FOREIGN DIRECT INVESTMENT, TECHNOLOGICAL INNOVATION AND RENEWABLE ENERGY MITIGATING CARBON DIOXIDE EMISSIONS IN MALAYSIA: NEW EVIDENCE FROM ARDL MODEL

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Abstract. Over recent decades, economic expansion in developing nations has exerted growing pressure on environmental systems, emerging as a critical driver of global climate change. However, only a limited number of studies have investigated the synergistic effects of economic growth, foreign direct investment (FDI), technological innovation, and renewable energy on carbon dioxide (CO_2) emissions in Malaysia. This study employs the autoregressive distributive lag (ARDL) bound test methodology to examine both the short-term dynamics and long-term equilibrium relationships among Malaysia's economic development, FDI, technological innovation, renewable energy consumption, and CO_2 emissions from 1995 to 2023. The cointegration analysis substantiates an inverted U-shaped relationship between economic growth and CO_2 emissions, providing empirical validation for the Environmental Kuznets Curve (EKC) hypothesis in the studied context. The empirical findings demonstrate that FDI and renewable energy consumption exert significant mitigating effects on CO_2 emissions, whereas technological innovation exhibits an adverse environmental impact during the observed period. The research findings offer several practical insights for policy-making, including setting clear sustainable performance indicators, encouraging the industrial sector to adopt clean technologies and renewable energy sources, introducing advanced foreign technologies and environmental protection enterprises, supporting the advancement of sustainable technologies and optimizing the structure of energy consumption.

Keywords: *environmental Kuznets curve (EKC), sustainable development goals (SDGs), environmental degradation, developing country, causality analysis*

Introduction

Excessive combustion of fossil fuels for energy has significantly contributed to global warming among anthropogenic climate changing factors (Al-Ghussain, 2019). Over recent decades, developing nations have exhibited an accelerating trend in carbon dioxide (CO_2) emissions (Jiang et al., 2019). In addition to economic growth and fossil fuel consumption, factors such as the influx of foreign investment, technological innovation and development, and the utilization of renewable energy sources may also contribute to environmental impact. Particularly in developing countries financial resources and capabilities for mitigating the impacts of climate change are often limited. Consequently, analyzing the interrelationship between economic growth, foreign direct investment (FDI), technological innovation, renewable energy consumption, and CO_2 emissions has

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emerged as a critical research focus, with the ultimate goal of informed policy interventions for sustainable development goals (SDGs) (Mehmood, 2022; Iqbal et al., 2023; Dunyo et al., 2024).

As one of the emerging economies, Malaysia has undergone significant structural reforms and economic transformation, but remains heavily dependent on fossil fuels as its primary energy source (Akhtar et al., 2023). While Malaysia's economy is projected to expand, the anticipated surge in energy demand required to sustain this growth tendency poses substantial environmental challenges. According to the findings of Zoundi (2017), the adverse effect of climate change on economic growth in developing countries is expected to amount to 2% to 4% by the year 2040. Consequently, an expanding body of scholarly work has emerged to examine the applicability of the Environmental Kuznets Curve (EKC) hypothesis to Malaysia's development context, while proposing policy recommendations that simultaneously advance economic growth and environmental sustainability. However, existing EKC literature predominantly examines the nexus between economic growth (Saboori et al., 2012), renewable energy consumption (Gill et al., 2018; Mohamed et al., 2024), urbanization (Awan et al., 2022), population size (Begum et al., 2015) and CO_2 emissions, while lacking comprehensive consideration of critical factors such as FDI and technological innovation.

Despite the extensive research conducted in this area, studies exploring the effects of FDI, technological innovation, and renewable energy on environmental quality under the EKC hypothesis are inadequate. Technological innovation enhances energy efficiency and accelerates the adoption and deployment of renewable energy solutions (Chen et al., 2018). FDI inflows have recently been identified as a key factor in determining environmental quality, given their capacity to exert influence over pollution (Seker et al., 2015). Renewable energy sources can deliver energy services with minimal environmental pollution compared to conventional fossil fuels. Consequently, it is imperative to investigate the relationship between FDI, technological innovation, renewable energy and CO_2 emissions in order to achieve sustainable goals in the long term. The present study seeks to investigate the interrelationships between FDI, technological innovation, renewable energy adoption, and CO_2 emissions within an integrated framework, while empirically testing the EKC hypothesis in the context of Malaysia. Additionally, this research aims to provide valuable insights and actionable policy recommendations that will support Malaysia's SDGs. Firstly, the study assesses time series stationarity using unit root tests, including the augmented Dickey-Fuller (ADF), Dickey-Fuller generalized least squares (DF-GLS), and Ng-Perron procedures. Secondly, this study employs the autoregressive distributed lag (ARDL) bounds testing approach to examine both short-run dynamics and long-run equilibrium relationships between FDI, technological innovation, renewable energy consumption, and CO_2 emissions in Malaysia. Furthermore, the empirical results validate the EKC hypothesis in the Malaysian context. Thirdly, in this study, the robustness tests of the long-term estimation coefficients of the ARDL model are conducted using the cointegration regression methodologies of fully modified least squares (FMOLS), dynamic ordinary least squares (DOLS), and canonical cointegrating regression (CCR) methods. Fourthly, the stability of the model is assessed using LM serial correlation tests, along with the cumulative sum of recursive residuals (CUSUM) and its squared counterpart. Finally, the present research establishes the causal relationship between variables through Granger causality test.

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This study contributes to existing research in the following aspects. First, this study contributes to Malaysia's environmental economics literature by examining the combined impact of FDI, technological innovation, and renewable energy adoption on CO_2 emissions within a unified analytical framework. Second, the empirical results of this study corroborate the presence of a rebound effect between technological innovation and CO_2 emissions in developing economies. This finding underscores that the effect of technological innovation on environmental quality is contingent upon a nation's developmental stage and is inherently dynamic in nature. Last, the study provides actionable policy insights for developing nations pursuing SDG-compatible growth, with specific relevance to middle-income economies undergoing similar energy transitions as Malaysia.

The remaining part of this article is arranged as follows: Section 2 provides an overview of the extant literature related to this study. Section 3 outlines the data sources and methodology that were utilized in the present study. Section 4 presents the results and discussions of the empirical analysis. Section 5 summarizes the conclusions, policy recommendations, limitations and future research directions of this study.

Review of the literature

Evidence of EKC hypothesis in Malaysia

The EKC hypothesis was first formally proposed by Grossman et al. (1991) in their seminal study of trade barriers' environmental impacts. They analyzed the nexus between air quality and economic growth under conditions of reduced trade barriers. Their empirical results demonstrated that the concentration of pollutants in the air will first increase and then decrease in accordance with the continuous growth of per capita GDP. The introduction of the EKC hypothesis has generated substantial academic debate regarding its theoretical foundations and empirical validity. The majority of early scholars refuted the inverted U-shaped relationship between environmental quality indicators and income through academic evidence and empirical research. Ekins (1997) performed a comprehensive analysis of the existing literature that examined the interplay between environmental quality and economic development. The findings of the research highlighted the existence of a monotonically increasing or curvilinear relationship between income and environmental quality indicators. Moomaw et al. (1997) compared the EKC model with the structural transition models using data from 16 industrialized countries from 1950 to 1992 and found that the shift in CO_2 emissions was associated with historical events related to oil price shocks and subsequent policies, rather than to per capita income.

Following the millennium, researchers have increasingly recognized the significant influence of energy consumption on environmental quality, incorporating this factor into empirical tests of the EKC hypothesis. Utilizing the panel vector error correction model, Apergis et al. (2009) examined the causal relationship among CO_2 emissions, energy consumption and output in a sample of six central American countries from 1971 to 2004. The empirical findings revealed that in long-run equilibrium, energy consumption exerts a statistically significant positive effect on emissions, whereas actual output exhibits the characteristic inverted U-shaped relationship posited by the EKC hypothesis. Utilizing time series data from 19 European countries, Acaravci et al. (2010) examined the dynamic interrelationships between CO_2 emissions, energy consumption, and economic growth. The results of the study provided substantial evidence in support of the validity of the

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EKC hypothesis in Denmark and Italy. Saboori et al. (2012) employed the ARDL methodology to examine the validity of the EKC hypothesis in the Malaysian context. Their analysis revealed a consistent inverted U-shaped relationship between CO_2 emissions and GDP across both short-run and long-run horizons, providing further support for the EKC hypothesis. Awan et al. (2022) utilized the quantile autoregressive distributed lag (QARDL) methodology to investigate the combined nonlinear impact of urbanization and economic growth in Malaysia. Their empirical findings indicated an inverted U-shaped relationship between economic growth and CO_2 emissions, but a U-shaped correlation exists between urbanization and CO_2 emissions, hence corroborating the validity of the EKC hypothesis.

However, some scholars have demonstrated through empirical research that the EKC hypothesis lacks validity in Malaysia. utilizing econometric techniques, Begum et al. (2015) analyzed the dynamic effects of GDP growth, energy consumption, and population growth on CO_2 emissions in Malaysia. The findings confirmed that both per capita energy use and per capita GDP exhibit statistically significant long-run positive relationships with per capita emissions. From this, it can be known that the answer to the question of whether the EKC hypothesis is valid in Malaysia remains ambiguous. Consequently, it is necessary to ascertain the validity of the EKC hypothesis through the utilization of contemporary time series data. As previously noted, fossil fuels dominate Malaysia's energy portfolio, currently accounting for over 90% of total energy consumption, while dependence on imported coal for electricity generation continues to escalate (EIA, 2023). Based on the trajectory of Malaysia's economic expansion, it can be inferred that, in the short term, the significant rise in fossil fuel consumption driven by economic growth is likely to result in a deterioration of environmental quality. Concurrently, Malaysia's economic restructuring has precipitated a transition toward service-led growth, with the tertiary sector contributing about 53% of GDP in recent years (World Bank, 2023), signaling a structural shift in the nation's development paradigm (Raihan et al., 2022a). Economic growth propelled by the tertiary sector generates significantly lower environmental deterioration compared to secondary industry-led development, due to reduced energy intensity and material throughput (Muhammad et al., 2022). Consequently, Malaysia's ongoing economic structural transformation is projected to yield progressive environmental quality improvements. In summary, this study posits that as Malaysia's economy continues to expand, the quality of the environment will initially exhibit an upward trend followed by a subsequent decline, which is consistent with the EKC hypothesis.

FDI, technological innovation, renewable energy and CO_2 emissions

In the preceding decade, the academic community has increasingly focused on critical factors that influence CO_2 emissions, including the consumption of renewable energy, FDI, and technological innovation, in order to provide more targeted policy guidance and long-term strategies for the country. Menyah et al. (2010) explored the causal linkages among CO_2 emissions, renewable and nuclear energy consumption, and real GDP in the United States from 1960 to 2007. Employing the stochastic impacts by regression on population, affluence, and technology (STIRPAT) model with OECD country data, Shafiei et al. (2014) analyzed the differential effects of non-renewable and renewable energy consumption on CO_2 emissions. Their empirical results showed that the consumption of non-renewable energy significantly increases CO_2 emissions, while the consumption of renewable energy contributes to CO_2 emissions reductions. Bilgili et al. (2016) used panel datasets from 17 OECD countries between 1977 and 2010 to examine the potential impact of renewable energy consumption on environmental quality. Their research also lends support to the

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hypothesis that the consumption of renewable energy has a negative impact on CO_2 emissions. Electricity generation from renewable sources plays a pivotal role in mitigating environmental degradation by reducing greenhouse gas emissions and minimizing air pollutants in comparison with conventional fossil fuel power production (Raghutla et al., 2023). Moreover, the substitution of traditional energy sources with renewable energy alternatives can lead to a substantial decrease in environmental quality degradation (Pata, 2021). This study posits the hypothesis that, within the Malaysian context, the consumption of renewable energy can assist in the mitigation of CO_2 emissions.

Given the potential of FDI to exert a considerable influence on environmental quality, particularly in developing economies, there has been an increasing interest among scholars in investigating its impact on CO_2 emissions. Zhang et al. (2016) investigated the effects of FDI on China's CO_2 emissions at the national and regional levels using provincial panel data from 1995 to 2010. The research results indicated that FDI plays a role in the reduction of CO_2 emissions, with this impact exhibiting a decrease in magnitude from the western to the eastern and central regions. Using the ARDL model, Hanif et al. (2019) assessed both short-run and long-run impacts of fossil fuel consumption, FDI, and economic growth on CO_2 emissions across 15 developing Asian economies. Their research suggested that FDI is a primary cause of environmental deterioration and will result in a rise in CO_2 emissions in developing countries. In general, the environmental consequences of FDI in developing nations exhibit significant cross-country variation, contingent upon host-country regulatory frameworks and the specific sectoral composition of investment inflows. In response to global climate imperatives, Malaysia has established ambitious decarbonization targets: a 45% reduction in greenhouse gas emission intensity relative to GDP by 2030 through renewable energy deployment, and carbon neutrality by 2050 (Yahoo et al., 2024). Consistent with its sustainable development agenda, the Malaysian government has strategically channeled FDI toward environmentally sustainable sectors, with particular emphasis on green technology innovation and infrastructure development. Foreign investment facilitates carbon emission reduction through the transfer and implementation of cleaner production technologies, enabled by research and development initiatives (Faheem et al., 2022). Therefore, this study hypothesizes that FDI contributes to CO_2 emission reduction in Malaysia.

The relationship between technological innovation and CO_2 emissions has long been a central research focus in environmental economics. Chen et al. (2020) applied a spatial econometric model to study the impact of technology innovations on CO_2 emissions in 96 countries from 1996 to 2018. The empirical results demonstrated that there is a negligible mitigating effect of technological innovation on global CO_2 emissions, and in fact political globalization can promote the impact of such innovation. Utilizing panel quantile regression analysis on balanced data of 35 OECD countries from 1996 to 2015, Cheng et al. (2021) verified that technological innovation exerts a direct mitigating effect on CO_2 emissions. Rafique et al. (2020) analyzed the effect of technological innovation on carbon emissions in BRICS countries using data from 1990 to 2017. Their findings revealed that technological development exhibits a long-term negative correlation with pollution, though its beneficial effects manifest only after a significant time lag. Technological innovation has catalyzed the swift expansion of new technology applications, consequently enhancing energy efficiency and diminishing energy consumption. According to Raihan et al. (2022a), technological development enables a shift from production-based to innovation-based economic models, thereby reducing industrial carbon emissions in the process. Existing literature generally concurs that technological innovation exerts a mitigating effect on

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carbon emissions. Building upon this consensus, the present study hypothesizes an inverse relationship between technological innovation and CO_2 emissions in the Malaysian context.

Recently, scholars have attempted to synthesize and analyze these three significant factors affecting CO_2 emissions in order to explore the connections and relationships between them. Rahman et al. (2022) adopted the panel non-linear autoregressive distributed lag (NARDL) method to investigate the asymmetric dynamics between CO_2 emissions and four key variables: GDP, renewable energy consumption, technological innovation, and export quality. Their findings validated the EKC hypothesis while identifying renewable energy adoption and high-quality exports as significant drivers of CO_2 emission reductions. Adebayo et al. (2023) analyzed the dynamic interrelationships among technological innovation, renewable energy adoption, natural resource utilization, and CO_2 emissions across BRICS nations from 1990 to 2019. The findings demonstrated that technological innovation, renewable energy consumption, and natural resource utilization collectively enhance environmental sustainability in both the short and long term by mitigating carbon dioxide emissions. Based on panel data from 1990 to 2019, Abid et al. (2022) empirically examined the effects of technological innovation, financial development, FDI, energy consumption, and urbanization patterns on carbon emissions in G8 member countries. The results of the research indicated a significant long-term negative correlation between FDI, financial development, technological innovation and CO_2 emissions. Several studies have incorporated these three variables within their analytical models to investigate their impact on carbon dioxide emissions. Kayani et al. (2024) systematically examined the complex relationship between FDI and CO_2 emissions across BRICS nations from 2000 to 2022. Their empirical analysis confirmed that FDI, technological innovation, and renewable energy adoption exerted significant mitigating effects on CO_2 emissions in the studied countries. Xuan (2025) applied ARDL bounds testing to investigate both transient and persistent relationships between innovation, renewable energy consumption, FDI, GDP, and CO_2 emissions in Vietnam. Their empirical evidence suggested that innovation and the consumption of renewable energy can lead to a substantial reduction in CO_2 emissions, while FDI has a positive promoting effect on both economic growth and CO_2 emissions. While limited studies have examined the emission-mitigating potential of renewable energy adoption, technological innovation, and FDI, the existing empirical evidence in the context of Malaysia remains inconclusive and requires further substantiation.

Data and methodology

Data

To empirically analyze the relationship between CO_2 emissions and FDI, technological innovation, and renewable energy, this study employs time series data spanning from 1995 to 2023. The data utilized in this study sourced from two authoritative databases: The World Bank Indicators (WBI) and the U.S. Energy Information Administration (EIA). *Table 1* presents the descriptions, symbols, and data sources for the variables. CO_2 indicates carbon dioxide emissions (metric tons per capita), GDP denotes economic growth per capita (constant 2015 US$), RE stands for renewable energy consumption (measured as the percentage of renewable energy consumption relative to total energy consumption), PA shows patent applications (expressed by the number of applications submitted to the patent office) and FDI refers to foreign direct investment (expressed as the ratio of net FDI inflows to GDP). The trends of the time series are illustrated in *Figures 1, 2, 3, and 4*. As demonstrated in *Figures 1 and 3*, there is a clear upward trend

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in both CO_2 emissions and the number of patent applications in Malaysia. *Figure 2* indicates cyclical fluctuations in FDI inflows, whereas *Figure 4* demonstrates a dip followed by sustained growth in Malaysia's renewable energy consumption share. Notably, Malaysia experienced significant concurrent declines in CO_2 emissions, FDI, and patent applications in 2008, a phenomenon directly attributable to the global financial crisis. While Malaysia's regulatory restrictions on financial derivatives insulated its economy from direct systemic risks, the global financial crisis nevertheless precipitated a severe export contraction and significant FDI reduction (Bekhet et al., 2014). As Malaysia is significantly reliant on export trade, the substantial contraction of the manufacturing sector has led to a decrease in the final energy demand of the industrial sector, which fell from 16,454 ktoe to 12,928 ktoe between 2007 and 2010 (MEIH, 2023). This abrupt decline in energy demand served as an unexpected mitigation mechanism, temporarily reducing Malaysia's carbon emission pressure during the crisis period.

Table 1. *Explanation of the variables used in this study*

Variable	Definition	Unit of measurement	Symbol
CO_2 emissions	CO_2 emissions excluding LULUCF per capita	Metric tons per capita	CO_2
Economic growth	Gross domestic product per capita	Constant 2015 US$	GDP
Foreign direct investment	The ratio of net FDI inflows to GDP	Percentage (%)	FDI
Patent applications	The number of patent applications	Percentage (%)	PA
Renewable energy consumption	The ratio of renewable energy consumption to total energy consumption	Percentage (%)	RE

Note: Land Use, Land-Use Change and Forestry (LULUCF)

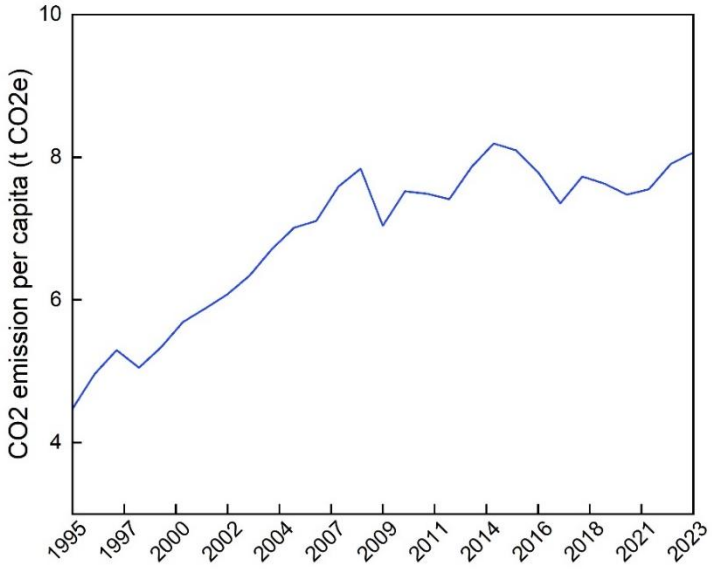

Figure 1. *Trend of per capita CO_2 emissions (1995-2023). Source: World Bank (2023) (https://databank.worldbank.org/)*

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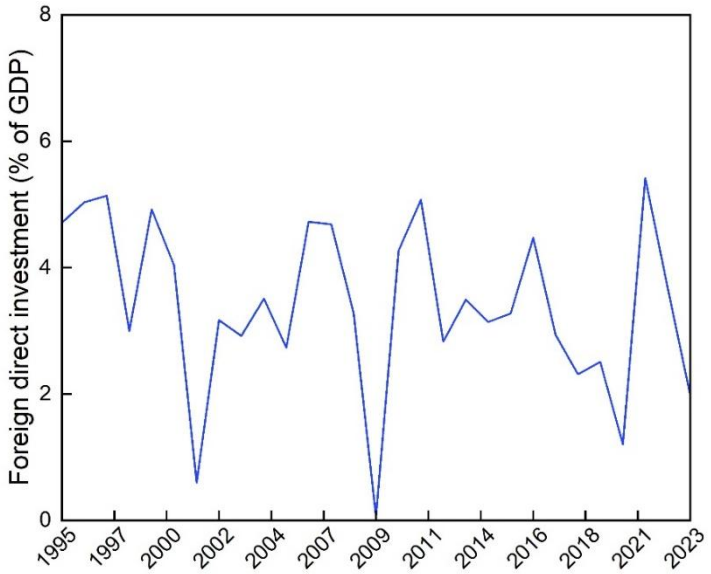

Figure 2. *Trend of foreign direct investment inflows (1995-2023). Source: World Bank (2023) (https://databank.worldbank.org/)*

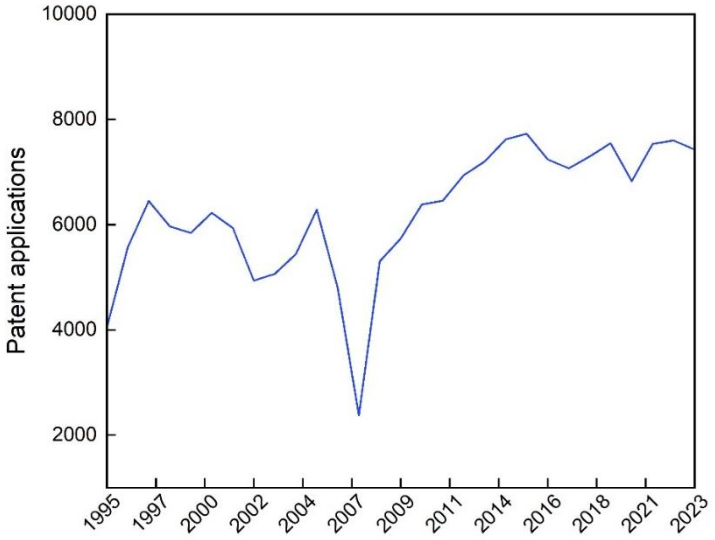

Figure 3. *Trend of patent applications (1995-2023). Source: World Bank (2023) (https://databank.worldbank.org/)*

Table 2 presents the descriptive statistics for the variables. From 1995 to 2023, the average per capita CO_2 emissions in Malaysia were 6.91 metric tons. During the specified study period, the average per capita GDP was 8263.59 US dollars, with FDI inflows accounting for an average of 3.42% and renewable energy consumption contributing an average of 1.86%. Additionally, the average number of patent applications submitted was 6236.38.

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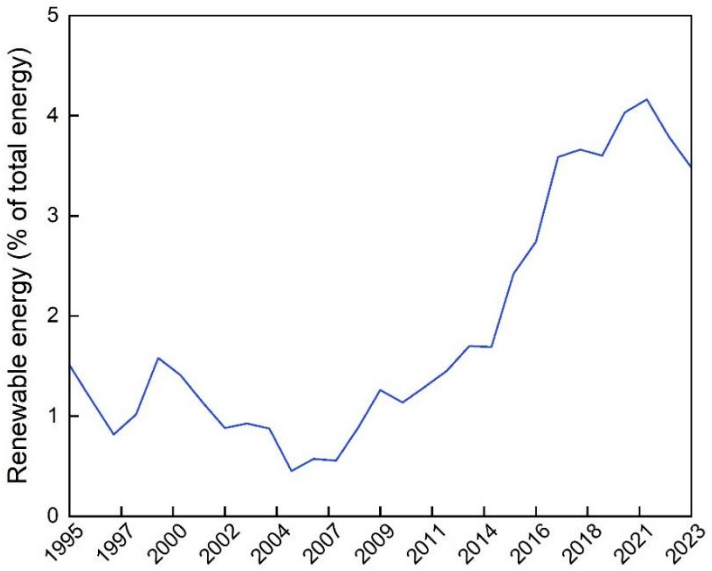

Figure 4. *Trend of renewable energy consumption (1995-2023). Source: EIA (2023) (https://www.eia.gov/)*

Table 2. *Descriptive statistics of variables*

Variable	CO_2	GDP	FDI	PA	RE
Mean	6.91	8263.59	3.42	6236.38	1.86
Median	7.41	7976.12	3.28	6383	1.41
Maximum	8.19	11429.59	5.42	7727	4.16
Minimum	4.47	5771.35	0.06	2372	0.45
Std. dev	1.09	1795.54	1.36	1237.73	1.20
Skewness	0.05	0.51	0.12	0.01	0.06
Kurtosis	0.54	0.01	0.61	0.06	0.20
Observations	29	29	29	29	29

Model specification

The foundational equation for this study is derived from the work of Saboori et al. (2012). In their study, the authors investigated the long-term dynamic relationship between economic growth and CO_2 emissions to test the EKC hypothesis for Malaysia, employing the following log-linear *Eq. 1*:

$$\mathrm{Ln}(E)_t = \alpha_0 + \alpha_1 \ln Y_t + \alpha_2 (\ln Y_t)^2 + \varepsilon_t \quad \text{(Eq.1)}$$

where E, Y, t and ϵ represent CO_2 emissions per capita, real GDP per capita, the time period, and the standard error term. A primary objective of this study is to test the validity of the EKC hypothesis in the Malaysian context. Accordingly, GDP and its squared term are proposed as independent variables in the model. Since the present study focuses on examining the impact of the scale of foreign investment, technological innovation, and renewable energy adoption on Malaysia's CO_2 emissions, three variables, FDI, patent applications and renewable energy consumption, are incorporated into the model. In order

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to reduce fluctuations and enhance the precision of the results, logarithmic processing was implemented for the variables within the model (Ali et al., 2021). The model proposed in this study is illustrated in *Eq. 2*:

$$\ln CO_{2,t} = \mu_0 + \mu_1 \ln GDP_t + \mu_2 (\ln GDP_t)^2 + \mu_3 \ln FDI_t + \mu_4 \ln PA_t + \mu_5 \ln RE_t + \varepsilon_t \quad \text{(Eq.2)}$$

The FDI_t denotes foreign direct investment, PA_t is patent applications, RE states renewable energy consumption, and ε_t refers to error term. μ_1, μ_2, μ_3, μ_4, and μ_5 represent long-term elasticity of the CO_2 emissions in relation to the corresponding model variables. According to the EKC hypothesis, the relationship between CO_2 emissions and economic growth follows an inverted U-shaped pattern. The validity of the EKC hypothesis can be confirmed under the condition that the coefficient μ_1 in the model is positive and μ_2 is negative.

Unit root tests

The model utilized in this study is not equipped to analyze non-stationary time series data, potentially leading to biased or unreliable predictions (Shrestha et al., 2018). Elliott et al. (1992) advanced the methodology originally proposed by Dickey et al. (1979) by implementing local detrending of the time series data to remove linear trends. Ng et al. (2001) developed a more efficient Ng-Perron test by employing the detrending program for the PP tests of Phillips et al. (1988). Therefore, to address the issue of spurious regression, the stationarity level of the included time series data was assessed using augmented Dickey-Fuller (ADF), Ng-Perron and Dickey-Fuller generalized least squares (DF-GLS) tests (Elliott et al., 1992) in this study. Subsequent analysis involves conducting cointegration tests to examine potential long-run equilibrium relationships among the study variables.

ARDL bound test

The ARDL bounds testing approach, developed by Pesaran et al. (2001), is a cointegration method used to examine the presence of long-run relationships among variables. This testing approach relaxes the conventional requirement for variables to be integrated of the same order, thereby accommodating a broader spectrum of time series data in cointegration analysis (Alam et al., 2012). Compared to traditional cointegration tests, the ARDL test demonstrates greater robustness and consistency, even in the context of small sample sizes (Ali et al., 2021). Moreover, the ARDL model enables simultaneous estimation of both short-run dynamics and long-run equilibrium relationships.

Given the aforementioned advantages, this study employs the ARDL method to investigate the relationship between CO_2 emissions, economic growth, FDI, technological innovation and renewable energy consumption. The equation for the ARDL bounds test can be found in *Eq. 3* below:

$$\begin{aligned}\Delta \ln CO_{2,t} = {} & \alpha_0 + \sum_1^p \alpha_{1i} \ln CO_{2,t-p} + \sum_0^q \alpha_{2i} \ln GDP_{t-q} + \sum_0^r \alpha_{3i} (\ln GDP_{t-r})^2 \\ & + \sum_0^s \alpha_{4i} \ln FDI_{t-s} + \sum_0^u \alpha_{5i} \ln PA_{t-u} + \sum_0^v \alpha_{6i} \ln RE_{t-v} \\ & + \varphi_1 \ln CO_{2,t-1} + \varphi_2 \ln GDP_{t-1} + \varphi_3 (\ln GDP_{t-1})^2 + \varphi_4 \ln FDI_{t-1} \\ & + \varphi_5 \ln PA_{t-1} + \varphi_6 \ln RE_{t-1} + \theta_t\end{aligned} \quad \text{(Eq.3)}$$

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where Δ and θ_t denote the first difference factor and residuals, α_0 represents drift component, α_{1i}, α_{2i}, α_{3i}, α_{4i}, α_{5i}, α_{6i} are corresponding short-run elasticity coefficients, and φ_1, φ_2, φ_3, φ_4, φ_5, φ_6 present long-run dynamic coefficients. Through straightforward linear transformation, the error correction model (ECM) can be derived from the ARDL model. This transformation captures both short-term dynamic adjustments and retains the long-term equilibrium relationship, thereby maintaining the integrity of the model's information (Nkoro et al., 2016). The significance level of the lagging explanatory variable reflects the causal relationship of the possible influencing variables, whereas the significance and negative value of ECT represent the long-term causal relationship between the variables (Ali et al., 2021). The ECM model's equation can be expressed as shown in the following *Eq. 4*:

$$\begin{aligned}\Delta \ln CO_{2,t} = {} & \alpha_0 + \sum_1^p \alpha_{1i} \ln CO_{2,t-p} + \sum_0^q \alpha_{2i} \ln GDP_{t-q} \\ & + \sum_0^r \alpha_{3i} (\ln GDP_{t-r})^2 + \sum_0^s \alpha_{4i} \ln FDI_{t-s} \\ & + \sum_0^u \alpha_{5i} \ln PA_{t-u} + \sum_0^v \alpha_{6i} \ln RE_{t-v} \\ & + \omega ECM_{t-1} + \theta_t\end{aligned} \quad \text{(Eq.4)}$$

where ω represent the speed of adjustments from short-run dynamics towards long-run equilibrium, thereby indicating the extent to which the dependent variable deviates from the long-term equilibrium relationship in the short term (Iqbal Chaudhry et al., 2013). Positive coefficients signify a divergence from equilibrium, whereas negative coefficients denote convergence toward the long-run steady state.

Robustness analysis

The long-run estimates derived from the ARDL estimator are further validated for robustness by employing alternative cointegration regression techniques, including fully modified ordinary least squares (FMOLS) (Hansen et al., 1988), dynamic ordinary least square (DOLS) (Stock et al., 1993), and canonical cointegrating regression (CCR) (Park, 1992). Compared to conventional approaches, both FMOLS and DOLS provide more reliable cointegration estimates when dealing with finite samples, autocorrelation, and endogenous regressors (Ali et al., 2017; Mohamed et al., 2024). The CCR estimator demonstrates robustness to non-stationary time series data, yielding both consistent and efficient estimates of cointegration vectors. Consequently, we employ this triad of robustness analysis techniques to enhance both the consistency and reliability of the identified long-run equilibrium relationships.

Moreover, this study employs the LM serial correlation test along with the cumulative sum of recursive residuals (CUSUM) and its corresponding sum of squares to identify any potential misspecification and structural instability within the model. When the CUSUM and CUSUM-squared (CUSUMSQ) plots remain within the critical thresholds established at the 5% significance level, it suggests that the regression model is stable, thus failing to reject the null hypothesis regarding parameter stability (Qiu, 2025).

Granger causality test

A rigorous examination of causal pathways is necessary to disentangle the individual and interactive effects of different variables on CO_2 emission reduction. To this end, this study employs Granger causality analysis to examine the interrelationship between key variables: CO_2, GDP, FDI, PA and RE. Compared to alternative causality tests, the

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analysis method proposed by Toda et al. (1995) offers superior efficiency and reliability, as it remains robust to mixed integration orders and substantially mitigates finite-sample distortion effects (Ortega-Ruiz et al., 2022). Under this method, the null hypothesis states no Granger causality exists between the variables, whereas the alternative hypothesis indicates a causal relationship. A statistically significant Granger-causal relationship is established when the test yields a *p*-value below the conventional 5% significance threshold, leading to rejection of the null hypothesis of non-causality. Thus, the bivariate autoregression model involved in the Granger causality test is *Eq. 5 and Eq. 6*:

$$W_t = \alpha_1 + \sum_1^m \alpha_{1i} W_{t-i} + \sum_1^m \varphi_{1j} Z_{t-j} + \theta_{1t} \quad \text{(Eq.5)}$$

$$Z_t = \alpha_2 + \sum_1^m \alpha_{2i} Z_{t-i} + \sum_1^m \varphi_{2j} W_{t-j} + \theta_{2t} \quad \text{(Eq.6)}$$

where m represents the optimal lag structure as determined by the Akaike Information Criterion (AIC), α_1, α_2, α_{1i}, α_{2i}, φ_{1j}, and φ_{2j} denote parameters used to determine causal relationships, and θ_{1t} and θ_{2t} are the residuals. Ordinary least squares (OLS) estimation is employed to derive coefficient estimates, while Granger causality is determined through F-tests of joint significance on lagged terms in the vector autoregression (VAR) models.

Empirical analysis and discussions

Descriptive statistics

As illustrated in *Table 2*, a variety of distributional tests for variables are summarized, encompassing skewness and kurtosis tests. The kurtosis result of the variable is marginally greater than 0, which indicates that the steepness of the overall data distribution is very similar to that of the normal distribution. The skewness of all variables is greater than 0, indicating that the right tail is longer than the left, and a larger proportion of values are situated to the left of the mean.

Unit root test

Tables 3 and 4 illustrate the stationarity test results for $\ln CO_2$, lnGDP, $(\ln GDP)^2$, lnFDI lnPA and lnRE derived from the ADF, DF-GLS, and NG-perron tests, respectively. As shown in *Tables 3 and 4*, the test results indicate that CO_2 emissions, economic growth and its square term, patent applications, and renewable energy consumption achieve stationarity at the first difference. The FDI data demonstrated stability at both levels and in all tests. This finding suggests that the integrated orders of the variables included in the study are different, thereby validating the appropriateness of the ARDL bound test method employed in this study. Given that the AIC and Final Prediction Error (FPE) maximize the likelihood of accurately determining the true lag length, this study selected the optimal lag length based on these criteria (Liew, 2004).

ARDL bound test

Given that the variables exhibit inconsistent orders of stationarity (as demonstrated in *Tables 3 and 4*), this study employed the ARDL bound testing approach to examine long-run cointegration among the variables. Therefore, the null hypothesis (H_0) $\varphi_1 = \varphi_2 = \varphi_3 = \varphi_4 = \varphi_5 = \varphi_6 = 0$ indicates no cointegration, while the alternative hypothesis (H_1)

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$\varphi_1 \neq \varphi_2 \neq \varphi_3 \neq \varphi_4 \neq \varphi_5 \neq \varphi_6 \neq 0$ rejects the null hypothesis and signifies the presence of cointegration.

Table 3. *Results of ADF and DF-GLS unit root test*

Variable	ADF		DF-GLS	
	I(0)	I(1)	I(0)	I(1)
$lnCO_2$	-2.174	-5.816***	-1.133	-4.617***
lnGDP	-3.184	-5.826***	-2.870	-5.671***
$(lnGDP)^2$	-3.139	-5.789***	-2.847	-5.624***
lnFDI	-5.454***	-7.875***	-4.406***	-6.040***
lnPA	-3.481*	-6.263***	-3.099*	-4.644***
lnRE	-2.174	-4.559***	-1.501	-3.701**

Noted: *, ** and ** represent 10, 5 and 1% levels of significance

Table 4. *Results of NG-perron unit root test*

	Variable	$lnCO_2$	lnGDP	$(lnGDP)^2$	lnFDI	lnPA	lnRE
Level	MZa	0.099	1.305	1.344	-13.860***	-8.073*	-1.359
	MZt	0.075	1.201	1.241	-2.619***	-1.930*	-0.662
	MSB	0.7544	0.920	0.923	0.189**	0.239*	0.487
	MPT	35.404	63.191	64.043	1.820**	3.324*	14.037
1st difference	MZa	-12.306**	-13.156**	-13.183**	-27.193***	-13.038**	-12.509**
	MZt	-2.470**	-2.558**	-2.562**	-3.681***	-2.541**	-2.500**
	MSB	0.201**	0.194**	0.194**	0.135***	0.195**	0.200**
	MPT	2.032**	1.887**	1.879**	0.922***	1.927**	1.960**

Noted: *, ** and ** represent 10, 5 and 1% levels of significance

As presented in *Table 5*, the calculated F statistic (4.246) is greater than the upper critical value at 5% significance level (4.18), which indicates that the null hypothesis of no cointegration is rejected. Consequently, the long-term co-integration relationship between CO_2 emissions, economic growth, FDI, patent applications, and renewable energy consumption is verified.

Table 5. *Results of ARDL bound test*

Dependent variable	F	k
$F(lnCO_2 \mid lnGDP, (lnGDP)^2, lnFDI, lnPA, lnRE)$	4.246**	5
Critical value	I(0)	I(1)
1% Significance level	3.41	4.68
2.5% Significance level	2.96	4.18
5% Significance level	2.62	3.79
10% Significance level	2.26	3.35

Noted: *, ** and ** represent 10, 5 and 1% levels of significance

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Long-run and short-run estimations

After verifying a long-term cointegration relationship among the variables using the ARDL bounds test, we proceeded to estimate both the short- and long-run effects of economic growth, FDI, technological innovation, and renewable energy consumption on CO_2 emissions in Malaysia. As presented in *Table 6*, the long-term coefficient for economic growth suggests that, ceteris paribus, a 1% rise in economic growth corresponds to a 16.079% increase in CO_2 emissions. The short-term economic growth coefficient yielded results consistent with the long-term coefficient, though its environmental impact is less pronounced than in the long run. Additionally, the empirical results reveal an inverse relationship between the quadratic term of economic growth and environmental degradation. Specifically, for every 1% increase in the squared economic growth variable, short-term and long-term CO_2 emissions have been found to decrease by 0.851% and 0.424%, respectively. The positive coefficient for economic growth and the negative coefficient for its squared term, confirm the existence of an inverted U-shaped relationship between CO_2 emissions and economic development, thereby validating the EKC hypothesis in the context of Malaysia. This finding aligns with the research outcomes of Ali et al. (2017), Jahanger et al. (2022), and Mohamed et al. (2024). The process of economic development typically intensifies industrial operations, transportation systems, and fossil energy use, thereby exacerbating carbon emission levels. Moreover, multiple structural factors constrain energy efficiency improvements in developing economies, including suboptimal energy pricing mechanisms, significant non-technical losses, capital market inefficiencies, and inadequate power quality (Adom, 2024). These systemic deficiencies contribute to substantial resource waste and accelerated environmental degradation. Economic development also accelerates urbanization processes, inevitably generating increased energy-intensive activities including infrastructure development, transportation network expansion, and residential construction (Bekhet et al., 2018; Mohamed et al., 2024). Nevertheless, Malaysia's sustained economic growth has precipitated significant structural transformation in its industrial composition. This shift from primary agriculture and secondary industries toward tertiary sector development represents an economic transition from energy-intensive production to relatively lower-carbon activities (Sohag et al., 2017). Consequently, Malaysia possesses the potential to sustain both robust economic growth and the achievement of sustainable development objectives in the long run.

The FDI estimate coefficients indicate that each 1% growth in foreign direct investment triggers to decrease of 0.046% and 0.016% carbon emissions concerning long and short run. These findings demonstrate that Malaysia's foreign capital inflow regulations are effectively mitigating environmental impacts, a conclusion supported by Akhtar et al. (2023). Recent empirical studies have demonstrated a significant negative correlation between FDI and environmental quality indicators across several developing economies, including Vietnam (Xuan, 2025), India (Tripathy et al., 2025), and Indonesia (Viphindrartin et al., 2020). Although classified as a developing economy, Malaysia has strategically leveraged foreign investment policies to channel capital into low-carbon and environmentally sustainable industries, thereby advancing progress toward SDGs. To effectively regulate foreign enterprises, the Malaysia government has formulated strict environmental protection laws and environmental quality regulations (Awad, 2020). This legal system incentivizes investors to incorporate environmental considerations during initial project planning phases. Pollution control measures mandate production line upgrades to minimize waste generation while promoting the recovery and reuse of

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materials throughout manufacturing processes. Currently, the service sector dominates FDI inflows into Malaysia, with the majority concentrated in information and communication technology (ICT) and financial services (Tiong et al., 2025). These outcomes reflect the long-term implementation of Malaysia's environmentally-conscious foreign investment policies, while simultaneously offering a promising solution for sustainable development in other emerging economies.

Table 6. *Results of ARDL model (1, 0, 1, 1, 2, 0) estimation*

Variable	Coefficient	Std. err	t-statistic	Prob.
Long-run estimation				
lnGDP	16.079*	7.987	2.01	0.061
(lnGDP)2	-0.851*	0.446	-1.91	0.074
lnFDI	-0.046*	0.024	-1.94	0.070
lnPA	0.121	0.110	1.10	0.288
lnRE	-0.115**	0.043	-2.65	0.017
Short-run estimation				
D(lnGDP)	8.418	5.500	1.53	0.145
D((lnGDP)2)	-0.424	0.305	-1.39	0.184
D(lnFDI)	-0.016	0.012	-1.43	0.173
D(lnPA)	0.013	0.032	0.40	0.692
D(lnRE)	-0.060**	0.023	-2.57	0.020
ECM(-1)	-0.524**	0.142	-3.70	0.002
Breusch-Godfrey serial correlation LM test				0.123

Noted: *, ** and ** represent 10, 5 and 1% levels of significance

The empirical results denote a positive correlation between technological innovation and carbon emissions growth. Notably, these findings contradict the study's hypothesis, revealing that PA exerted a negative influence on environmental quality throughout the observation period. The estimates show that a 1% increase in technological innovation is associated with a 0.121% rise in CO_2 emissions in the long run. This conclusion is supported by research results of Junsheng et al. (2024). Although energy efficiency can be improved through multiple policy instruments and market-based mechanisms, technological innovation yields a greater impact by directly relating to the energy efficiency production function (Sohag et al., 2015). Advanced production and energy technologies allow economies to increase output while reducing energy consumption, thereby enhancing energy productivity. However, energy efficiency improvements may trigger a rebound effect, wherein reduced energy prices can stimulate greater energy consumption, potentially offsetting some emission reduction benefits (Greening et al., 2000). The rebound effect is particularly pronounced in emerging economies due to their rapid economic expansion and growing energy demand. Although green technological innovation possesses the potential to mitigate the ongoing degradation of the environment, updates and iterations related to energy-consuming technologies, such as manufacturing equipment and transportation tools, may exert increased pressure on environmental resources. This finding not only reinforces the conclusion drawn by Shahbaz et al. (2020), but also offers new empirical evidence supporting the inverted U-shaped relationship between technological innovation and environmental quality in developing countries.

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As demonstrated in *Table 6*, the estimated coefficient of renewable energy exhibits statistical significance at the 5% level, signifying that for every 1% increase in renewable energy consumption, short-term and long-term CO_2 emissions will diminish by 0.115% and 0.06%, respectively. This empirical result is consistent with the research of Raihan et al. (2022a,b), and Suki et al. (2022). Malaysia's current energy supply remains predominantly fossil fuel-based, comprising coal, natural gas, and petroleum products (Begum et al., 2025). The combustion of these fossil fuels generates substantial CO_2 emissions and waste heat, representing major contributors to environmental degradation. Conversely, renewable energy has been shown to possess the potential to provide energy services with negligible or zero emissions of air pollutants and greenhouse gases (Panwar et al., 2011). Integrating renewable energy sources into the energy structure and progressively augmenting the penetration rate of renewables within energy supplies can facilitate the mitigation of climate change and reduce greenhouse gas emissions. The research by Ridzuan et al. (2023) demonstrated that FDI exhibits greater outcomes in mitigating environmental degradation compared to RE. Contrary to these findings, the present study utilizing updated time-series data establishes RE as significantly more effective than FDI in reducing CO_2 emissions, demonstrating superior mitigation potential. These findings further indicate that Malaysia's recent energy structure reforms have contributed significantly to its progress toward SDGs. The ECM captures the long-term equilibrium relationship between variables while demonstrating their short-term adjustment mechanisms when deviations occur. The ECM coefficient of -0.524 in *Table 6* indicates a rate of 5.24% correction of deviations from the short-term dynamics towards the long-run equilibrium in each period.

Robustness tests

This study employs the DOLS, FMOLS, and CCR tests to rigorously validate the robustness of long-term parameter estimates. *Table 7* presents the empirical outcomes from DOLS, FMOLS, and CCR tests. The coefficient estimates obtained from aforementioned three methods exhibit general directional consistency, with primary variations emerging in the magnitude and significance of the PA variable's parameter. There exists a positive correlation between Malaysia's GDP and CO_2 emissions. Specifically, for each 1% increase in GDP, CO_2 emissions rise by 0.99% (DOLS) and 0.98% (FMOLS, CCR), respectively. Aligning with our long-term cointegration findings, the analysis confirms statistically significant inverse relationships between both FDI and RE with CO_2 emissions. This indicates that a 1% surge in FDI results in a 0.09% (DOLS) and 0.01% (FMOLS, CCR) reduction in CO_2 emissions, respectively. In contrast to the FDI, RE demonstrates a more pronounced decarbonization impact, with a 1% upsurge in RE resulting in a 0.25% (DOLS) and 0.15% (FMOLS, CCR) decline in CO_2 emissions, according to its estimated long-term elasticity. Remarkably, the robustness tests corroborate and strengthen the finding of a statistically significant negative relationship between RA and environmental degradation in Malaysia throughout the study period. The estimated coefficient of 0.33 (DOLS) suggests that, holding other factors constant, each percentage point increase in RA is associated with a 0.33% rise in carbon emissions. The output results align with the long-run ARDL estimates, supporting that within Malaysia's development context: economic expansion and technological advancement have exerted adverse environmental impacts, while FDI inflows and renewable energy adoption have served as effective decarbonization mechanisms.

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Table 7. *Results of the DOLS, FMOLS and CCR tests*

	Variable	GDP	FDI	PA	RE
DOLS	Coefficient	0.99***	-0.09***	0.33***	-0.25***
	t-statistic	34.41	-8.09	6.71	-14.34
FMOLS	Coefficient	0.98***	-0.01***	-0.02	-0.15***
	t-statistic	34.12	-2.87	-0.87	-13.47
CCR	Coefficient	0.98***	-0.01*	-0.02*	-0.15***
	t-statistic	34.23	-1.68	-0.78	-13.06

Noted: *, ** and ** represent 10, 5 and 1% levels of significance

To validate parameter stability, we conducted recursive residual analyses using both CUSUM and CUSUMSQ tests, which systematically evaluate structural consistency throughout the estimation period. *Figures 5 and 6* illustrate the outcomes of the CUSUM test and the CUSUMSQ tests, respectively. As illustrated in the figures, the test statistic remains consistently within the critical bounds at both significance levels, providing further evidence for parameter stability. Consequently, the empirical findings presented in *Table 6* can serve as a valuable reference for the formulation of policy.

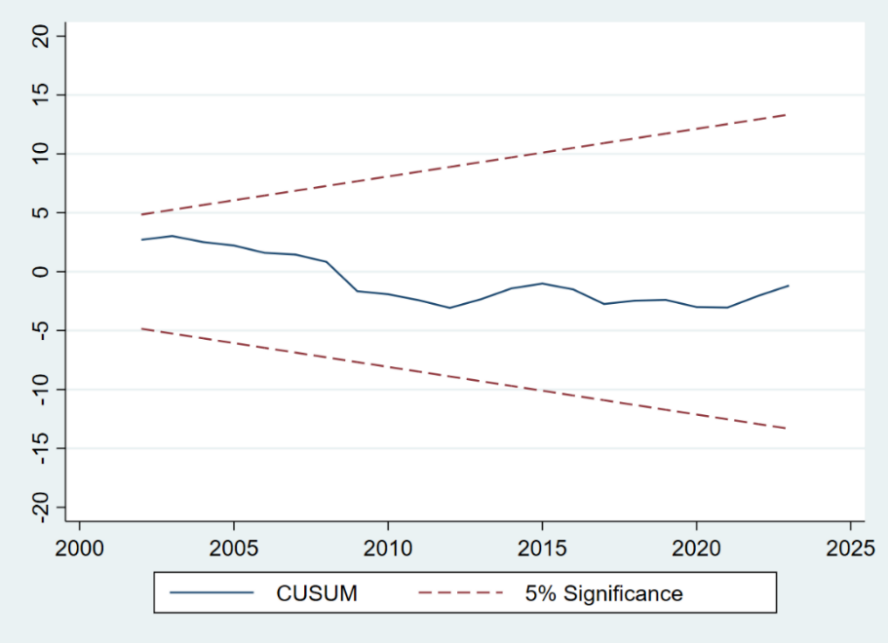

Figure 5. *CUSUM test for model stability*

Granger causality test

The cointegration test results indicate potential Granger-causal relationships among CO_2 emissions, GDP, FDI, PA, and RE, though the exact directional causality remains statistically ambiguous in our preliminary analysis. Building upon the detected cointegration relationships, we implement the Toda-Yamamoto Granger causality approach to properly assess causal dynamics. *Table 8* presents the Toda-Yamamoto Granger causality test results. As evidenced in *Table 8*, the results reveal a statistically

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significant unidirectional causality running from CO_2 emissions to PA. Additionally, the outcomes indicate FDI has a unidirectional causal relationship to both CO_2 emissions and PA. The analysis reveals a statistically significant one-way causal relationship where PA Granger-cause GDP and RE. Consistent with the findings of Lau et al. (2014), our results confirm FDI's role in improving environmental quality, suggesting Malaysia's investment policies could strategically leverage this effect by introducing environmentally friendly technologies and firms. The ambitious objective of attaining net zero carbon emissions by 2050 reflects the Malaysian government's strong commitment to sustainable development. The policies implemented to achieve this goal undoubtedly foster the advancement of environmentally friendly innovations. This phenomenon illuminates the manner in which CO_2 emissions influence PA within the Malaysian context. The widespread adoption of renewable energy faces two primary barriers: high costs and suboptimal efficiency. However, technological innovations are progressively addressing these challenges through cost-reduction effects and performance enhancements, thereby accelerating renewable energy deployment. The findings of this study regarding the Granger causality between PA and RE further substantiate the proposition put forth by Raihan et al. (2022a).

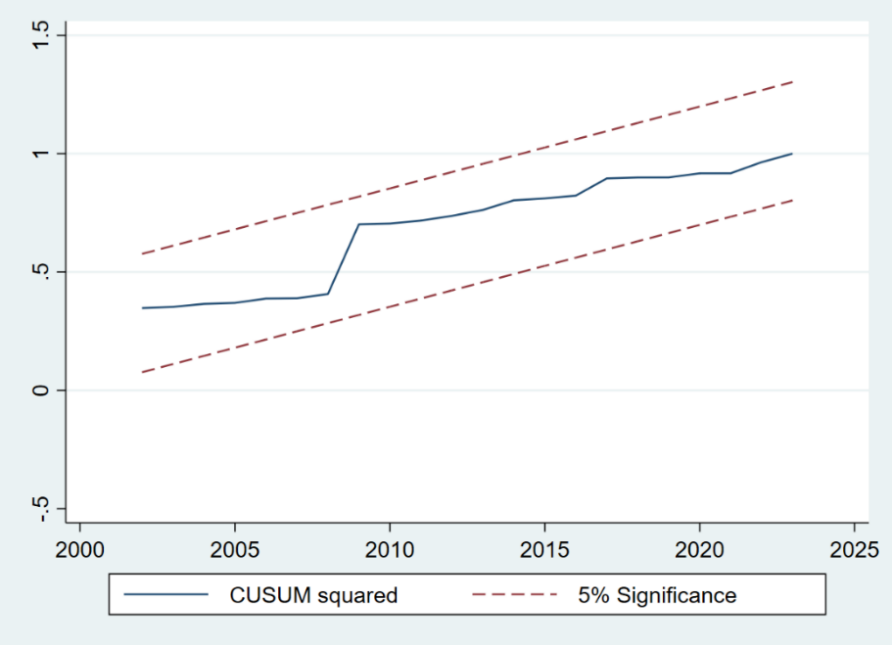

Figure 6. *CUSUMSQ test for model stability*

Building upon our empirical findings, we synthesize these relationships into an integrated conceptual framework (as shown in *Fig. 7*) that elucidates the multi-directional influence mechanisms among CO_2 emissions, GDP, PA, and RE in Malaysia. *Figure 7* underscores the significant role that FDI plays in reducing carbon emissions. Furthermore, both CO_2 emissions and FDI exert influence on GDP and RE through PA. In conclusion, Malaysia should prioritize technological innovation to modernize its energy infrastructure while strategically directing foreign investment toward renewable energy technologies and associated facilities.

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Table 8. *Results of Granger causality tests*

Null hypothesis	F-statistic	Decision on H_0	Causality
CO_2 does not Granger-cause GDP	0.369	√	$CO_2 \neq GDP$
GDP does not Granger-cause CO_2	1.356	√	$GDP \neq CO_2$
CO_2 does not Granger-cause FDI	2.871	√	$CO_2 \neq FDI$
FDI does not Granger-cause CO_2	6.388**	X	$FDI \rightarrow CO_2$
CO_2 does not Granger-cause PA	12.012**	X	$CO_2 \rightarrow PA$
PA does not Granger-cause CO_2	0.875	√	$PA \neq CO_2$
CO_2 does not Granger-cause RE	1.150	√	$CO_2 \neq RE$
RE does not Granger-cause CO_2	1.080	√	$RE \neq CO_2$
GDP does not Granger-cause FDI	0.220	√	$GDP \neq FDI$
FDI does not Granger-cause GDP	3.851	√	$FDI \neq GDP$
GDP does not Granger-cause PA	3.504	√	$GDP \neq PA$
PA does not Granger-cause GDP	11.134**	X	$PA \rightarrow GDP$
GDP does not Granger-cause RE	4.531	√	$GDP \neq RE$
RE does not Granger-cause GDP	1.579	√	$RE \neq GDP$
FDI does not Granger-cause PA	40.374***	X	$FDI \rightarrow PA$
PA does not Granger-cause FDI	2.093	√	$PA \neq FDI$
FDI does not Granger-cause RE	2.195	√	$FDI \neq RE$
RE does not Granger-cause FDI	4.896*	√	$RE \neq FDI$
PA does not Granger-cause RE	23.248***	X	$PA \rightarrow RE$
RE does not Granger-cause PA	0.445	√	$RE \neq PA$

Noted: *, ** and ** represent 10, 5 and 1% levels of significance

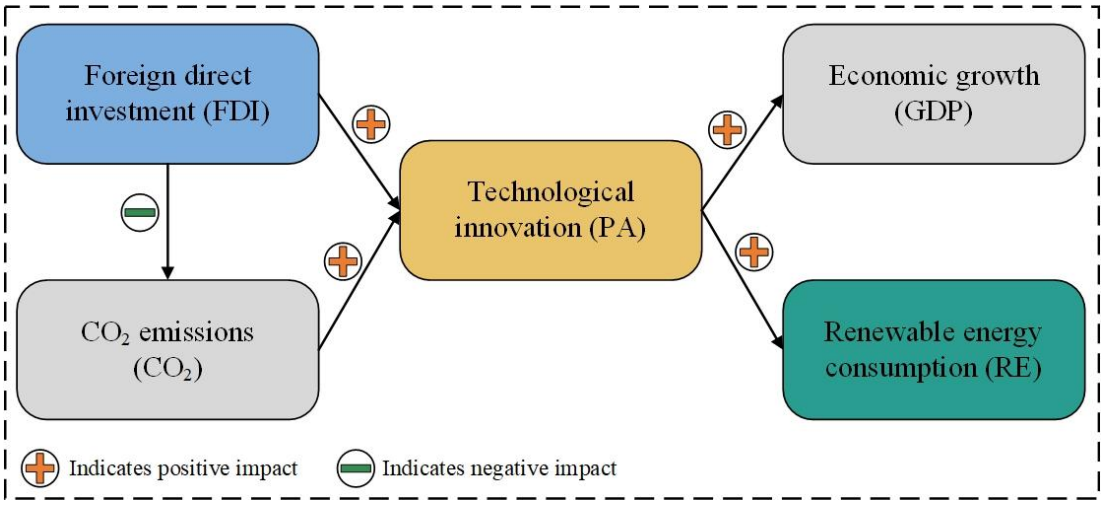

Figure 7. *Granger causality diagram of variables*

Conclusion and policy implications

Based on the EKC hypothesis, this study examines the dynamic relationships between economic growth, FDI, technological innovation, renewable energy consumption, and carbon dioxide emissions using Malaysian time-series data spanning 1995-2023. Given the ARDL bounds test's robustness in small-sample contexts, this study employs this

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methodology to investigate both long-run equilibria and short-run dynamics among the variables. The ARDL bounds test results validate both short-run and long-run EKC hypotheses for Malaysia, confirming an inverted U-shaped relationship between CO_2 emissions and economic growth. Furthermore, the ARDL analysis reveals short-run and long-run negative relationships between carbon emissions and both FDI and renewable energy consumption. The empirical analysis demonstrates a positive association between technological innovation and CO_2 emissions, suggesting that prevailing innovation patterns predominantly fuel economic expansion and energy demand rather than environmental mitigation. The Granger causality test results emphasize FDI's dual mechanism for environmental improvement. First, environmental regulatory oversight of foreign enterprises directly reduces carbon emissions. Second, FDI-induced technological innovation indirectly enhances environmental quality through renewable energy adoption.

Building on these findings, this study proposes policy recommendations to advance SDGs. The validated inverted U-shaped relationship between CO_2 emissions and economic growth underscores Malaysia's need to balance economic expansion with sustainable development objectives. National development strategies should incorporate clearly defined sustainable development targets for different sectors, accompanied by actionable plans and measurable performance indicators. Government policies should incorporate targeted incentives for industrial adoption of clean technologies and renewable energy sources to accelerate the transition toward sustainable production systems. Moreover, preferential policies, such as specialized loans and tax reductions, should be allocated to startup enterprises associated with new technologies and clean energy to foster the advancement of fundamental technologies and infrastructure. The phased implementation of carbon pricing mechanisms for energy-intensive industries represents an effective policy approach to reconcile economic growth with environmental protection. Over the past decade, Malaysia's CO_2 emissions have shown a gradual stabilization trend, underscoring the need for continued government commitment to enforcing and strengthening environmental policies.

Secondly, the empirical evidence demonstrates that FDI exerts a positive long-term effect on mitigating environmental degradation and significantly affects technological innovation and the use of renewable energy. This outcome underscores the Malaysian government maintains strict supervision over foreign capital inflows and intentionally introduces advanced foreign technologies and environmentally friendly enterprises. In general, the influx of foreign capital coincides with the introduction of advanced technologies. To maximize these benefits, governments can facilitate strategic partnerships between domestic and foreign enterprises to accelerate the adoption and localization of clean energy technologies. Furthermore, foreign investment policies should incorporate preferential measures for green technology ventures, including lowered entry barriers, tax incentives, and streamlined land-use approvals to accelerate sustainable sector growth.

Thirdly, the continuous innovation of science and technology exerts a significant adverse effect on environmental quality, especially in the long term, this impact is particularly severe. This conclusion is relevant to economies that are likely to remain developing countries for an extended period and are actively pursuing economic growth. While technological innovation serves as a powerful driving force for national development and economic expansion, it simultaneously generates substantial environmental and resource pressures. The research results emphasize that environmentally friendly innovations constitute only a marginal proportion of current

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technological innovations. Malaysia's long-term development strategy should prioritize innovations that improve energy efficiency and accelerate renewable energy adoption. Specifically, the government's fiscal expenditure can establish dedicated funds to support the development of environmentally friendly technologies. Additionally, it can promote the cultivation of technical talent in universities through policy guidance. In view of the fact that innovative technologies in developed countries have the potential to considerably enhance energy efficiency, the Malaysian government may consider the enhancement of cooperation with foreign enterprises specializing in green and innovative technologies, and actively introduce technologies and talents through tax breaks and immigration policies.

Lastly, renewable energy adoption yields significant air pollution mitigation effects, with demonstrable impacts in both short- and long-term analyses. The findings indicate that optimizing the energy consumption structure through increased renewable energy consumption represents a critical pathway for sustainable development. Presently, the renewable energy sources primarily utilized in Malaysia are hydropower and solar energy. However, their average proportion during the study period is merely 1.82%, suggesting substantial potential for further development of these resources. For core industrial sectors, Malaysia could implement targeted policy incentives and subsidies to accelerate the transition from coal to solar power, hydropower, and natural gas. For residential energy consumption, the government can encourage renewable energy adoption through incentive mechanisms, including subsidized electricity rates for solar power generation and buy-back programs for surplus electricity converted from solar energy. Furthermore, governments should prioritize investments in advanced technologies, with particular emphasis on energy efficiency innovations and low-carbon technological solutions. The economic viability and capital requirements constitute critical determinants influencing the widespread adoption potential of these technologies. This research enhances Malaysia's existing body of environmental economics literature by assessing the collective impact of FDI, technological innovation, and adoption of renewable energy on CO_2 emissions within a cohesive analytical framework. The present study proposes four targeted policy recommendations for developing economies across key dimensions, including (1) sustainable economic growth, (2) FDI regulation, (3) technological innovation incentives, and (4) renewable energy adoption, with the objective of facilitating the progress of these economies in achieving the SDGs.

This study has several limitations that should be acknowledged. Firstly, this study exclusively focuses on a single country's experience when examining the relationships between economic growth, FDI, technological innovation, renewable energy consumption, and carbon emissions within the EKC framework. Future studies could extend this research through comparative analyses across emerging economies, or between developed and developing nations, to enhance the generalizability of findings. Furthermore, the present study places emphasis on the analysis of time series data by employing the ARDL method. Future studies could consider employing alternative methodological approaches, such as the NARDL model, to examine the intricate relationship between variables and environmental quality.

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