, and establishing investment-friendly settings. The findings provide practical recommendations for enterprises, investors, and energy professionals, highlighting the need to synchronize financial and technical assets with the national energy objectives. This study enhances the understanding of the socioeconomic and environmental determinants affecting renewable energy consumption, establishing a basis for further research to investigate policy-specific impacts, technical advancements, and sectoral dynamics. This study endorses Sustainable Development Goals 7 and 13 by delineating strategies to promote renewable energy adoption and mitigate carbon emissions, aiding global initiatives for a more sustainable and inclusive energy future.

6.4. Limitations

This study offers substantial insights into the factors influencing renewable energy consumption across Asian countries, although it has major limitations. Initially, it depended on data from the World Development Indicators (WDI), which may inadequately include policy-specific factors such as renewable energy subsidies, carbon taxes, or regulatory frameworks, thus possibly neglecting the essential drivers of REC. Second, the research fails to explicitly include technical developments such as green technology inventions and renewable energy patents, which are critical catalysts for energy shifts. The research emphasizes aggregate national statistics, potentially obscuring sector-specific disparities in renewable energy adoption (e.g., industrial vs. residential sectors).

6.5. Future research directions

Future studies should rectify these shortcomings by integrating policy-specific and technological elements to provide a more thorough understanding of the REC. Investigating the impacts of recent policy innovations may provide significant insights into current developments. Furthermore, disaggregated assessments at the sectoral level may elucidate the contributions of various economic sectors to renewable energy transitions or their advantages. Future research might broaden the temporal framework to include more current data, reflecting the dynamic environment of renewable energy among global problems, such as climate change and economic upheavals. Furthermore, structural equation modeling (SEM) or machine learning methods may reveal intricate linkages and causal pathways. Comparative analyses across countries including Asia, Africa, and Latin America may provide a global perspective on renewable energy transitions and facilitate cross-regional policy learning.

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Credit author statement

Ali: Contributed to the conception and design of the study, coordinated the data collection process, performed the initial data analysis, and played a significant role in drafting and revising the manuscript.

Liu: Responsible for the acquisition of data, contributed to the interpretation of the data, assisted in drafting the manuscript, and provided critical revisions for important intellectual content.

Mehmood: Contributed to the design of the study, development of the questionnaire, data analysis and interpretation, and also contributed to drafting and revising the manuscript.

Khan: Provided substantial contributions to the conception of the study, interpretation of the data, played a key role in revising the manuscript critically for important intellectual content, and approved the final version to be published.

Judit: Responsible for the finalization of original documents, proofreading, supervision, and contributed to the revisions of the manuscript.

Declaration of competing interest

We declare it is an original work, and not under consideration elsewhere. We also declare no potential conflict of interest herein.

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Data availability

Data will be made available on request.

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