# RETHINKING GROWTH AND EMISSIONS: THRESHOLD EFFECTS OF ECONOMIC EXPANSION ON ENVIRONMENTAL SUSTAINABILITY IN MALAYSIA

**JUNAIDAH HASAN[1], ZALINA ZAINAL[2], NOOR SA'ADAH SABUDIN[3], ANIZAH MD. ALI[4], WAN ROSHIDAH FADZIM[5]**

[1]Senior Lecturer, School of Economics, Finance and Banking, Universiti Utara Malaysia, 06010 Sintok, Kedah, Malaysia
[2]Senior Lecturer, School of Economics, Finance and Banking, Universiti Utara Malaysia, 06010 Sintok, Kedah, Malaysia
[3]Lecturer, School of Economics, Finance and Banking, Universiti Utara Malaysia, 06010 Sintok, Kedah, Malaysia
[4]Senior Lecturer, School of Economics, Finance and Banking, Universiti Utara Malaysia, 06010 Sintok, Kedah, Malaysia
[5]Senior Lecturer, School of Economics, Finance and Banking, Universiti Utara Malaysia, 06010 Sintok, Kedah, Malaysia

junaidah.hasan@uum.edu.my[1]
z.zalina@uum.edu.my[2]
saadah@uum.edu.my[3]
anizah@uum.edu.my[4]
wanroshidah@uum.edu.my[5]

**Abstract**
This study explores how economic expansion and environmental sustainability interact in Malaysia, focusing on their non linear relationship through the Multiple Threshold Nonlinear Autoregressive Distributed Lag (MTNARDL) model. By accounting for asymmetries and structural thresholds, the analysis captures dynamics that are often missed by conventional models. The findings suggest that while moderate economic growth is accompanied with lower carbon emissions, the benefits taper off and reverse beyond certain growth levels, where further expansion contributes to environmental deterioration. Additional analysis shows that low to moderate population growth supports emission control, but higher rates exert negative pressure. Energy consumption consistently raises emissions, although its marginal impact declines at higher usage thresholds. These results point to the need for differentiated policy responses that consider threshold effects. For Malaysia to achieve sustainable development, economic, demographic, and energy policies must be aligned to manage trade-offs effectively.

**Keywords:** Environmental sustainability, Threshold Effects, MTNARDL, Carbon emissions, Malaysia.

## 1. Introduction

Economic growth and environmental conservation are still at the edge of the paradigm of the world, particularly under increasing environmental stress. The discussion in the domain of ecological economics has typically been focused around environmental degradation, predominantly fuelled by carbon dioxide ($CO_2$) emissions (Hunjra et al., 2024). $CO_2$ emissions is among a few of the major degraders to environment as they pose negative externalities to human survival forestalling climate change (Ehigiamusoe et al., 2020). Consequently, governments and policymakers are providing measures, in an attempt to prevent further environmental damage by aligning economic growth with environmental goals(Hunjra et al., 2024; Junshenget al., 2024; Azam et al., 2022). The problem is particularly pronounced in many developing countries that prioritize economic growth while paying limited attention to its environmental impact. Acknowledging the environmental impact of economic growth is essential for moving toward sustainable development in such settings. (Ehigiamusoeet al., 2022).

Within Southeast Asia, Malaysia stands among the largest emitters of $CO_2$ emissions, stems from its rising energy demand driven by urbanization and transport, land-use practices, industrial structure and fossil fuel-based energy system. Although developed economies such as Japan, Australia and Germany also face significant environmental challenges, Malaysia is the focus of this study because of clear empirical trends. Between 1980 and 2023, the country's per capita $CO_2$ emissions rose from 2.49 to 8.07 metric tons, marking a 224% increase (World Bank Development Indicators, 2024). Over the same period, Malaysia's position in the Environmental Performance Index fell sharply, from 9th out of 133 countries in 2006 to 118th out of 180 in 2024, indicating a substantial decline in relative environmental performance and a pressing need for stronger environmental policies. Key drivers of environmental stress also expanded considerably: real Growth Domestic Product (GDP) per capita climbed from USD 3,216.29 to USD 11,429.59 (an increase of about 255%), while per capita energy consumption grew from 861.9 to 3,003.5 kilograms of oil equivalent, up by 248% (World Bank Development Indicators, 2024). Together, these developments make Malaysia a timely and relevant case for studying these issues.

Extensive studies have examined how economic growth (EG), population growth (PG) andenergy consumption (EC) influence $CO_2$ emissions using a range of econometric approaches (Pachiyappan et al., 2021). The evidence, however, is far from conclusive. Some studies reported that EG positively correlates with $CO_2$ emissions (Zhang et al., 2024; Gao, 2023; Ahmad et al., 2023; Nair et al., 2023; Munir et al., 2020), whereas others identify a negative relationship (Ganda, 2024). Some have found evidence supporting for the Environmental Kuznets Curve (EKC) hypothesis (Zhang et al., 2022; Andriamahery et al., 2022; Qamruzzaman, 2022; Ahmad et al., 2021; Wasti & Zaidi, 2020). Some studies demonstrated that EC directly impacts $CO_2$ emissions (Ehigiamusoe& Lean, 2019), whereas others find the opposite effect (Gershon et al., 2024). In terms of demographics, some scholars report that rising PG contributes to higher emissions (Khan et al., 2021). Population density has also been incorporated into models by Kihombo et al. (2022) and Ahmad et al. (2021), noting that higher density can exacerbate environmental pressures by increasing resource consumption, traffic congestion, and waste production.

The prevailing methodology utilised in most studies within this research area is the Autoregressive Distributed Lag (ARDL) model introduced by Pesaran et al. (2001) (e.g., Pachiyappan et al., 2021; Aslam et al., 2022; Alam & Hossain, 2024; Meirun et al., 2021; Musa et al., 2024; Pata & Caglar, 2021; Sikder et al., 2022; Usman et al., 2022).The ARDL approach is built on the assumption of a linear and symmetric link between the dependent and explanatory variables. Yet, these assumptions do not always reflect the complexity of economic policy processes. Macroeconomic indicators are subject to volatility, shaped by external shocks as well as structural adjustments occurring at both the sectoral and aggregate levels. Variations in business cycles further undermine the plausibility of these assumptions. Consequently, reliance on a purely linear and symmetric estimation technique risks producing results that may be inaccurate or unreliable.

To overcome the limitations of the conventional ARDL framework, two notable extensions have been developed. Shin and Yu (2014) proposed the Nonlinear ARDL (NARDL) model, which distinguishes between the short- and long-run impacts of positive and negative changes in explanatory variables on the dependent variable, thereby accounting for potential asymmetries. Building on this, Pal and Mitra (2015, 2016) introduced the Multiple Threshold NARDL (MTNARDL), which segments the data into several threshold levels to provide a more detailed assessment of variations in the explanatory variables. The present study employs this advanced methodology to explore the effect of EG, EC and PG on $CO_2$ emissions in Malaysia. The MTNARDL approach accommodates nonlinear interactions across varying growth levels, providing a better understanding of how different EG, EC and PG thresholds influence emissions.

In empirical research, $CO_2$ emissions are commonly used as a central indicator of environmental degradation since they directly reflect fossil fuel consumption and industrial activities, making them a suitable proxy for human-induced environmental pressures (e.g., Adebayo et al., 2023; Akhtar et al., 2023; Azam et al., 2022). Nevertheless, limited attention has been given to examining the joint influence of of EG, EC and PG on Malaysia's $CO_2$ emissions. In addition, much of the existing work has relied on either symmetric or asymmetric models rather than considering both. This study seeks to fill this gap by applying ARDL, NARDL, and MTNARDL techniques to provide a broader evaluation of how these factors are interrelated.

Several key contributions emerge from this study, enhancing our understanding of environmental sustainability and economic development in Malaysia: (1) By examining how EG, EC, and PG interact to influence $CO_2$ emissions, it presents a more comprehensive view of their combined effects. This approach offers more profound insights into their interdependencies, contributing to a broader understanding of emissions dynamics. (2) This study distinguishes the effects of low, moderate, and high levels of EG, EC, and PG on $CO_2$ emissions - an aspect that, to our knowledge, has not been examined before. This refined estimation is made possible by applying the MTNARDL model developed by Pal and Mitra (2015, 2016). Examining these relationships at multiple thresholds is essential, as it allows us to identify specific points at which EG, EC, and PG may intensify emissions or, conversely, support environmental stability. (3) This research adds to the sustainability literature by offering threshold-based insights into the factors that drive emissions within a developing country context. Findings will inform policy formulation in Malaysia, demonstrating how economic, energy, and population policies can be fine-tuned to foster sustainable development while mitigating environmental impacts. A detailed understanding of these dynamics supports policymakers in crafting targeted interventions that align with sustainable development objectives without compromising economic and demographic growth.

## 2. Literature review

Grossman and Krueger's (1995) study initiated a debate on how economic growth interacts with environmental degradation. Their influential work encouraged a surge of empirical investigations into the environmental impacts of economic growth (Hassan et al., 2024; Raihan &Tuspekova, 2022; Ashraf, 2022; Lu, 2020; Ntarmah et al., 2021; Wan & Sheng, 2022). The link between the two is often explained by the early stages of development, when economies focus heavily on expanding production to drive economic progress and improve human well-being. This growth-oriented approach generates a scale effect, where production rises without sufficient pollution control, resulting in greater resource use and higher levels of environmental degradation.


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Over time, as economies advance, structural changes shift production away from heavy industry toward services, a process known as the composition effect. Since the service sector generally has a lighter environmental footprint, this shift eases some of the strain on natural resources. Countries also tend to produce less energy-intensive goods at this stage (Adebayo et al., 2021). In the most advanced phase, technological innovation and stronger environmental priorities take center stage, allowing pollution to decline even as incomes rise. This dynamic produces the well-known inverted U-shaped relationship between environmental deterioration andincome (Afroz et al., 2024; Kirikkaleli& Adebayo, 2021).
However, research shows that many developing countries have yet to reach this turning point, meaning that economic growth still puts upward pressure on emissions (Solaymani, 2022). Beyond growth itself, EC plays a central role in shaping $CO_2$ emissions, especially in developing countries where increasing incomes often lead to greater energy demand (Shaari et al., 2021; Raihan et al., 2022). Evidence suggests that greater EC has a strong, long-term link to emissions, especially from high-impact sectors like industry and transport (Shaari et al., 2022). In the case of Malaysia, electricity generation remains a key driver of $CO_2$ emissions, with coal and natural gas dominating the energy mix (Abdul Latif et al., 2021). While Malaysia has expanded investments in hydropower, solar, and biomass since 2010, fossil fuels still constitute a large share of energy production, posing challenges to achieving carbon neutrality. Shaari et al. (2020) and Abdollahi (2020) argued that the growth of income and the urbanisation process are significant factors that explain the increased emissions. Shaari et al. (2020) highlight the increased electricity consumption by urban households. Abdollahi (2020) highlights unplanned urbanisation as a circumstance that increases emissions both at the national and regional levels.
Population growth has been shown to play a key role in driving $CO_2$ emissions, largely through its influence on energy demand, urbanisation, and industrial expansion. Research consistently finds a positive link between population increases and higher emission levels, with sectors such as agriculture, transportation, and infrastructure contributing most to the resulting environmental strain (Mobaseri et al., 2021; Hasnawati et al., 2024). Rapid population growth intensifies energy demand, reinforcing the link between demographic trends and environmental stress (Hussain et al., 2021). Beyond direct population growth, demographic transitions and urbanisation patterns further shape $CO_2$ emissions. While urban expansion initially supports energy efficiency, excessive population density may ultimately contribute to higher emissions due to congestion and increased resource use (Yang et al., 2021; Wang & Li, 2021).
Ageing populations in advanced economies tend to lower emissions due to reduced consumption of energy-intensive goods. Wealthier nations with slower population growth tend to invest more in clean energy technologies, indicating that the link between demographic trends and emissions is complex. This underscores the need for policies that combine sustainable urban planning, renewable energy investments, and strategies responsive to demographic changes. Rehman and Rehman (2022) notethat nations with large populations, such as India and China, tend to record higher levels of emissions. Population growth remains a key driver of emissions, with urbanisation amplifying its environmental impact.Rahman et al. (2022) examined Malaysia's $CO_2$ emissions concerning population growth, economic expansion, and energy use, emphasising that reliance on coal and oil exacerbates environmental degradation.
Existing research has produced a substantial evidence on the connections between EG, EC, and PG on $CO_2$ emissions. However, much of this work relies on linear or symmetric models, which may overlook nonlinear and regime-specific patterns, an omission that is particularly

relevant for developing economies. In Malaysia, previous studies have shed light on environmental performance, especially in relation to fossil fuel use, urbanisation, and demographic trends. Yet, few have explored how these relationships might shift across different thresholds or regimes. To our knowledge, no prior study has used the MTNARDL framework to jointly examine EG, EC, and PG in shaping Malaysia's $CO_2$ emissions. This study fills that gap by adopting a regime-dependent approach that can capture the nonlinear characteristics of these interactions.

## 3. Research methodology

### Data

We examined the long-term and short-term relationships between EG, EC and PG on $CO_2$ emissions. We used time series data from 1980 to 2022 extracted from the World Development Indicator (WDI) datasets specifically for Malaysia. Information about the data is in Table 1.

Table 1: Source of data and variables.

| Variables | Symbol | Description | Data Sources |
|---|---|---|---|
| $CO_2$emissions | $CO_2$ | Metric tons per capita | WDI |
| Economic Growth | EG | GDP per capita (constant 2015 US$) | WDI |
| Energy Consumption | EC | Kg of oil equivalent per capita | WDI |
| Population Growth | PG | Population growth | WDI |

This study employs three econometric approaches: the ARDL model by Pesaran et al. (2001), the NARDL model by Shin and Yu (2014), and the MTNARDL model developed by Pal and Mitra (2015, 2016). These methods offer several strengths. Notably, they remain applicable whether the variables are integrated of order zero [I(0)] or order one [I(1)], making them versatile across different data conditions. Second, they allow for the simultaneous estimation of both long-run and short-run relationships between variables. Third, the MTNARDL framework goes a step further by considering the influence of the dependent variable on extreme positive and negative values of the independent variable and identifies the response to moderate changes in the independent variable.

Theoretical connections exist between EG, EC, PG, and $CO_2$ emissions. Drawing on the concept of market equilibrium, where emissions tend to rise alongside economic activity, PG, and EC, we adapt the Cobb–Douglas production function to develop Eq. (1) (Biddle, 2012). This specification enables the evaluation of how these socioeconomic factors influence the quality of $CO_2$ emissions.

$$CO_2 = f(EG, EC, PG) \quad (1)$$

where $CO_2$ denotes carbon dioxide emissions, EG refers to GDP per capita, EC represents energy consumption, and PG captures population growth. To account for heterogeneity across variables, the model is expressed in logarithmic form, consistent with the approach used by Junsheng et al. (2024). For the linear ARDL model, both the dependent and independent variables include lagged terms to capture dynamic relationships over time. When the dependent variable is lagged p times and the independent variables are lagged q times, the ARDL framework can be written as:

$$CO_{2t} = \beta_0 + \sum_{i=1}^{p} \beta_1 CO_{2t-i} + \sum_{i=0}^{q} \beta_2 EG_{t-i} + \sum_{i=0}^{q} \beta_3 EC_{t-i} + \sum_{i=0}^{q} \beta_4 PG_{t-i} + \varepsilon_t$$
(2)

In this model, $CO_2$ emissions serve as the dependent variable, while EG, EC, and PG are the independent variables. The term $\beta_0$ represents the intercept, and $\beta_1$ through $\beta_4$ are the coefficients corresponding to $CO_2$, EG, EC, and PG, respectively. The ARDL bounds testing approach is specified as in Eq. (3):

$$\Delta LCO2_t = \beta_0 + \sum_{i=1}^{p} \beta_1 \Delta LCO2_{t-i} + \sum_{i=0}^{q} \beta_2 \Delta LEG_{t-i} + \sum_{i=0}^{q} \beta_3 \Delta LEC_{t-i} + \sum_{i=0}^{q} \beta_4 \Delta LPG_{t-i} + \theta_1 LCO2_{t-1} + \theta_2 LEG_{t-1} + \theta_3 LEC_{t-1} + \theta_4 LPG_{t-1} + \varepsilon_t \quad (3)$$

The symbol Δ refers to the differencing operator, while L indicates the natural logarithm of the variables. In Equation (3), the short-run dynamics are represented by θi (for i= 1 to 4) whereas the long-run relationships are captured by $\beta_1, \beta_2, \beta_3$ and $\beta_4$. Using a reduced form together with the error correction mechanism, Equation (3) can be rewritten in a simplified form as follows:

$$\Delta LCO2_t = \beta_0 + \sum_{i=1}^{p} \beta_1 \Delta LCO2_{t-i} + \sum_{i=0}^{p} \beta_2 \Delta LEG_{t-i} + \sum_{i=0}^{p} \beta_3 \Delta LEC_{t-i} + \sum_{i=0}^{p} \beta_4 \Delta LPG_{t-i} + \theta_i ECT_{t-1} + \varepsilon_t \quad (4)$$

The error correction term (ECT), denoted as θ, reflects the longrun relationship among the variables and indicates how quickly the system returns to equilibrium after short-term disruptions. To build a nonlinear model that accounts for both long run and shortrun asymmetries, the independent variable$x_t$, which influences the dependent variable $y_t$, is divided into two components:$x_t^+$ and $x_t^-$. The positive component $x_t^+$ represents increases in the variable, while the negative component $x_t^-$captures its decreases, allowing the model to distinguish between upward and downward movements in the explanatory variables.

$$x_t^+ = \sum_{i=1}^{t} \Delta x_i^+ = \sum_{i=1}^{t} \max(\Delta x_{i,}, 0) \quad (5)$$

$$x_t^- = \sum_{i=1}^{t} \Delta x_i^- = \sum_{i=1}^{t} \min(\Delta x_{i,}, 0) \quad (6)$$

This method of decomposing independent variables into partial sums to capture asymmetric cointegration has also been applied in recent studies, such as Ahmed et al. (2023) and Akhtar et al. (2023).

By adopting a single threshold NARDL model, this study investigates potential asymmetrical relationships among variables. The choice of this approach stems from the limitations of the conventional symmetric assumption, which treats the impact of independent variables on the dependent variable as uniform when testing for long-run relationships through cointegration. To address this, positive and negative changes in EG, EC, and PG are separated into two distinct series for each variable. This decomposition forms the basis for the equations presented below.

$$LEG_t^+ = \sum_{i=1}^{t} \Delta LEG_i^+ = \sum_{i=1}^{t} \max(\Delta LEG_{i,}, 0) \quad (7)$$

$$LEG_t^- = \sum_{i=1}^{t} \Delta LEG_i^- = \sum_{i=1}^{t} \min(\Delta LEG_{i,}, 0) \quad (8)$$

$$LEC_t^+ = \sum_{i=1}^{t} \Delta LEC_i^+ = \sum_{i=1}^{t} \max(\Delta LEC_{i,}, 0) \quad (9)$$

$$LEC_t^- = \sum_{i=1}^{t} \Delta LEC_i^- = \sum_{i=1}^{t} \min(\Delta LEC_{i,}, 0) \quad (10)$$

$$LPG_t^+ = \sum_{i=1}^{t} \Delta LPG_i^+ = \sum_{i=1}^{t} \max(\Delta LPG_{i,}, 0) \quad (11)$$

$$LPG_t^- = \sum_{i=1}^{t} \Delta LPG_i^- = \sum_{i=1}^{t} \min(\Delta LPG_{i,}, 0) \quad (12)$$

Equations (7) - (12) are integrated into Eq. (3) to form the NARDL model, which is represented as follows:

$$\Delta LCO2_t = \alpha_0 + \gamma_1 LCO2_{t-1} + \gamma_2^+ LEG_{t-1}^+ + \gamma_3^- LEG_{t-1}^- + \gamma_4^+ LEC_{t-1}^+ + \gamma_5^- LEC_{t-1}^- + \gamma_6^+ PG_{t-1}^+ + \gamma_7^- LPG_{t-1}^- + \sum_{i=1}^{p} \alpha_i \Delta LCO2_{t-i} + \sum_{i=0}^{p} (\alpha_i^+ LEG_{t-i}^+ + \alpha_i^- LEG_{t-i}^-) + \sum_{i=0}^{p} (\alpha_i^+ LEC_{t-i}^+ + \alpha_i^- LEC_{t-i}^-) + \sum_{i=0}^{p} (\alpha_i^+ LPG_{t-i}^+ + \alpha_i^- LPG_{t-i}^-) + \mu_i \quad (13)$$

In the equations above, the coefficients $\gamma_1$ to $\gamma_7$ indicate the long-run elasticity coefficients, while $\alpha_i$ denotes the short-run elasticity coefficients.
To study the effects of small and large exchange rate movements on the exports of Economic and Monetary Union (EMU) countries to the United States, Verheyen (2013) extended the single-threshold NARDL model of Shin and Yu (2014) into a two-threshold NARDL framework. In his application, thresholds were set at the 30th and 70th percentiles of exchange rate fluctuations. Building on this, Pal and Mitra (2016) introduced the more general MTNARDL model, demonstrating that multiple-threshold approaches can capture nonlinear relationships more effectively than a single-threshold specification.

The MTNARDL model works by dividing the independent variables into multiple quantiles, enabling analysis of how both small and large changes affect the dependent variable. Following the approach of Pal and Mitra (2015, 2016), later applied by Ayad et al. (2023), Uche and Effiom (2021), Jalal and Gopinathan (2022), Li and Guo (2022), Uche et al. (2023), and Ben-Salha and Ayad (2025), this study examines the asymmetric effects of EG, EC, and PG on $CO_2$ emissions by decomposing each variable into quintiles. Specifically, the independent variables are split at the 25th and 75th percentiles, generating three partial sum series to capture minor, moderate, and major changes in these variables. These quantiles are widely used in empirical research to distinguish low, moderate, and high regimes, as they are data-driven, provide sufficient observations within each regime, and facilitate meaningful economic interpretation.

$$EG_t = EG_0 + EG_t(w_1) + EG_t(w_2) + EG_t(w_3) \quad (14)$$
$$EC_t = EC_0 + EC_t(w_1) + EC_t(w_2) + EC_t(w_3) \quad (15)$$
$$PG_t = PG_0 + PG_t(w_1) + PG_t(w_2) + PG_t(w_3) \quad (16)$$

In Eq. (14), (15) and (16), $EG_t(w_1)$, $EG_t(w_2)$, $EG_t(w_3)$, $EC_t(w_1)$, $EC_t(w_2)$, $EC_t(w_3)$, $PG_t(w_1)$, $PG_t(w_2)$, and $PG_t(w_3)$ are three partial sums where 25th and 75th quintiles of EG, EC and PG are set as two thresholds represented by $\tau_{25}$ and $\tau75$, respectively, and derived as follows:

$$EG_t(w_1) = \sum_{i=1}^{t} \Delta EG_i(w_1) = \sum_{i=1}^{t} \Delta EG_i \, I\{\Delta EG_i \le \tau_{25}\} \quad (17a)$$
$$EG_t(w_2) = \sum_{i=1}^{t} \Delta EG_i(w_2) = \sum_{i=1}^{t} \Delta EG_i \, I\{\tau_{25} \le \Delta EG_i \le \tau_{75}\} \quad (17b)$$
$$EG_t(w_3) = \sum_{i=1}^{t} \Delta EG_i(w_3) = \sum_{i=1}^{t} \Delta EG_i \, I\{\Delta EG_i > \tau_{75}\} \quad (17c)$$
$$EC_t(w_1) = \sum_{i=1}^{t} \Delta EC_i(w_1) = \sum_{i=1}^{t} \Delta EC_i \, I\{\Delta EC_i \le \tau_{25}\} \quad (17d)$$
$$EC_t(w_2) = \sum_{i=1}^{t} \Delta EC_i(w_2) = \sum_{i=1}^{t} \Delta EC_i \, I\{\tau_{25} \le \Delta EC_i \le \tau_{75}\} \quad (17e)$$
$$EC_t(w_3) = \sum_{i=1}^{t} \Delta EC_i(w_3) = \sum_{i=1}^{t} \Delta EC_i \, I\{\Delta EC_i > \tau_{75}\} \quad (17f)$$
$$PG_t(w_1) = \sum_{i=1}^{t} \Delta PG_i(w_1) = \sum_{i=1}^{t} \Delta PG_i \, I\{\Delta PG_i \le \tau_{25}\} \quad (17g)$$
$$PG_t(w_2) = \sum_{i=1}^{t} \Delta PG_i(w_2) = \sum_{i=1}^{t} \Delta PG_i \, I\{\tau_{25} \le \Delta PG_i \le \tau_{75}\} \quad (17h)$$
$$PG_t(w_3) = \sum_{i=1}^{t} \Delta PG_i(w_3) = \sum_{i=1}^{t} \Delta PG_i \, I\{\Delta PG_i > \tau_{75}\} \quad (17i)$$

where $I\{\cdot\}$ is an indicator function with value 1 given the conditions expressed within { } in Eqs. (17a)–(17i) are satisfied. Otherwise, it is zero. This splitting of EG, EC, and PG in quintiles is expressed in a NARDL framework as follows:

$$\Delta CO2_t = \sum_{i=1}^{n1} a_{1i} \Delta CO2_{t-i} + \sum_{j=1}^{3} \sum_{i=0}^{n} a_{ki} \Delta EG_{t-i} w_j + \sum_{j=1}^{3} \sum_{i=0}^{n} a_{ki} \Delta EC_{t-i} w_j + \sum_{j=1}^{3} \sum_{i=0}^{n} a_{ki} \Delta PG_{t-i} w_j + \gamma_1 CO2_{t-1} + \sum_{j=1}^{3} \gamma_k EG_{t-1} w_j + \sum_{j=1}^{3} \gamma_k EC_{t-1} w_j + \sum_{j=1}^{3} \gamma_k PG_{t-1} w_j + \varepsilon_t (18)$$

where k=j+1.

Cointegration among the long-run variables in Eq. (18) can be tested under the null hypothesis $H_0 : \gamma_1 = \gamma_2 = \gamma_3 = \gamma_4 = \gamma_5 = \gamma_6 = \gamma_7 = \gamma_8 = \gamma_9 = \gamma_{10} = 0$.The bounds test can then be conducted using the critical values reported by Wan and Sheng (2022). Following this, we test the null hypothesis$H_0 : \gamma_2 = \gamma_3 = \gamma_4 = \gamma_5 = \gamma_6 = \gamma_7 = \gamma_8 = \gamma_9 = \gamma_{10}$.Rejecting this null at a chosen significance level would indicate the presence of long-run asymmetry between the independent and dependent variables.

## 4. Results and discussions

**Table 2** presents the descriptive statistics for all variables. The statistics show that EC has the highest mean value, whereas PG has the lowest value. Regarding standard deviation, $CO_2$ displays the most significant volatility, reflecting higher variability, while EG shows the least volatility. All variables have standard deviations that are smaller than their corresponding means, indicating that the data is relatively stable and suitable for estimation. From the Skewness statistics, EC and PG show more pronounced negative skewness, suggesting stronger asymmetry compared to $CO_2$ and EG. The lowest kurtosis is observed in $CO_2$, while PG exhibits the highest. These distributional features imply that symmetric linear models may be inadequate. Instead, models that account for asymmetries or non-linear effects may provide a more accurate reflection of the relationships among these variables.

**Table 2:** Descriptive statistics of the data set.

| | **$CO_2$** | **EG** | **EC** | **PG** |
|---|---|---|---|---|
| Mean | 5.446349 | 8.73986 | 10.0389 | 2.25408 |
| Maximum | 8.577 | 9.34132 | 10.5771 | 3.01956 |
| Minimum | 2.121 | 8.05825 | 9.16747 | 1.07936 |
| Std. Dev. | 2.10469 | 0.39759 | 0.46751 | 0.60857 |
| Skewness | -0.244683 | -0.23508 | -0.5678 | -0.6007 |
| Kurtosis | 1.690015 | 1.82257 | 1.8363 | 1.90005 |

**Table 3**presents the results of the unit root tests. The order of integration of the variables was assessed using the Augmented Dickey–Fuller (ADF) test (Dickey & Fuller, 1979) and the Phillips–Perron (PP) test (Phillips & Perron, 1988). Both tests consistently indicate that all variables are nonstationary in their levels but become stationary after first differencing. These findings confirm that none of the variables are integrated at the I(2) level. Based on these findings, the ARDL, NARDL and MTNARDL econometric techniques are recommended, as they accommodate stationary variables at both levels and first differences.

**Table 3:** ADF and PP unit root tests.

| | **Levels** | | | | **First Difference** | | | |
|---|---|---|---|---|---|---|---|---|
| | **Constant** | | **Constant & Trend** | | **Constant** | | **Constant & Trend** | |
| | ADF | PP | ADF | PP | ADF | PP | ADF | PP |
| $LCO_2$ | -1.5826 | -1.6581 | -1.5688 | -1.4757 | -7.5493*** | -7.5091*** | -7.7211*** | -7.7121*** |
| LEG | -0.8711 | -0.8584 | -1.8474 | -2.0098 | -5.4357*** | -5.3894*** | -5.3806*** | -5.3257*** |
| LEC | -2.739 | -2.2891 | -0.7975 | -0.5737 | -6.1559*** | -6.1519*** | -3.9764** | -7.1258*** |
| LPG | 1.1555 | 2.7277 | -1.8597 | -1.2794 | -2.6566* | -2.6331* | -4.5736*** | -3.5986** |

***, **, and * denote statistical significance at 1%, 5%, and 10% respectively.
Source: Authors' own computation.

**Table 4** summarises the results of the ARDL, NARDL, and MTNARDL bounds cointegration tests. The F-statistics are used to determine whether a long-run cointegrating relationship exists among $CO_2$, EG, EC, and PG. Across all three models, the calculated F-statistics exceed the upper bound critical values at the 1%, 5%, and 10% levels, confirming the presence of cointegration among the variables. Thus, the measured cointegration results support the cointegration verification in the ARDL, NARDL and MTNARDL models.

**Table 4:**Bounds cointegration tests.

| Model | Significance level | Critical bound values I(0) | I(1) | F-statistic | Decision |
|---|---|---|---|---|---|
| ARDL | 1% | 3.65 | 4.66 | 9.791*** | Cointegration |
| | 5% | 2.79 | 3.67 | | |
| | 10% | 2.37 | 3.2 | | |
| NARDL | 1% | 2.88 | 3.99 | 6.423*** | Cointegration |
| | 5% | 2.27 | 3.28 | | |
| | 10% | 1.99 | 2.94 | | |
| MTNARDL | 1% | 2.5 | 3.68 | 7.675*** | Cointegration |
| | 5% | 2.04 | 2.08 | | |
| | 10% | 1.8 | 2.8 | | |

*** denote statistical significance at 1%.
Source: Authors' own computation.

**Estimation of linear ARDL Model:**
**Table 5** presents the empirical findings on the short- and long-run effects of EG, EC, and PG on $CO_2$ emissions in Malaysia. The ARDL results reveal a significant positive relationship between EG and $CO_2$ emissions, suggesting that economic expansion contributes to environmental deterioration in the country. This outcome supports previous findings of Junsheng et al. (2024), Aslam et al. (2022), Raihan &Tuspekova (2022), Raihan et al. (2023), Nurgazina et al. (2021) and Aeknarajindawat et al. (2020). Similarly, the results indicate a significant positive relationship between EC and $CO_2$ emissions. This implies that Malaysia's dependence on energy-intensive activities continues to drive up emissions, especially given its reliance on fossil fuel, a trend consistent with Raihan et al. (2023) and Nurgazina et al. (2021). Comparable patterns are also evident in broader contexts, including Ehigiamusoe& Lean (2019), Phrakhruopatnontakitti et al. (2020) and Adeleye et al. (2021), all of which confirm the strong relationship between environmental deterioration and EC. Furthermore, PG is found to have a statistically significant and positive long-run impact on $CO_2$ emissions. This finding aligns with the results of Mobaseri et al. (2021), Hasnawati et al. (2024), as well as Hussain & Rehman (2021), suggesting that Malaysia's PG, coupled with rising energy demand and resource consumption, contributes to increased $CO_2$ emissions. These results emphasize the importance of sustainable population and energy policies to mitigate long-term environmental risks.

**Table 5:** Results of ARDL.

| Variables | Coefficient | Std err. | t-statistic | Probability |
|---|---|---|---|---|
| Long run | | | | |
| LEG | 0.952*** | 0.248 | 3.830 | 0.001 |
| LEC | 0.328* | 0.166 | 1.973 | 0.056 |
| LPG | 0.319*** | 0.104 | 3.083 | 0.004 |
| Short run | | | | |
| ECT(−1) | -0.786*** | 0.107 | -7.365 | 0.000 |
| **Diagnostic tests** | **F-statistic** | **P-value** | | |
| R-squared | 0.985 | | | |
| BGSC LM test | 0.760 | 0.389 | | |
| Adjusted R-squared | 0.984 | | | |
| B-P-G Heteroscedasticity test | 1.035 | 0.402 | | |
| Normality test | 1.314 | 0.518 | | |
| CUSUM | S | | | |
| CUSUMSQ | S | | | |

*** and * denote statistical significance at 1% and 10% respectively.
Source: Authors'own computation.

**Estimation of Nonlinear ARDL model:**
The NARDL approach is employed to assess the asymmetric impacts of EG, EC, and PG on Malaysia's $CO_2$ emissions, with the findings reported in **Table 6**. An unfavourable change in EG exhibits a statistically significant and positive long-run relationship with $CO_2$ emissions at the 5% significance level. This result suggests that an economic downturn contributes to increased $CO_2$ emissions, potentially due to inefficiencies in EC, structural rigidities in the economy, or increased reliance on carbon-intensive industries during recessions. Conversely, a positive change in EG is statistically insignificant. These findings suggest that economic growth in Malaysia may not be inherently carbon-intensive, but downturns exacerbate environmental challenges.

**Table 6:** Results of NARDL.

| Variables | Coefficient | Std err. | t-statistic | Probability |
|---|---|---|---|---|
| Long run | | | | |
| LEG_POS | 0.388 | 0.406 | 0.956 | 0.346 |
| LEG_NEG | 2.257** | 0.988 | 2.284 | 0.029 |
| LEC_POS | 0.719** | 0.287 | 2.504 | 0.018 |
| LEC_NEG | -0.979 | 1.548 | -0.632 | 0.532 |
| LPG_POS | 0.432 | 0.477 | 0.905 | 0.372 |
| LPG_NEG | 0.127 | 0.211 | 0.601 | 0.552 |
| Short run | | | | |
| Δ LP_POS | -1.257 | 0.768 | -1.637 | 0.111 |
| ECT(−1) | -0.793*** | 0.100 | -7.913 | 0.000 |

| Diagnostic tests | F-statistic | P-value |
|---|---|---|
| R-squared | 0.986 | |
| BGSC LM test | 0.119 | 0.888 |
| Adjusted R-squared | 0.983 | |
| B-P-G Heteroscedasticity test | 0.873 | 0.549 |
| Normality test | 2.816 | 0.245 |
| ARCH test (Heteroscedasticity) | 0.461 | 0.501 |
| CUSUM | S | |
| CUSUMSQ | S | |

*** and ** denote statistical significance at 1% and 5% respectively.
Source: Authors' own computation.

For EC, the results show that a positive shock significantly raises $CO_2$ emissions at the 5% level. Specifically, a 1% rise in energy consumption increases $CO_2$ emissions by 0.719%, underscoring Malaysia's reliance on fossil fuel–driven energy sources. This aligns with earlier studies showing that in developing economies, energy growth often comes with greater environmental strain (Shaari et al., 2021; Raihan et al., 2022). Conversely, the negative component of EC shows no significant link to emissions. As for PG, the NARDL results show that neither positive nor negative changes have a significant effect on $CO_2$ emissions. This suggests there may be underlying patterns that the model does not capture. While NARDL is useful for detecting asymmetries, it works under the constraint of a single threshold for separating positive and negative shocks—meaning that relying solely on its results may provide only a partial view of the dynamics at play.

Given the complexity of real-world dynamics, EG, EC, and PG are likely to exert nonlinear effects on $CO_2$ emissions across different quantiles. While the standard NARDL model accommodates asymmetric adjustments, it imposes a uniform structure that may overlook variation across economic conditions. In contrast, the MTNARDL approach captures multiple threshold effects by allowing for heterogeneous responses at various quantile levels. This enhanced framework reduces the risk of oversimplifying asymmetric relationships, which is a key limitation when relying solely on conventional NARDL estimates. Policymaking based on such restricted models may miss critical inflection points in economic, energy, or demographic transitions. By incorporating multiple thresholds, the MTNARDL approach offers a more refined and policy-relevant perspective. This strengthens the reliability of the estimates and provides a more precise understanding of the complex link between economic development and environmental sustainability.

**Estimation of Multiple Thresholds Nonlinear ARDL model:**
**Table 7** presents the MTNARDL results, which shows the effects of independent variables on $CO_2$ emissions in Malaysia when the independent variables are differentiated across low ($w_1$), moderate ($w_2$), and high ($w_3$) levels. The long-run coefficients indicate that EG exerts heterogeneous effects on $CO_2$ emissions across different thresholds. At a moderate level, the coefficient is negative and statistically significant at the 5% level, suggesting that a 1% increase in EG reduces $CO_2$ emissions by about 1.88%. However, at a high level, EG shows a positive and statistically significant effect, leading to an approximate 0.98% rise in $CO_2$ emissions.

**Table 7:** Results of MTNARDL.

| Variables | Coefficient | Std err. | t-statistic | Probability |
|---|---|---|---|---|
| Long run | | | | |
| LEGw1 | -1.280 | 1.101 | -1.162 | 0.260 |
| LEGw2 | -1.884** | 0.653 | -2.885 | 0.010 |
| LEGw3 | 0.986*** | 0.290 | 3.398 | 0.003 |
| LECw1 | 6.718*** | 2.270 | 2.959 | 0.008 |
| LECw2 | -0.789 | 1.220 | -0.646 | 0.526 |
| LECw3 | 0.098 | 0.317 | 0.309 | 0.760 |
| LPGw1 | -2.310*** | 0.713 | -3.241 | 0.004 |
| LPGw2 | -4.463** | 1.932 | -2.310 | 0.032 |
| LPGw3 | 3.284** | 1.294 | 2.537 | 0.020 |
| C | 0.417 | 0.045 | 9.369 | 0.000 |
| Short run | | | | |
| ΔLEGw2 | 0.075 | 0.345 | 0.219 | 0.829 |
| ΔLEGw2(-1) | -0.556 | 0.351 | -1.585 | 0.129 |
| ΔLECw1 | 3.501*** | 0.422 | 8.302 | 0.000 |
| ΔLECw1(-1) | -0.842* | 0.408 | -2.065 | 0.053 |
| ΔLECw2 | -0.541 | 0.315 | -1.720 | 0.102 |
| ΔLECw2(-1) | 2.586*** | 0.334 | 7.745 | 0.000 |
| ΔLPGw1 | -1.539*** | 0.279 | -5.518 | 0.000 |
| ΔLPGw1(-1) | 1.497*** | 0.278 | 5.388 | 0.000 |
| ΔLPGw2 | -2.161*** | 0.573 | -3.774 | 0.001 |
| ΔLPGw2(-1) | 3.568*** | 0.657 | 5.433 | 0.000 |
| ECT(−1) | -0.936*** | 0.082 | -11.352 | 0.000 |
| | | | | |
| **Diagnostic tests** | **F-statistic** | **P-value** | | |
| R-squared | 0.995 | | | |
| BGSC LM test | 3.275 | 0.063 | | |
| Adjusted R-squared | 0.991 | | | |
| B-P-G Heteroscedasticity test | 1.135 | 0.393 | | |
| Normality test | 1.343 | 0.511 | | |
| ARCH test (Heteroscedasticity) | 0.571 | 0.455 | | |
| CUSUM | S | | | |
| CUSUMSQ | S | | | |

***, **, and * denote statistical significance at 1%, 5%, and 10% respectively.
Source: Authors' own computation.

A significant negative relationship observed at the moderate economic growth level suggests that as Malaysia's economy grows moderately, $CO_2$ emissions decline. This pattern may indicate that, during periods of moderate growth, there is greater investment in cleaner energy sources and a shift toward more energy-efficient technologies. It also indicates a possible structural shift in the economy, from carbon-intensive sectors such as heavy manufacturing to less polluting industries like services and high-tech sectors. Moreover, the decline in emissions may signal the effectiveness of environmental regulations and sustainability initiatives implemented during this phase of economic development.

The significant positive relationship observed at the high economic growth level indicates that rapid expansion is linked to increased $CO_2$ emissions. Such growth often brings intensified industrial activity, greater energy consumption, and expanded transportation, as all of which contribute to higher emissions, especially if the energy mix remains fossil fuel–dependent. During these periods, the pursuit of output growth may take precedence over environmental considerations, and rate of economic growth may surpass the speed at which clean technologies are adopted. While this finding generally aligns with the EKC hypothesis, as emissions initially rise with income, it also highlights that, in developing economies, sustained high growth can aggravate environmental degradation unless green transitions keep pace. This result echoes the conclusions of Hunjra et al. (2024), underscoring the need for stronger integration of environmental policies during high-growth phases.

EC exerts a significant positive effect on $CO_2$ emissions at the lower quantiles, where a 1% increase in energy use leads to a 6.72% rise in emissions, statistically significant at the 1% level. At higher quantiles, however, this relationship weakens and loses statistical significance. This suggests that in less developed economic conditions, emissions are largely driven by the carbon-intensive nature of energy use. As the economy advances, the impact of EC becomes less marked, likely due to greater adoption of cleaner energy sources and improvements in energy efficiency. This pattern is consistent with Zhou et al. (2018), who employed a panel quantile regression model and showed that the influence of independent variables on $CO_2$ emissions differs across quantiles, with EC exerting its greatest effect at certain thresholds depending on the development stage of the economies studied.

PG exhibits a nonlinear relationship with $CO_2$ emissions. At the low and moderate levels, PG has a significant negative effect, approximately -2.31% and -4.46%, respectively, implying that population increases at these levels may correspond with more efficient energy use per capita or the benefits of urbanization, such as the adoption of greener infrastructure. However, at higher level, PG shows a significant positive effect of 3.28%, suggesting that once a certain threshold is crossed, the rising population increases demand for energy-intensive goods and services, thereby offsetting earlier efficiency gains. These results align with the findings of Yang et al. (2021) and Wang and Li (2021), who emphasise that while early stages of urban expansion may support energy efficiency, excessive population density can drive up emissions due to congestion, infrastructure strain, and increased resource consumption.

The short-run estimates highlight the immediate and asymmetric effects of the EG, EC and PG on $CO_2$ emissions. The model reveals varying effects across different thresholds. EG does not significantly impact emissions, which is consistent with the short-run neutrality hypothesis. However, EC remains a key driver of $CO_2$ emissions, with positive and significant effects across all levels. Specifically, a 1% increase in EC raises emissions by 3.50% at the low level, while the coefficient for ΔLECw2(-1) is also positive and significant (2.59), underscoring the role of EC as a persistent driver of emissions at the moderate level. This finding is in line with the findings reported by Shaari et al. (2022). PG exhibits strong asymmetric effects. At low and moderate levels, PG exerts significant adverse effects on emissions. However, the effect reverses at high levels. This suggests that PG initially reduces emissions through resource conservation but eventually increases emissions as consumption pressures intensify. This pattern mirrors the long-run results, reinforcing the uneven influence of PG on environmental quality.

The Error Correction Model (ECM) coefficient is negative and statistically significant at the 1% level, indicating a speed of adjustment of approximately 93.6%. This suggests a rapid convergence to the long-run equilibrium following short-run shocks. Thus, Malaysia's

environmental policies should focus on both short-term interventions and long-term sustainability strategies. Short-term policies could include stricter vehicle emission regulations and subsidies for electric vehicles, while long-term policies should focus on transforming energy infrastructure and industrial production methods to achieve net-zero emissions. These recommendations align with Malaysia's national sustainability objectives, including the Shared Prosperity Vision 2030 and the Low Carbon Cities Framework, while ensuring that economic progress is achieved without compromising environmental integrity.
The diagnostic test results confirm the model's reliability. The Breusch-Godfrey LM test shows no serial correlation at the 10% significance level, and the Breusch-Pagan-Godfrey test finds no signs of heteroskedasticity. The Jarque-Bera test indicates that the residuals follow a normal distribution. Both the CUSUM and CUSUMSQ tests confirm the model's stability throughout the sample period. With an adjusted R-squared of 0.991, the model demonstrates strong explanatory power, indicating that the MTNARDL framework offers a better fit than linear or zero-threshold alternatives.

**Robustness analysis.**

**Table 8**presents the results for DOLS, FMOLS, and CCR tests. We validated the long-term estimates derived from the ARDL estimator using these three single-equation estimator techniques. The FMOLS estimator assumes a single cointegration relationship and employs a semiparametric correction to address issues stemming from the long-term association between cointegration and stochastic factors. Similarly, the CCR estimator resolves cointegration challenges without altering stationary data. The DOLS test is advantageous for removing endogeneity, reducing sample size bias, and accommodating variables with varying integration orders within the cointegration framework. By comparing the results from the long-term ARDL estimation and the results from these three tests, we can see that the signs for EG, EC, and PG are consistent. Additionally, the findings of DOLS, FMOLS, and CCR align with the long-run outcomes from the nonlinear ARDL model for EG, EC, and PG.

**Table 8**:DOLS, FMOLS and CCR estimation results.

| Variables | Coefficient | Std err. | t-statistic | Probability |
|---|---|---|---|---|
| Method: DOLS | | | | |
| LEG | 1.046*** | 0.314 | 3.334 | 0.003 |
| LEC | 0.278 | 0.213 | 1.305 | 0.203 |
| LPG | 0.350** | 0.140 | 2.507 | 0.019 |
| C | -4.615 | 0.407 | -11.351 | 0.000 |
| Method: FMOLS | | | | |
| LEG | 1.008*** | 0.238 | 4.234 | 0.000 |
| LEC | 0.300* | 0.159 | 1.884 | 0.067 |
| LPG | 0.342*** | 0.099 | 3.464 | 0.001 |
| C | -4.556*** | 0.311 | -14.638 | 0.000 |
| Method: CCR | | | | |
| LEG | 0.993*** | 0.239 | 4.156 | 0.000 |
| LEC | 0.308* | 0.162 | 1.900 | 0.065 |
| LPG | 0.339*** | 0.098 | 3.464 | 0.001 |
| C | -4.529 | 0.291 | -15.566 | 0.000 |

***, **, and * denote statistical significance at 1%, 5%, and 10% respectively.
Source: Authors' own computation.

## 5. Conclusion

This study examines how EG, EC, and PG influence $CO_2$ emissions in Malaysia, by applying the ARDL, NARDL, and MTNARDL models. The ARDL approach captures both short and long term relationships but is limited by its assumption that the effects are symmetrical. The NARDL model addresses this by allowing asymmetry, although it still applies uniform relationships across different stages of development indicators. The MTNARDL further advances the analysis by incorporating multiple thresholds, enabling a more nuanced understanding of how EG, EC, and PG affect emissions under varying economic conditions.

The findings reveal that EG reduces emissions at moderate growth levels but contributes to higher emissions at advanced stages. EC is consistently a major driver of emissions, particularly at lower consumption levels, though its effect diminishes as energy efficiency improves. PG demonstrates asymmetric behavior, initially contributing to lower emissions but eventually driving them upward as consumption intensifies. In the short run, EC remains the dominant factor influencing emissions, while PG shows varying effects across population levels.

These outcomes suggest the need for tailored policy responses. As Malaysia advances toward a high-income economy, sustainability must be embedded in growth strategies. Green growth policies, stricter regulations for high-emission sectors, and increased investment in clean technology, particularly in energy-intensive industries are essential. The strong link between EC and emissions underscores the urgency of implementing carbon pricing mechanisms, enhancing energy efficiency and transitioning to renewable energy. Energy efficiency must be improved through updated infrastructure standards and industry incentives. Additionally, policies addressing PG should include sustainable urban planning, support for rural development, and public awareness campaigns on responsible consumption. Strengthening regulatory institutions and participating in international climate initiatives can further support emission reduction efforts.

Overall, the MTNARDL approach provides deeper insight into the complex and nonlinear relationships among EG, EC, PG, and $CO_2$ emissions. Despite its contributions, the study has certain limitations. Its focus is solely on Malaysia, which may restrict the applicability of the findings to other contexts. Future work could expand the scope by applying the MTNARDL model in a cross-country setting to enable broader comparisons. The use of national-level data may also overlook sector-specific variations, which disaggregated studies could help clarify. Finally, incorporating environmental policy variables would improve understanding of how regulations influence the emissions–growth nexus. In summary, the MTNARDL model offers deeper insight into the complex and changing relationships among EG, EC, PG, and $CO_2$ emissions. The results highlight the need for differentiated evidence-based policy responses to support Malaysia's transition toward a low-carbon and sustainable development path.

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