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Does clean energy and technological innovation matter for economic growth? An Asian countries perspective

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A B S T R A C T

In recent years, Asian countries have invested heavily in renewable energy technologies as a means of fulfilling energy demand while reducing carbon emissions. This study focuses on the relationship between clean energy, technological innovation, and economic growth in Asian countries. The study analyzes panel data for 38 Asian countries from 1990 to 2021, utilizing several statistical models such as the second-generation unit root test, Westerlund co-integration test, and AMG regression model. Based on empirical findings, the study suggest a positive and significant relationship between clean energy consumption, technological innovation, and economic growth. Additionally, financial development was found to have a positive impact on economic growth, while population size and CO2 emissions had negative impacts. The study emphasizes that promotion of clean energy and technological innovation is essential for achieving sustainable economic growth in Asia while reducing carbon emissions and improving the environment for future generations.

1. Introduction

The rapid economic growth in Asia has led to a surge in energy demand, making the region one of the largest emitters of greenhouse gases globally. There is a growing recognition that renewable energy technologies offer a sustainable and cost-effective way to meet this demand while reducing carbon emissions. In recent years, countries in Asia have been investing heavily in renewable energy technologies, driving innovation, and generating economic growth. According to the International Energy Agency (IEA), the Asia Pacific region is expected to account for the largest share of renewable energy capacity growth in the world over the next five years, with China and India leading the way. As the demand for clean energy continues to rise, Asia is poised to become a major player in this emerging sector, driving innovation and economic growth in the region. On the other hand, green economic recovery is one of the main priorities in addressing the climate crisis and has a significant impact on society (Holden, 2016). Whereas "green" development considers both

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environmental conservation and economic growth. It can be defined as when the environment is protected, economic growth increases, and material resources for environmental conservation are provided (Adams, 2019). The eco-economic development model is an economic development model based on the ecological environment's capability and resource carrying capacity to achieve resource preservation, ecological acceptability, environmental preservation, and product safety. Green development is an evolutionary process that involves adjustments in all three sectors: economic, societal, and the natural environment (Shahbaz et al., 2019). A central aspect of green development is the transformation of the economic growth structure, which involves a shift from unsustainable, resource-intensive growth to a focus on environmental sustainability (Siddiqui and Qamar, 2019).

The Paris Agreement and the European Green Deal provide comprehensive visions for achieving this goal, based on energy efficiency and the increased use of renewable energy sources. By 2050, Asian countries will be striving to achieve sustainable economic growth and development (Sison, 2013). Because of its past achievements, Asia is on the verge of a historic shift into the future. It is predicated on the idea that Asian economies may continue to grow for another 40 years while adjusting to the rapidly changing global technology and economic landscape. In this regard, the GDP of Asian countries would rise from $17 trillion in 2010 to $174 trillion in 2050, accounting for half of the global GDP, which is comparable to its proportion of the world's population. The efforts made by Asian countries to achieve high incomes would be led by seven economies with a per capita GDP of $40,800. It is assumed that by 2050 they will be comparable to those of today's Europe. Unlike other Asian countries, there are eight impoverished nations with average per capita GDPs below $1000 (Kohli et al., 2011). The Paris Agreement (2015) and the policies of Asian economies will be implemented in part through the State Climate Agreement (Horowitz, 2016). The Climate Agreement sets a goal of a 48 percent reduction in carbon emissions by 2030. The regional energy strategies and municipal environmental mitigation techniques are two further regional initiatives. These initiatives all aim to reduce energy use and produce sustainable energy.

Because many Asian countries are significantly dependent on fossil fuels, which are the primary source of energy used (Al-Mulali et al., 2016; Bilgili et al., 2016; Heal, 2009; and Forsberg, 2009). The dependence on fossil fuels is one of the main contributing factors to the strong positive correlation between energy use and efficiency (Al-Mulali et al., 2016). Switching to renewable energy sources could decouple energy usage from economic development and reduce the use of fossil fuels, improving the environment. The trade sector's reliance on fossil fuels also imposes additional environmental costs, such as species extinction, depletion of natural resources, and ecosystem contamination (Baloch et al., 2019). Moreover, the Asian farm-to-fork strategy calls for a sustainable agricultural sector and a significant move away from fossil fuels. Because many Asian countries aim to become carbon neutral by 2050 with the introduction of the Green Deals (Hale et al., 2021). However, non-renewable energy still has a significant share in overall consumption, with fossil fuels accounting for 70% and renewable energy accounting for only 6.3% (Majeed and Luni, 2019). Thus, understanding the use of clean energy in Asian countries is crucial for achieving these goals and creating the necessary regulations. The importance of clean energy and technological innovation in promoting sustainable economic growth is widely recognized, there is a dearth of research that has specifically examined the effects of these factors on economic growth in the context of Asia. This is particularly relevant given the rapid economic growth of Asian countries and the increasing demand for energy in the region, which has significant implications for global greenhouse gas emissions and climate change. Therefore, understanding the impact of clean energy and technological innovation on economic growth can provide valuable insights into how countries can achieve sustainable economic development and address the pressing issue of climate change.

The remainder of the study is organized as follows: The first section provides a brief introduction; Section 2 provides scholarly studies conducted in areas of growth such as renewable energy, technological innovation, and other dimensions of economic growth and provides a summary of the findings. Section 3 provides the theoretical and conceptual framework. Section 4 discusses the methodology and data used to achieve the study's objectives. Section 5 contains the empirical analysis and discussion of the results. Section 6 summarizes the study findings and policy suggestions.

2. Literature review

Numerous studies have examined the relationship between clean energy, technology innovation, and economic growth, producing mixed results. Some studies suggest that the adoption of clean energy technologies can lead to economic growth, while others argue that the cost of transitioning to cleaner energy sources may hamper economic growth.

For instance, a study by Wang and Li (2020) found that clean energy technology innovation can lead to economic growth by increasing productivity and promoting sustainable development. Similarly, a study by Cai et al. (2020) found that investment in clean energy can have positive effects on economic growth, especially in the long run. However, other studies have found that the transition to clean energy may have short-term costs that could potentially offset long-term benefits. For example, a study by Green and Stern (2017) argues that the transition to clean energy may initially require significant investments that could have negative effects on economic growth. In addition, the finding is consistent in the case of other developed countries. For instance, Oliveira and Moutinho (2021) examined the impact of renewable energy on economic growth in Portugal and found that an increase in renewable energy consumption has a positive effect on economic growth, as well as promoting energy security and reducing greenhouse gas emissions. A recent study such as Zhang and Dilanchiev (2022) examined the relationship between financial stability, industrial structure, and resource utilization efficiency, and examines the impact of these factors on green economic recovery. The study uses the entropy weight technique and the coupling coordination degree assessment method to analyze data from 2005 to

2020 in China. The results show that although there is a link between industrial structure and resource efficiency, it is not as significant as expected. Natural resource utilization efficiency improves because of economic advancement, and investment and financial sector redistribution can be used to invest scarce resources in sectors with greater efficiency and economic performance. The study also finds that foreign direct investment has a greater impact on natural resource use efficiency than government investment behavior. Wang et al. (2022d) examined the impact of environmental regulation on the development of a green economy through green technology innovation. The study focuses on the effect of new regional environmental regulations and their different types on the emergence of new initiatives. It also investigates the influence of economic growth on environmental regulation in 29 developing countries with strong environmental policies. The findings suggest that new environmental regulations positively affect low levels of economic development and grey knowledge generation. The study also reveals that stricter environmental regulations negatively impact the start-up of new businesses, particularly in the fossil fuel industry.

The other dimensions of innovation, growth, and clean energy have been explored in the various literature. For instance, a study by Salim and Shafiei (2014) looked at the impact of renewable energy consumption and technological innovation on economic growth in the context of the Asia-Pacific Economic Cooperation (APEC) countries. The results suggested that renewable energy consumption has a positive impact on economic growth, while technological innovation can amplify the positive effects of renewable energy consumption. Another study by Apergis and Danuletiu (2014) examined the impact of renewable energy consumption on economic growth and found a positive relationship, especially in the long run. The authors suggest that promoting the use of renewable energy can be an effective way to promote sustainable economic growth. The recent study by Li et al. (2022) explores the impact of financial inclusion on renewable energy demand in China. The study finds that improved financial inclusion can promote renewable energy development in China and presents characteristics of green finance. The impact of financial inclusion on renewable energy demand is asymmetric and heterogeneous, with higher impact in northern China and regions with higher renewable energy development. Wind and photovoltaic power generation are effective mediators between financial inclusion and renewable energy industry. The study suggests that fiscal and tax incentives, as well as green investment subsidies, need to be further improved to increase renewable energy consumption. Whereas Shahbaz et al. (2022) investigates the impact of fiscal decentralization on renewable energy demand in China. Using quarterly data from 1980 to 2018 and considering factors such as income inequality, economic growth, urbanization, and economic globalization, the study finds that fiscal decentralization has a positive impact on renewable energy demand. The study also reveals that economic growth and urbanization contribute to the increased use of renewable energy, while income inequality is negatively linked to renewable energy consumption. The authors suggest that fiscal decentralization can be used as an effective tool for developing long-term energy policies aimed at increasing the use of renewable energy sources. The study's findings can help policymakers and practitioners in China and other countries formulate more effective energy policies aimed at reducing dependence on non-renewable energy sources. The study conducted by Wang et al. (2021) aims to investigate the impact of renewable energy on reducing carbon dioxide emissions in 25 countries along the Belt and Road Initiative from 2005 to 2019. The study uses the Generalized Divisia Index Method to decompose the effect of renewable energy on CO2 emissions and to explore the decoupling relationship. The study finds that the growth of renewable energy scale is the primary driving force for promoting CO2 emissions, while carbon intensity of renewable energy inhibits CO2 emissions. The study also suggests that the increase in the proportion of renewable energy has a higher carbon mitigation effect than technological improvements. Finally, the study highlights that carbon efficiency is essential for reducing CO2 emissions in the future. Similarly, Dong et al. (2020) examined the impact of renewable energy consumption on carbon dioxide emissions, focusing on the differences across countries with different income levels. The analysis is based on a global panel of 120 countries and four subpanels over the period 1995–2015, using econometric techniques to address cross-sectional dependence and slope heterogeneity. The study finds that the environmental Kuznets curve hypothesis is valid for the global panel, high-income subpanel, and upper-middle-income subpanel. However, the effect of renewable energy consumption on CO2 emissions is not significant, possibly due to higher economic growth and increasing non-renewable energy consumption, and there exist significant differences in the effect of renewable energy consumption on CO2 emissions across the different income-based subpanels.

In the context of southeast Asian countries, Wang et al. (2022a) examined the impact of renewable energy consumption and technological innovation on economic growth in ASEAN countries. The results suggest that renewable energy consumption and technological innovation can have positive effects on economic growth in the region, while also reducing carbon emissions and promoting sustainable development. Another study by Bhattacharya et al. (2016) explored the relationship between renewable energy consumption and economic growth in Asian countries. The results suggest that renewable energy consumption can have positive effects on economic growth, while also reducing carbon emissions and promoting energy security. Furthermore, a study by Jiang et al. (2022) examined the impact of renewable energy policies on economic growth in Asia-Pacific Economic Cooperation (APEC) countries. The results suggest that policies promoting the adoption of renewable energy technologies can have positive effects on economic growth, while also promoting energy security and reducing environmental impacts. In addition, a study by Miao et al. (2022) explored the impact of technological innovation on energy consumption and economic growth in China. The results suggest that technological innovation in clean energy technologies can help to reduce energy consumption and promote economic growth, while also reducing environmental impacts. In addition, a study by Zhang et al. (2021) explored the relationship between technological innovation and carbon emissions reduction in fastest growing country such as China. The results suggest that innovation in clean technologies can help to reduce carbon emissions, while promoting economic growth.

Furthermore, a study by Lin et al. (2021) investigated the relationship between clean energy consumption and economic growth in the Belt and Road Initiative (BRI) countries. The authors found that the adoption of clean energy technologies can help to promote economic growth in these countries, while also reducing greenhouse gas emissions and promoting sustainable development. Acaravci and Ozturk (2010) explored the relationship between renewable energy consumption, CO2 emissions, and economic growth for a panel of 15 European countries. The authors found that an increase in renewable energy consumption has a positive effect on economic growth and can help to reduce carbon emissions. Similarly, Yeng et al. (2022) looked at the impact of China's clean energy policies on economic growth and found that these policies have led to significant economic benefits, including job creation, and increased economic competitiveness. Tavoni et al. (2012) explored the impact of technological innovation on the transition to a low-carbon economy in the European Union. The results suggest that technological innovation can be a key driver of the transition to a low-carbon economy, and that policies promoting innovation in clean technologies can have significant economic benefits. The study by Batool et al. (2022) aimed to explore energy poverty in rural areas of Pakistan and to determine the best renewable energy choice for such areas. The authors found that energy poverty exposed residents to various problems such as health dangers, fire accidents, time poverty, financial poverty, and illiteracy. Solar energy was identified as the best renewable energy source for Pakistan in terms of pricing, life duration, operation, and maintenance costs. The study also identified key barriers that continue to promote energy poverty in rural areas of the country. Usman et al. (2019) examined the impact of renewable energy policies on economic growth in India. The authors found that the adoption of renewable energy technologies has the potential to create jobs, increase energy security, and promote economic growth, especially in rural areas. Whereas Malla (2022) explored the relationship between renewable energy consumption and economic growth in Nepal. The results suggest that increasing the use of renewable energy can have positive effects on economic growth, while also promoting sustainable development and reducing greenhouse gas emissions.

Furthermore, a study by Islam and Islam (2021) examined the impact of technological innovation on energy consumption and economic growth in Bangladesh. The results suggest that technological innovation can help to reduce energy consumption and promote economic growth, while also reducing environmental impacts. In addition, a study by Uddin Ahmed et al. (2019) explored the relationship between clean energy consumption and economic growth in Pakistan. The authors found that the adoption of clean energy technologies can have positive effects on economic growth, while also reducing carbon emissions and promoting sustainable development. Kirikkaleli et al. (2022) examined the relationship between financial development, renewable energy consumption, economic growth, and electricity consumption on CO2 emissions in Chile using various econometric techniques. The study finds that financial development and renewable energy consumption have a negative impact on CO2 emissions, while economic growth and electricity consumption increase CO2 emissions.

Overall, the literature suggests that the relationship between clean energy, technology innovation, and economic growth is complex and multifaceted. While some studies suggest that promoting the adoption of clean energy and innovation in clean technologies can lead to economic growth and other benefits, other studies highlight the potential costs and challenges associated with the transition to a low-carbon economy. Further research is needed to fully understand this relationship and to inform policy decisions in clean energy and economic development particularly in Asian regions.

2.1. Research gap

Despite the growing recognition that renewable energy technologies offer a sustainable and cost-effective way to meet energy demands while reducing carbon emissions, there is a lack of comprehensive studies on the impact of clean energy and technological innovation on economic growth in Asian countries. The existing literature primarily focuses on the developed countries' experiences, while some studies have focused on the relationship between renewable energy and economic growth, they tend to be limited to a single country or region, ignoring the heterogeneity of Asian economies. Moreover, there is a need to understand how technological innovation in the renewable energy sector affects economic growth in Asia. Therefore, this study aims to fill this research gap by investigating the relationship between clean energy, technological innovation, and economic growth in a sample of Asian countries.

3. Theoretical and conceptual framework

The relationship between technological innovation, renewable energy consumption, and economic growth can be understood through different theoretical perspectives. One such perspective is the ecological modernization theory, which posits that modern industrialized societies can address environmental challenges by adopting sustainable practices. According to Huber et al. (2000), this can be achieved through technological innovation and by embracing clean energy alternatives. However, natural resources are finite, and the rapid expansion of production and consumption is depleting them while also causing environmental damage. The treadmill of production theory argues that economic growth and natural resource exploitation are the main causes of environmental degradation. Despite this, both ecological modernization theory and endogenous growth theory suggest that technology breakthroughs can promote sustainable economic growth while preserving the environment. As societies transition from traditional to industrial bases, they tend to increase energy consumption and urban infrastructure, which can harm the environment. However, as they become wealthier, they can adopt clean technologies, implement stronger environmental regulations, and undertake structural reforms to improve their relationship with the environment. Therefore, their study suggests a null hypothesis that.

Ho: There is no effect of environmental sustainability on economic growth.

3.1. Technological innovation-renewable energy and environment

The process of technology transfer and innovation in response to environmental concerns depends on the phase and era of the invention. During the industrialization period of the 1960s, non-renewable energy sources like coal and oil-fired plants were heavily relied upon for input consumption. However, there is now a growing need for more ecologically friendly technology to address contemporary environmental issues. Implementing radical, environmentally sustainable technologies often requires lengthy development cycles, specialized infrastructure, and institutional changes. Policymakers have increasingly recognized the relationship between technological change and environmental policy, with renewable energy sources replacing non-renewable energy in many industrialized countries by the late 1990s. Nevertheless, emerging nations still heavily rely on non-renewable energy, making the shift to renewable energy a pressing issue. The literature on technical innovation and renewable energy outlines various processes through which these factors can enhance environmental quality.

3.1.1. Technological innovation and economic growth

Technological advancement and the creation of new knowledge are significant drivers of economic growth (Mankiw et al., 1992). They are critical in ensuring that the transition to ecologically sustainable development occurs at the lowest possible cost to the economy. Increasing the amount of these components of production boosts economic output by increasing the labor force or developing equipment and constructing eco-friendly infrastructure. Furthermore, technical advancements and improvements in the quality of these production elements boost productivity and output. Technical advancement and the gathering and applying of knowledge (i.e., Patents or Trademarks) enable new investment and improved methods of integrating the various inputs of production to generate output. Recent investigations, on the other hand, have come to different results. International technology spillovers (Technical Grants), for example, may cause a country to invest less in environmental R&D (since it profits from R&D undertaken by others — reducing duplication and allowing investment elsewhere), resulting in an overall gain in innovation. Gerlagh (2008) discovers that when investment levels climb, knowledge accumulation switches from energy production to energy conservation technologies, implying a higher degree of technical change per unit of expenditure. Carraro et al. (2009a) and Carraro et al. (2009b) examine climate policy and show that investing in energy-related R&D does not crowd out investments in other sectors, nor does it result in a decline in the level of human capital. Therefore, their study suggests a null hypothesis that:

Ho: There is no effect of technological innovation on economic growth

3.1.2. Renewable energy consumption and economic growth

Majeed and Luni (2019) list various advantages of renewable energy, including its lack of pollutant emissions, reduction of environmental damage through substitution effects, absence of depletion of resources, and production of dynamic effects through economies of scale and spillover effects. Renewable energy can also prevent thermal pollution. However, some researchers claim that renewable energy can harm the environment by increasing the ecological footprint and relying on limited water and land resources (Al-Mulali et al., 2016). Additionally, the intermittent of renewable energy output and lack of appropriate storage technologies can require the support of fossil fuels for large-scale peak energy generation (Heal, 2009; Forsberg, 2009). Despite these challenges, technological innovation along with renewable energy consumption can reduce environmental degradation and the risk of increasing costs derived from the restriction on economic growth (Majeed and Luni, 2019). Summarizing the above theoretical model Fig. 3.1, it is concluded that using technological innovation along with renewable energy consumption reduces environmental degradation and the risk of increasing costs derived from the restriction on economic growth. Therefore, their study suggests a null hypothesis that:

Ho: There is no effect of renewable energy consumption on economic growth

4. Data and methodology

4.1. Data

The data for this study were collected from world bank Indicator (WDI) and International Energy Agency (IEA) and Global footprint network (GFN). The panel consist of the 38 Asian countries, (based on availability of data series) covering the period from 1990 to 2021. The study used panel data, which provides a comprehensive way to analyze changes in variables over time and across countries. The panel data consisted of real GDP growth, number of total patents in country registered by resident and non-residents, renewable energy consumption percentage of total energy, foreign direct investment, domestic credit to private sector (% of GDP) as a proxy of financial development CO^2 emission and Population size. The abbreviation and complete definition of these variables with corresponding data source are reported in Table 4.1.

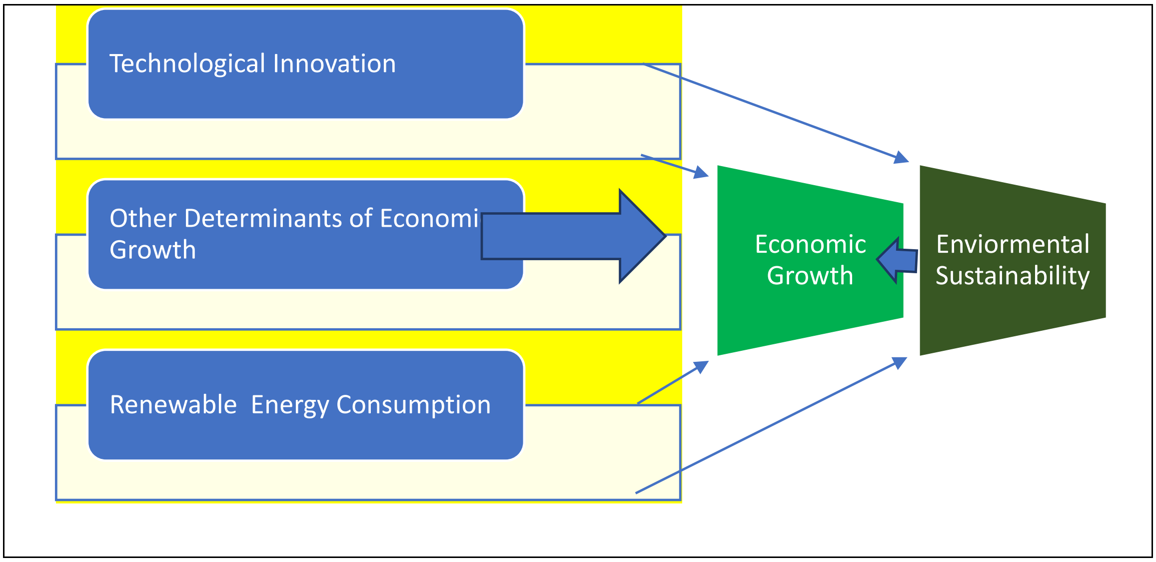

Fig. 3.1. Theoretical and conceptual framework.
Source: Author's own.

Table 4.1
Variable definitions and data sources.

Variables	Definition	Units	
CO^2	CO^2 emissions (kt)	In Million	WDI
RE	Renewable energy % Total Energy consumption	Percentage	EIA
TECH	Total number of Patents (residents + Non-residents)	Numbers	WDI
RGDP	GDP (measured at constant 2015 US Dollar)	Million	WDI
FD	Financial development, domestic credit to private sector (% of GDP)	Percentage	WDI
FDI	Foreign direct investment, net inflows (% of GDP)	Percentage	WDI
POP	Population Size	People (In million)	WDI

4.2. Cross-section dependence test

Before conducting empirical estimations, it is necessary to examine the cross-sectional dependency (CSD) among the variables. This is important as variables in the dataset may impact each other due to unobserved common shocks and externalities, whether positive or negative, in cross-country and panel analyses. The strength of the CSD can be weak or strong but ignoring it can result in generating inconsistent and insufficient standard errors of parameters.

4.3. Panel unit root tests

When cross-dependency exists, it is crucial to use second-generation unit root tests as they provide robust coefficients and solve the issue of CSD and heterogeneity. This study utilizes the cross-sectionally augmented Dickey–Fuller (CADF) and cross-sectionally augmented Im, Pesaran, and Shin (CIPS) stationary tests with an intercept, intercept, and trend, as proposed by Pesaran (2007).

4.4. Econometric model specification

The main aim of this article is to explore how technological advancements and the adoption of clean energy impact the economic development of Asia. The ecological footprint is used as a comprehensive measure of environmental harm. Through a thorough analysis of existing literature, it has been determined that the variables in question play a significant role in promoting sustainable growth in Asian nations. Based on these findings, it is evident that several Asian countries possess substantial potential for clean and sustainable energy sources and are embracing new technologies to promote all-inclusive progress. Taking all these factors into account, we can present an econometric model for selected variables as shown in Eq. (1).

$$RGDP = f\,(FD, TECH, RE, FDI, POP, CO2) \tag{1}$$

In the given equation, Y represents actual economic growth, FD represents financial development, TECH represents technological advancement, RE represent renewable energy consumption, FDI represent the foreign direct investment, POP represent the population size and CO2 emission represent the environmental quality. To reduce heteroscedasticity and improve data precision, we have utilized the natural logarithm process for the selected variables. As a result, our model has been transformed into a log-linear format, which is shown in Eq. (2) as follows:

$$lnRGDP_{j_t} = d_t + \beta_i lnFD + \beta_i lnTECH + \beta_i lnRE + \beta_i lnFDI + \beta_i lnPOP + \beta_i ln\mathrm{CO2} + u_{it} \quad (2)$$

In the given equation, the intercept term is represented by the symbol 'c', while the slope parameters are represented by the symbol β_i. The variables included in the equation are $lnFD$, $lnTECH$, $lnRE$, $lnFDI$, $lnPOP$ and $ln\mathrm{CO}$, all of which are presented in logarithmic form with the corresponding slope parameters. Additionally, the equation includes a stochastic error term represented by the symbol u_{it}.

4.4.1. Panel cointegration test

To tackle the problem of common correlated effects in panel data, Westerlund (2007) introduced the error correction model (ECM) that relies on a structural dynamic cointegration test. This test employs two group test statistics, Gt and Ga, and two panel test statistics, Pt and Pa. The formula for this test is presented in Eq. (3) below:

$$\Delta y_{j_t} = \delta^1 d_t + \psi_i \left(y_{it-1} - \beta_i' x_{it-1}\right) + \sum_{j=i}^{p_i} \psi_{ij} \Delta y_{j_{t-j}} + \sum_{j=i}^{p_i} \gamma_{ij} \Delta x_{it-j} + u_{it} \quad (3)$$

The adjustment speed of the system as it corrects back to a stable state is represented by the symbol ψ_i. The four test statistics, namely Gt, Ga, Pt, and Pa, are calculated using Eqs. (4) and (5), which are presented below:

$$G_t = \frac{1}{N} \sum_{i=1} \frac{\psi_i}{SE(\hat{\psi}_i)} \quad (4)$$

$$G_a = \frac{1}{N} \sum_{i=1} \frac{T\psi_i}{\hat{\psi}_i(1)} \quad (5)$$

Whereas the panel cointegration test statistics is estimated by Eqs. (6) and (7) as:

$$P_t = \frac{1}{N} \sum_{i=1} \frac{\hat{\psi}_i}{SE(\hat{\psi}_i)} \quad (6)$$

$$P_a = T\hat{\psi}. \quad (7)$$

4.4.2. Augmented Mean Group estimator (AMG)

According to Wang and Dong (2019), traditional panel data methods are inadequate in addressing the problem of common correlated effects and slope heterogeneity among panels, whereas the second-generation panel estimation techniques are better equipped to handle these issues. In the presence of common correlated effects, this study has employed the augmented mean group (AMG) estimation method, which is more suitable for addressing such issues across cross sections. The AMG approach is also capable of handling common correlated effects by using the common dynamic effect coefficient. Additionally, Wang and Dong (2019) have suggested a constrained two-stage AMG approach, in which the first stage of the AMG estimator is represented by Eq. (8) below:

$$\Delta y_{j_t} = \delta_t + \beta_i \Delta x_{it} + \pi_i f_t + \sum_{t=n}^{t} \psi_{ij} \Delta D_t + u_{it} \quad (8)$$

While the second stage of AMG estimator is reported in Eq. (9) as follows.

$$\hat{\beta}_{AMG} = N^{-1} \sum_{i=1}^{N} \hat{\beta}_i \quad (9)$$

The given equation includes several elements, including the constant term represented by "δ_i" the observables represented by "y_{j_t}" and "x_{j_t}", the common latent component with heterogeneous factor represented by 'f_t', the initial difference operator represented by 'Δ', the dummy coefficient related to time dimensions represented by "ψ_{ij}", the AMG group mean estimators represented by "$\hat{\beta}_{AMG}$", and the contemporaneous error expression represented by "u_{it}".

Table 5.1
Descriptive statistics.

Variable	Obs	Mean	Std. Dev.	Min	Max
Real GDP	1178	709 100	1 627 000	1739	14 300 000
FDI % GDP	1178	3.7%	5.9%	37.1%	55%
Population size	1178	162.5	336.7	0.40663	1408
Total patents	1178	44 155	152 023	3	1 542 002
Patent by non-residents	1178	21%	14%	33%	10%
Patent by residents	1178	79%	88%	33%	90%
Renewable energy % overall energy	1178	19%	22.1%	0.1%	94.1%
CO^2 emission	1178	0.5375	1.415	0.0006	10.70
Credit % GDP	1178	70.9%	48.7%	7.4%	252.4%

Author estimates: Data source: WDI, EIA

4.4.3. Error Correction Model (ECM) for short-run elasticity estimates

This article aims to estimate the short-run coefficients/elasticity of real economic growth variables with respect to regressors such as *lnFD, lnRE, lnTECH, ln FDI, lnPOPand ln*CO^2. To achieve this goal, we have utilized the error correction model (ECM), which has been previously used by scholars such as Hossain (2011), Khalid et al. (2021), and Usman et al. (2020b). The formula for the ECM is presented in Equation 10 below:

$$\Delta RGDP_{j_t} = \delta_i + \beta_i \Delta LnFD_{it} + \beta_i \Delta LnRE_{it} + \beta_i \Delta LnTECH_{it} + \beta_i \Delta LnFDI_{it} + \beta_i \Delta LnPOP_{it} + \beta_i \Delta lnCO2_{it} + \Omega_i ECM_{it-1} + u_{it}$$

The given equation involves several parameters, including the short-term coefficients represented by "β_i" the ECM parameter represented by "Ω_i", which indicates the annual movement from short-run to long-run speed of adjustment, and the stochastic error term represented by "u_{it}".

5. Results and discussion

5.1. Descriptive statistics

Table 5.1 presents the descriptive statistics for key variables in our study of renewable energy consumption and technological innovation in Asian countries. We find that the average share of renewable energy sources is 19%, with a standard deviation of 22%. This indicates significant variation in renewable energy consumption among Asian countries, ranging from a low of 0.1% to a high of 94%. Meanwhile, the panel's average number of registered patents is 44 thousand, with a standard deviation of 152 thousand. These findings demonstrate that many Asian countries are making significant strides in technological advancement. Our analysis also reveals an interesting pattern in patent registration, with an average of 79% of patents being registered by locals compared to 21% by non-residents. This suggests that domestic innovation is a key driver of technological progress in the region. Turning to economic indicators, we find that the average real GDP is $709 100 million, with a standard deviation of $1 627 000 million. This points to wide variations in economic output among Asian countries, with some economies significantly outpacing others in terms of size and productivity. However, foreign investment as a percentage of GDP is relatively low, with a mean of 3.7% and a standard deviation of 5.9%. This indicates that foreign capital inflows do not play a major role in Asian economic development. Population size also varies greatly among Asian countries, with an average of 162.5 million and a standard deviation of 336.7 million. This highlights the diverse demographic profiles of the countries in the region. Our analysis of carbon emissions shows an average of 0.5375 million, with a standard deviation of 1.415 million. These findings reveal significant variation in environmental impact among Asian countries, with some emitting much more carbon than others. Finally, our examination of financial development indicates an average of 70.9%, with a standard deviation of 48.7%. This suggests that financial sector development in Asian countries varies widely, with some countries having well-established financial systems while other countries are lagging behind.

5.2. Multicollinearity analysis

The presence of multicollinearity can lead to a high degree of correlation between variables, which in turn may increase the variance of the estimated parameters. Such collinearity can result in biased information about the coefficients and unreliable forecasts. Therefore, detecting multicollinearity is essential to reveal the relationship between the variables. To detect this problem, we used the variance inflation factor (VIF) method, as shown in Table 5.2. The VIF measures the increase in variance of the estimated coefficients as the correlation between variables increases. A high VIF value indicates a greater likelihood of collinearity among variables. In energy-technological innovation and growth nexus research, where variables are highly interrelated, it is crucial to ensure that there is no multicollinearity. A VIF value exceeding 5 indicates that the variable is too influential and should be dropped. In our study, all variables, including lnRE, lnFDI, lnTECH, lnPOP, and $lnCO^2$, had VIF values below 5, and the tolerance values were greater than 0.2 for all variables. Therefore, we conclude that these variables are not correlated with each other.

Table 5.2
Variance Inflation Factor (VIF).

Series	Tolerance	VIF
lnRE	0.343	2.663
lnFDI	0.302	3.020
lnTECH	0.452	2.020
lnPOP	0.386	2.356
lnCO^2	0.315	2.891

Author estimates.

Table 5.3
Cross-section dependence test.

Series	Breusch–Pagan LM		Pesaran scaled LM		Bias-corrected scaled LM		Pesaran CD	
	Stats.	Prob.	Stats.	Prob.	Stats.	Prob.	Stats.	Prob.
lnRE	45.51*	0.000	23.93*	0.000	22.89*	0.000	8.875*	0.000
lnFDI	66.32*	0.000	16.22*	0.000	16.67*	0.000	9.48*	0.000
lnTECH	58.89*	0.000	20.21*	0.000	15.20*	0.000	3.40*	0.002
lnPOP	78.03*	0.000	49.28*	0.000	49.17*	0.000	12.81*	0.000
lnCO2	112.71*	0.000	48.67*	0.000	49.40*	0.000	13.31*	0.000
lnRGDP	241.621*	0.000	59.42*	0.000	58.22*	0.000	9.95*	0.000

Author estimates; Note *, ** and *** Indicates 1%, 5%, and 10% level of significance.

Table 5.4
CADF panel unit root test.

Series	Intercept				Intercept and trend			
	Level I (0)		First difference I (1)		Level I (0)		First difference I (1)	
	Statistics	Prob.	Statistics	Prob.	Statistics	Prob.	Statistics	Prob.
lnRE	−1.563	0.290	−4.193*	0.004	−2.021	0.510	−4.382*	0.002
lnFDI	−1.312	0.393	−6.113*	0.000	−2.387	0.166	−6.368*	0.000
lnTECH	−1.305	0.256	−5.121*	0.000	−1.928	0.604	−5.058*	0.003
lnPOP	−1.070	0.868	−4.928*	0.000	−1.582	0.834	−5.477*	0.000
lnCO2	−1.500	0.814	−3.825*	0.001	−2.041	0.490	−7.431*	0.000
lnRGDP	−1.099	0.891	−4.953*	0.000	−2.180	0.346	−5.117*	0.001

Author estimates; Note *, ** and *** Indicates 1%, 5%, and 10% level of significance.

5.3. Cross-section dependence test

In Table 5.3, the results of various CSD tests conducted on both dependent and independent variables are presented. Based on these results, the null hypothesis of no cross-sectional dependency among variables is rejected because their probability values are statistically significant, indicating the presence of CSD among variables. This suggests that a shock occurring in one country may impact another. The confirmation of CSD highlights the need for second-generation approaches such as unit root, cointegration, and long-run estimation.

5.4. Panel unit root

The results of the CADF and CIPS panel unit root tests are presented in Tables 5.4 and 5.5 respectively. According to the CADF unit root test, all variables are non-stationary at the level, but after taking the first difference, they follow a stationary process in both cases (intercept and trend). Similarly, the CIPS unit root test results show that the variables are mixed in being stationary at the level, while all variables follow a stationary process at their first integrated order I(1) with an intercept, intercept, and trend.

5.5. Co-integration test

After testing the cross-section dependence, Unit root test for stationarity of series, and multicollinearity in above sections. The next step in the econometric procedure is to estimate the long-run relationship among variables. However, first-generation cointegration tests are unable to address the issues of heterogeneity and cross-sectional dependency as reported in Table 5.3. In contrast to econometrics constraints, the "Westerlund cointegration test" is more robust as it deals with both issues (İnal et al., 2022; Khalid et al., 2021; and Usman et al., 2020a). To determine whether a long-run co-integration relationship exists in our model, we employed a panel long-run co-integration test. The null hypothesis (Ho) of this test posits the absence of cointegration, while the alternative hypothesis (H_1) validates the presence of cointegration in the Asian growth model. Table 5.6 presents the results of the panel co-integration test for the Growth Model. The

Table 5.5
CIPS panel unit root test.

Series	Intercept				Intercept and trend			
	Level I (0)		First difference I (1)		Level I (0)		First difference I (1)	
	Statistics	Prob.	Statistics	Prob.	Statistics	Prob.	Statistics	Prob.
lnRE	−2.561*	0.001	−5.580*	0.000	−2.991**	0.034	−5.672*	0.000
lnFDI	−1.682	0.176	−5.158*	0.000	−2.176	0.125	−5.118*	0.000
lnTECH	−1.685	0.223	−5.126*	0.000	−1.765	0.228	−5.113*	0.000
lnPOP	−1.480	0.180	−5.486*	0.000	−1.749	0.218	−6.177*	0.000
lnCO2	−1.449	0.197	−5.376*	0.000	−1.811	0.142	−5.449*	0.000
lnRGDP	−2.531*	0.001	−4.608*	0.000	−3.149**	0.023	−4.556*	0.000
Critical values		2.51	2.25	2.12		3.3	2.94	2.76
Significance level		1%	5%	10%		1%	5%	10%

Author estimates; Note *, ** and *** Indicates 1%, 5%, and 10% level of significance.

Table 5.6
Westerlund co-integration test.

Statistics	Values	Z values	P-values	Robust P-values
G_t	−3.322*	−2.351	0.000	0.001
G_a	−11.073*	−0.759	0.627	0.021
P_t	−8.022*	−2.527	0.000	0.003
P_a	−10.872*	−0.169	0.335	0.035

Author estimates; Note *, ** and *** Indicates 1%, 5%, and 10% level of significance.

results of both the group and panel test statistics (G_t, G_a, P_t, and P_a) reject the null hypothesis of no cointegration and accept the alternative hypothesis, establishing the existence of cointegration in our Growth model.

5.6. Augmented Mean Group (AMG) estimators

Asian countries are facing a multitude of challenges, including high population growth, energy demand, high CO^2 emissions, low financial development, slow technological innovation, and weak economic growth. As a result, it is critical to identify the key factors that have a significant impact on economic growth. To this end, we estimate the long-term relationship between renewable energy, technological innovation, and sustainable economic growth in Asia. Table 5.7 presents the long-run AMG estimates, which offer an insightful overview of the effects of financial development, renewable energy, technological innovation, population growth, and CO^2 emissions on economic growth in Asian countries

5.6.1. Long run estimates

In the long run, the slope coefficient of RE indicates that a 1% increase in renewable energy consumption is associated with a 0.239% increase in economic growth in Asia. This positive relationship could be explained by the fact that the use of renewable energy can reduce reliance on fossil fuels and improve the sustainability of the economy, which can lead to higher economic growth in Asia. Our findings are in line with the findings of earlier studies such as Apergis and Danuletiu (2014), Oliveira and Moutinho (2021), Wang and Li (2020), and Cai et al. (2020). They also found investment in clean energy technology can lead to long-term economic growth by increasing productivity, reducing greenhouse gas emissions, and promoting sustainable development. However, the long-run slope coefficient of TECH demonstrates that a 1% increase in technological innovation is associated with a 0.043% increase in economic growth. This positive relationship could be explained by the fact that technological innovation can lead to productivity gains and more efficient use of resources, which can lead to higher economic growth. Our findings are in line with those of earlier studies such as Salim and Shafiei (2014), Wang and Li (2020), and Wang et al. (2022d,a). They found that technological innovation can have a positive effect on economic growth in terms of reducing carbon emissions with environmental regulations such as avoiding the extraction of natural resources and preserving ecology, recycling existing goods, generating grey knowledge, boosting the start-up of new businesses, and promoting sustainable development.

The other control variable, financial development (FD), shows that a 1% increase in FD is associated with a 0.488% increase in economic growth. This positive relationship could be explained by the fact that financial development enables easier access to credit and funding for businesses, which can lead to more investment and economic growth. Our findings are consistent with previous research by Kirikkaleli et al. (2022) and Saqib (2022). They found that financial development can have a positive impact on economic growth through various channels. It can increase investment, promote innovation, encourage entrepreneurship, help individuals and firms better manage risks, and facilitate the efficient allocation of capital and investment. Moreover, other financial intermediaries, such as banks, can play a significant role in promoting economic growth by facilitating the flow of funds from savers to borrowers, leading to increased productivity and output. The long-run slope coefficient of POP shows that a 1% increase in population size is associated with a 0.381% decrease in economic growth. Our finding is consistent with earlier studies such as Simon (2019) and Sasaki and Hoshida (2017).

Table 5.7
AMG for long-run and short-run estimates.

AMG for long-run					
LnRGDP	Coef.	St.Err.	*t*-value	*p*-value	Sig
LnFD	0.488	0.002	2.120	0.034	**
lnPOP	−0.381	0.059	−6.450	0.000	*
LnFDI	0.061	0.006	10.020	0.000	*
$\ln CO^2$	−0.588	0.053	−11.170	0.000	*
LnRE	0.239	0.029	8.324	0.000	*
LnTECH	0.043	0.016	2.650	0.008	*
Constant	11.782	0.672	17.530	0.000	*
ECM for short-run					
ECM_{t-1}	−0.460	0.117	−3.918	0.001	*
ΔLnFD	0.343	0.203	−1.690	0.091	***
ΔLnPOP	−0.131	0.075	−1.740	0.082	***
ΔLnFDI	0.123	0.230	0.537	0.644	
ΔLnCO2	0.171	0.027	6.380	0.000	*
ΔLnRE	0.002	0.001	1.220	0.222	
ΔLnTECH	0.035	0.006	5.670	0.000	*
Time	0.040	0.003	11.450	0.000	*
Diagnostics test for Robustness	**Test statistics**		**P-values**		
JB Normality test	0.4841		0.8944		
LM Serial correlation	1.608		0.2414		
BPG heteroscedasticity	0.7081		0.3214		
ARCH heteroscedasticity	0.1828		0.71412		
Durbin-Watson stats	1.8216				
CUSUM and CUSUM2 test		Stable			

Author estimates; Note *, ** and *** Indicates 1%, 5%, and 10% level of significance.

This negative relationship could be explained by the fact that a large population may lead to various social and economic issues such as higher demand for resources (i.e., land and water), income poverty, inequality, unemployment, and proper infrastructure, which could strain the economy and lead to lower economic growth. Moreover, the long coefficient of FDI demonstrates that a one percent increase in FDI is associated with a 0.61 percent increase in economic growth. This positive relationship could be explained by the fact that FDI can bring new technologies, capital, and expertise to a country, which can boost economic growth. Our findings are consistent with those of Wang et al. (2022b), and Odhiambo (2022). They found that FDI can increase economic growth by bringing in new capital, technology, and knowledge to the host country, creating jobs, improving trade, and promoting competition and innovation. Lastly, in the long-run, a 1% increase in CO2 emissions is associated with a 0.588% decrease in economic growth. This negative relationship could be explained by the fact that high levels of CO2 emissions can lead to environmental degradation, which can have negative effects on public health, agriculture, and tourism, all of which can hurt economic growth. The findings are consistent with those of Wang et al. (2022c). They argued that the rise in CO2 emissions can harm the environment in terms of overall climate change, which can reduce economic growth by decreasing agricultural productivity, increasing health costs, damaging infrastructure, reducing tourism, and increasing energy costs. Rising temperatures and changes in precipitation patterns can lower agricultural output, while climate-induced extreme weather events can damage infrastructure and property, leading to higher costs for repairs and replacements.

5.6.2. Short-run estimates

The study found that the short-run dynamics results were almost same as the long-run estimates except for statistical insignificance of renewable energy consumption on economic growth. The error correction term estimated ECM with a year lag was found to be negative and highly significant, indicating an equilibrium association among the series. The use of observables allowed for a 46% yearly divergence from the long-run equilibrium and demonstrated a rate of convergence from short-run to long-run equilibrium. The Asian countries would require more than 2 years to achieve 100% long-run equilibrium. The positive but statistically insignificant impact of renewable energy consumption on economic growth could justified as the renewable energy projects often require significant upfront investments, and the benefits may not be immediately realized in the short run. However, in long run, however, investments may start to pay off and have a positive impact on economic growth (Apergis and Danuletiu, 2014; Oliveira and Moutinho, 2021; Wang and Li, 2020; and Cai et al., 2020). Another possibility is that renewable energy is not yet widespread enough to have a significant impact on economic growth in the short run. As more renewable energy projects are developed and implemented, the positive impact on economic growth may become more pronounced. Lastly, to avoid any errors in the estimation, the study performed several diagnostic tests and robustness checks, including the LM serial correlation test and Normality test for the residual term, as well as heteroscedasticity tests. The results show that there is no issue of serial correlation, heteroscedasticity, as well as residual normality. The calculated statistics for these tests were found to be statistically insignificant. To verify the structural stability, the study also used CUSUM and CUSUM squared tests, which indicated stable statistics within critical bounds, demonstrating the consistency of the model's parameters over the selected period.

6. Conclusion and policy recommendation

In recent decades, many Asian countries have taken steps towards eliminating poverty and implementing green policies to achieve economic development. However, it also caused a significant increase in energy consumption, leading to China becoming one of the primary global greenhouse gas emitters. Moreover, there is a growing concern that renewable energy technologies provide a sustainable and cost-efficient means to fulfill this demand while reducing carbon emissions. Consequently, Asian countries have substantially invested in renewable energy technologies in recent years, leading to innovation and economic growth. The study investigates the role of clean energy and technological innovation on economic growth in the context of Asia. Using a panel set of data, the study covers panel data for 38 Asian countries from 1990 to 2021. Moreover, the study employed several statistical techniques, such as the second-generation panel unit root test, the panel cointegration test, and the AMG model for the long- and short-run elasticity of the proposed variable in relation to economic growth. Based on the AMG estimate, the results reveal that there is a positive and significant relationship between renewable energy consumption and economic growth. However, the study discovered a positive and significant relationship between technological innovation and Asian economic growth. The empirical findings exhibit that a 1% increase in renewable energy consumption was associated with a 0.239% increase in economic growth, while a 1% increase in technological innovation led to a 0.043% increase in economic growth. Moreover, the study found that financial development has a positive impact on economic growth, with a 1% increase in FD associated with a 0.488% increase in economic growth. On the other hand, a 1% increase in population size was associated with a 0.381% decrease in economic growth, while a 1% increase in CO2 emissions led to a 0.588% decrease in economic growth. The study's findings were consistent with earlier research on the positive effects of investment in clean energy technology, technological innovation, and financial development, as well as the negative impacts of population size and CO2 emissions on economic growth. Overall, the study concludes the importance of investing in sustainable and innovative technologies and reducing CO2 emissions to promote economic growth in Asia. Based on its findings, the study also provides some policy suggestions in the next section.

6.1. Policy implementation

To implement this policy, there is a need for continued investment in research and development of clean energy technologies and policies that incentivize the adoption of these technologies in the energy sector. Governments can also support the transition to a low-carbon economy by providing funding and subsidies for clean energy projects, as well as offering tax incentives to companies that invest in technological innovation. The private sector can play a crucial role in driving the adoption of clean energy and innovation through investments in research and development and through partnerships with governments to support the implementation of policies and regulations. Furthermore, education and public awareness campaigns can increase awareness of the benefits of clean energy and drive demand for sustainable products and services. The promotion of clean energy and technological innovation is essential for achieving sustainable economic growth and addressing the challenges of climate change in Asia. Continued investment and support for these initiatives will drive innovation and economic growth while reducing carbon emissions and improving the environment for future generations.

6.2. Contribution of study

These findings contribute to the ongoing policy debate on the best strategies for achieving sustainable economic growth in Asia. Policymakers can use the study's results to develop targeted policies that promote clean energy technologies and encourage innovation in the region. The study also highlights the importance of reducing CO^2 emissions to mitigate the adverse impacts of climate change on economic growth. Moreover, the study's use of advanced econometric techniques, such as the panel unit root and cointegration tests, provides a robust framework for analyzing the relationship between clean energy, technological innovation, and economic growth. This methodology can serve as a guide for future studies that investigate the relationship between renewable energy consumption, technological innovation, and economic growth in other regions of the world.

6.3. Limitation and future research recommendation

There are several limitations, such as access to literature and relevant data for many Asian countries. Since there are different regions in Asia that follow different economic and environmental policies in the shape of different economic or trade groups (i.e., SAARC, ASEAN), Therefore, the study is limited to the 38 countries without exhibiting these groups. Thus, it is recommended that future research test the same empirical model for different Asian regions.

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