

Examining the Relationship between CO₂ Emissions and Economic Efficiency in Malaysia: A Longitudinal Analysis

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Abstract: *Current statistics reveal that Malaysia's greenhouse gas emissions have risen in recent decades, notably carbon dioxide (CO₂) emissions, mostly attributable to a surge in the nation's energy demand. Comprehending the impact of CO₂ emissions on economic efficiency is significant, as Malaysia needs to optimise efficiency to achieve high-income status. Nonetheless, there have been limited previous studies on the impact of CO₂ emissions on Malaysia's economic efficiency. Therefore, this study aims to determine how CO₂ emissions affect Malaysia's economic efficiency through two phases: quantitative and qualitative approaches. This study contributes to the existing knowledge by examining the effect of CO₂ emissions on Malaysia's economic efficiency (1970-2018) through the ARDL (Autoregressive Distributed Lag) cointegration method. The findings indicate that CO₂ emissions and economic efficiency have a favourable correlation in the short term, but a negative correlation in the long term. The green total factor productivity (GTFP) is also used in this study as an additional indicator of how efficient the economy is. A positive GTFP shows that Malaysia is making quick progress in becoming economically efficient. Appropriate environmental protection policies related to CO₂ emissions, such as a carbon pricing scheme, were suggested to increase economic efficiency and accomplish sustainability in Malaysia.*

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1. Introduction

People often view efficiency as a solution to the transition towards a more sustainable economy and society. Efficiency allows the economy to grow unimpeded while reducing resource consumption (Dahmus & Gutowski, 2005). Kalirajan (1989) suggests that economic efficiency has two main components: the ability to maximise output from a given set of inputs and the ability to maximise profits by equating the marginal revenue product with the marginal cost of inputs. Generally, economic efficiency measures the difference between potential and actual output for a given input combination to achieve profit maximisation. In fact, a substantial improvement in economic efficiency could help to explain the more rapid economic growth. Furthermore, economic efficiency serves as a key indicator of economic performance, reflecting how effectively a country or firm utilises its resources to achieve its intended goals (Succurro, 2021). High economic efficiency enables countries to achieve their objectives more effectively, resulting in increased productivity, higher standards of living, and sustainable growth. A country needs to be efficient, with every resource allocated optimally, and the production of goods is at its lowest cost, which directly enhances overall economic performance.

In the context of analysing how efficiently the input and output are employed in the economy, the capital-labour ratio and economic output ultimately play an important role. For equal rates of capital formation, economies that convert inputs (e.g., labour force) into output (e.g., Gross Domestic Product) relatively inefficiently will grow more slowly than efficient economies. Thus, labour is an essential element of a sustainable economy, and investing in human capital is critical to sustaining increases in economic efficiency. Any change in labour supply (as input) can have an impact on workers' productivity, production output, and economic growth, resulting in an inefficient economy (Schipke, 2001). However, given that air pollution has become a widespread health hazard in many countries, its moderate effects on poor health outcomes may exert important influences on labour productivity and an inefficient economy (Zivin & Neidell, 2012).

Malaysia is one of the ASEAN countries with the highest per capita greenhouse gas emissions (World Bank, 2020). Although Malaysia's GHG emissions account for only 0.1 per cent of global GHG emissions, the rising trend of GHG emissions in Malaysia has become a leading environmental issue (World Bank, 2020). When many developed countries have successfully reduced GHG emissions, Malaysia seems to increase its emissions level, largely driven by major sources such as industrial and agricultural sectors, as well as increasing energy demand to support economic growth and urbanisation (Abidin, 2015; Ismail et al., 2020; Zaid et al., 2015). Malaysia's CO₂ emissions have steadily increased from 2000 to 2019, according to the World Bank (2020). Malaysia's cumulative CO₂ emissions have increased by 212 per cent since 2000, rising from 1.84 billion tonnes in 2000 to 5.73 billion tonnes in 2019.

Studies that have already been done on CO₂ emissions in Malaysia have only looked at big issues like the current situation, problems, and the creation of new policies (Babatunde, Said & Md Noor, 2018); the impact of CO₂ emissions on different economic sectors (Azmi & Tokai, 2016); and the link between carbon emissions and economic growth (Tan & Tan, 2018). To our knowledge, very few studies have explored the relationship between CO₂ emissions and economic efficiency. This paper fills these gaps in the literature and adds to what is known by showing that we must study how CO₂ emissions affect economic efficiency. The main goal of this study is to find out how CO₂ emissions affect Malaysia's economic efficiency. The first part uses the Data Envelopment Analysis (DEA) as a quantitative method to measure economic efficiency. Additionally, in the second phase, this study incorporates the green total factor productivity (GTFP) as a qualitative measure of economic efficiency in Malaysia. This is consistent with the government's Green Technology Master Plan 2017-2030, which aims to transform Malaysia into a low-carbon and resource-efficient economy. Understanding the effect of CO₂ emissions on economic efficiency is important as Malaysia must be efficient to become a high-income country. Besides that, this study may have important practical policy implications for both the government and private sectors, proposing appropriate policies for controlling CO₂ emissions to increase economic efficiency.

The remainder of the paper is organised as follows: Section 2 reviews the related literature and develops the main hypothesis, Section 3 outlines the research method, Section 4 presents the empirical findings, and the final section concludes with policy recommendations.

2. Reviews of Literature

2.1 *Reviews related to economic efficiency*

Farrell (1957) was among the first scholars to classify efficiency into three types: technical, allocative, and economic efficiency. In this study, we focus on economic efficiency, which reflects overall production performance and is defined as the product of technical and allocative efficiency (Iticha, 2020). According to Meireles (2023) and Murillo-Zamorano (2004), economic efficiency captures the firm's ability to maximise profit by equating the marginal revenue product of each input to its marginal cost. Barro's model establishes a theoretical link between efficiency and growth. Later, in a basic fiscal policy model by Barro and Sala-i-Martin (1995), it is simple to explicitly introduce efficiency and illustrate how it affects growth. In summary, both models indicate the relevance of measuring economic growth and identifying the determinants of economic efficiency. Additionally, Succurro (2021) recognised that economic efficiency can lead to increased economic growth and, consequently, enhanced overall economic performance. By referencing Barro's models and Succurro's findings, this study expands the literature on the impact of CO₂ emissions on economic growth, reflecting the importance of economic efficiency.

2.2 *Reviews related to carbon dioxide (CO₂) and economic growth*

Recent studies have increasingly explored the relationship between CO₂ emissions and economic growth (Choudhury et al., 2023; Khan et al., 2024). Studies such as Mardani et al. (2019) and Bekar (2018) indicate that while greenhouse gas emissions can harm the environment, they can also support economic growth due to high energy demand. Increased energy consumption, associated with production and industrial activity, generally boosts economic development but can reduce economic efficiency if excessive (Liou et al., 2015; Halkos & Tzeremes, 2013). Several studies across countries, including Begum et al. (2020) and Omri et al. (2014), report a positive and significant relationship between CO₂ emissions and per capita economic growth. These findings support the Environmental Kuznets Curve (EKC) theory, which suggests that in the early stages of growth, industrialisation and urbanisation increase environmental degradation even as they drive

economic development. Based on the discussion above, it is hypothesised that:

H₁ Carbon dioxide has a positive impact on economic efficiency

Reducing carbon emissions is critical to mitigating the effects of global warming. However, the government is unwilling to reduce carbon emissions at the expense of economic growth (Du et al., 2022). Previous studies have shown mixed effects of emissions on growth. For example, Borhan et al. (2011) found that higher pollution reduces income by lowering labour and capital productivity, while Xiong et al. (2017) reported that decreases in carbon emissions are linked to faster economic value growth. Other studies highlight the broader relationship between economic growth and environmental quality. For instance, Stern (2004) showed that higher income can improve environmental quality through reduced emissions, and Tamazian and Rao (2010) found that growth in BRIC countries helps reduce environmental degradation. Wu et al. (2018) observed similar trends in some developed countries, whereas Schandl et al. (2016) argued that rapid development can increase emissions. Based on the discussion above, it is hypothesised that:

H₂ Environmental degradation increases in the early stages of economic growth

2.3 Reviews related to macroeconomic factors and economic growth

Government spending is a key tool for development, influencing economic performance by improving income distribution, allocating resources to key sectors, and affecting national income (Ahuja & Pandit, 2020; Chandana et al., 2020). Previous studies show that inflation often negatively impacts economic growth, though the strength of this effect varies with inflation levels, highlighting the importance of monitoring price stability (Azam & Khan, 2022; Ekinici et al., 2020). Money supply also significantly affects growth, with a higher supply encouraging spending and boosting GDP (Buthelezi, 2023; Dinh, 2020). Meanwhile, trade openness can either reduce growth by exposing countries to external shocks, particularly when exports are concentrated, or promote growth, as seen in high-income economies (Kong et al., 2021; Smaoui & Nechi, 2017).

2.4 Reviews related to Green Total Factor Productivity (GTFP)

Prior studies on green total factor productivity (GTFP) have examined both macro-level determinants (Li & Liao, 2020; Martinez-Zarsozo et al., 2019) and factors affecting specific industries or regions (Balenzentis et al., 2020; Ghosal et al., 2019). Traditional total factor productivity (TFP) measures focus on quantitative inputs, often overlooking qualitative aspects of economic efficiency (Elfaki & Ahmed, 2023; Syed & Alola, 2023). To address this, GTFP incorporates environmental and technological impacts in production (Cao, 2007). Studies show that labour, physical capital, technology, and globalisation positively influence economic growth (Elfaki & Ahmed, 2024; Zhang et al., 2023), highlighting the importance of these factors in sustainable economic development.

In conclusion, our study fills the gap in the literature and makes contributions to the body of knowledge by analysing the effect of CO₂ emissions on economic efficiency in Malaysia, whereby economic efficiency is measured by using the Data Envelopment Analysis (DEA) approach and green total factor productivity (GTFP) approach. Understanding the impact of CO₂ emissions on economic efficiency is therefore essential for formulating effective government policies that address environmental concerns while promoting sustainable economic growth in Malaysia. This is a critical issue, as Malaysia must enhance its economic efficiency to remain competitive and achieve the status of high-income economy.

3. Model, Data and Empirical Methodology

3.1 Empirical model for first phase

The main objective of this study is to determine how carbon dioxide (CO₂) emissions affect Malaysia's economic efficiency. To achieve the objective, the econometric model is estimated as in Equation (1), where economic efficiency is the dependent variable. We control for government spending, inflation, money supply and trade openness to determine the effect of CO₂ emissions on a country's economy in the model. According to Noman and Khudri (2015) and Tan et al. (2020) the government's monetary and fiscal policies have a significant impact on the country's growth; thus, such variables should be regarded as control variables. Thus, we use a

Multivariate regression equation that can be written as in Equation (1).

$$EFFC_t = \beta_0 + \beta_1 CO_{2t} + \beta_2 GOV_t + \beta_3 INF_t + \beta_4 MS_t + \beta_5 TRADE_t + \varepsilon_t \quad (1)$$

where, *EFFC* represents Malaysia's efficiency at year *t*. CO₂ represents Malaysia's carbon dioxide (CO₂) emissions at year *t*. Variables *GOV*, *INF*, *MS* and *TRADE*, as shown in Equation (1), represent Malaysia's government spending, inflation, money supply and trade openness at year *t*.

To measure the country's economic efficiency, we use the non-parametric Data Envelopment Analysis (DEA) approach. DEA can optimise the relationship between GDP and CO₂ emissions (Wang et al., 2016). Since undesirable outputs like CO₂ emissions must be considered (Singpai & Wu, 2021), this study applies DEA to assess economic efficiency while accounting for the impact of carbon emissions

Following Banker and Morey (1986), we measure Malaysia's economic efficiency based on the production of two inputs and one output (without reducing the level of output). In examining the country's efficiency analysis, we use the variable return to scale (VRS) model, which implies that output levels cannot exceed the levels of input. The technical efficiency scores for Malaysia can be obtained by solving the following model as in Equation (2).

$$\begin{aligned} & \text{Max } \theta \\ & \text{Subject to} \\ & \sum_{i=1}^n \mu_i x_{ij} \leq x_{i0} \quad j = 1, 2, \dots, m \\ & \sum_{i=1}^n \mu_i y_{ri} \geq \theta y_{r0} \quad r = 1, 2, \dots, m \\ & \sum_{i=1}^n \mu_i = 1 \\ & \theta_i \geq 0 \quad i = 1, 2, \dots, n \end{aligned} \quad (2)$$

where;

x_i represents inputs; are total labor force and gross capital

y_r represents output; is Gross Domestic Product (GDP)

This study adopts the Slack-Based Measure (SBM) model proposed by Tone (2001) to measure the efficiency of Decision-Making Units (DMUs) under variable returns to scale (VRS) technology. It also builds upon studies by Kao and Hwang (2021), and Liu et al. (2010), which highlight the incorporation of undesirable outputs in efficiency measurement. In summary, when undesirable outputs U_{fk} , $f = 1, \dots, h$ are generated, the efficiency of a DMU under the conventional disposability assumption can be measured as in Equation (3).

$$\rho = \min. \frac{1 - \frac{1}{m+h} \left(\sum_{i=1}^m \frac{s_i^X}{X_{ik}} + \sum_{f=1}^h \frac{s_f^U}{U_{fk}} \right)}{1 + \frac{1}{s} \sum_{r=1}^s \frac{s_r^Y}{Y_{rk}}} \quad (3)$$

where p is the efficiency score. The inputs (labour and capital) are represented by X_{ik} and s_i^X represents the excess amount of each input that could be reduced. The undesirable outputs (in this study, referring to CO₂ emissions), represented by U_{fk} and s_f^U , refers to the extent to which these emissions exceed the efficient levels. The desirable outputs (GDP) are denoted by Y_{rk} , and s_r^Y reflects any shortfall in achieving optimal output levels.

3.2 Autoregressive distributed lag (ARDL) test

The stationary properties of the variables are tested using the Augmented Dickey-Fuller (ADF) unit root test. The Johansen Cointegration Test was also employed to identify stable, long-term relationships among the variables. In exploring the long-run relationship between economic efficiency, carbon emissions and other macroeconomic drivers such as government spending, inflation, money supply and trade openness, the autoregressive distributed lag (ARDL) framework is used in this study. In this study, the Akaike information criterion (AIC) is employed to determine the optimal number of lags in the model.

The ARDL approach for cointegration by Pesaran et al. (2001) can be performed via the error correction version of the ARDL model as in Equation (4).

$$\Delta y_1 = c + \gamma_0 y_{t-1} + \gamma_1 y_{t-1} + \sum_{i=1}^{p-1} b_{1i} \Delta y_{t-1} + \sum_{i=1}^{p-1} b_{2i} \Delta x_{t-1} + u_t \quad (4)$$

In testing the cointegration relationship between x and y , we test $H_0: \gamma_0 = \gamma_1 = 0$ (nonexistence of the long-run relationship) against $H_A: \gamma_0 \neq 0, \gamma_1 \neq 0$ (a long-run relationship) by using the F-statistic. If the F-statistic value is higher than the critical value, then the null hypothesis can be rejected. Thus, there is a long-run relationship between the variables in the model. In Equation (4), all variables are as previously defined. The orders of the lag of explanatory variables are selected using the Akaike Information Criterion (AIC).

From the estimated ARDL model, the long-run and short-run estimated coefficients provide some useful information on the relationship. Following Chia and Lim (2015), the estimation on the long-run ARDL model for the economic efficiency is as in Equation (5).

$$\begin{aligned} \ln EFFC_t = & \delta_{1,0} + \sum_{i=1}^{p_{11}} \delta_{1,1i} \ln EFFC_{t-1} + \sum_{i=0}^{q_{11}} \delta_{1,2i} \ln CO_{2t-1} + \sum_{i=0}^{q_{12}} \delta_{1,3i} \ln GOV_{t-1} \\ & + \sum_{i=0}^{q_{13}} \delta_{1,4i} \ln INF_{t-1} + \sum_{i=0}^{q_{14}} \delta_{1,5i} \ln MS_{t-1} + \sum_{i=0}^{q_{15}} \delta_{1,6i} \ln TRADE_{t-1} + \xi_{2,t} \end{aligned} \quad (5)$$

The estimated residual series of the model is known as the error correction term (ECT). Next, the error correction model associated is estimated with one lagged ECT to obtain the short-run dynamic parameters. The error correction model is based on the re-parameterisation of the estimated long-run ARDL model and it is stated as in Equation (6).

$$\begin{aligned} \Delta \ln EFFC_t = & \mu_{1,0} + \sum_{i=1}^{p_{11}} \mu_{1,1i} \Delta \ln EFFC_{t-1} + \sum_{i=0}^{q_{11}} \mu_{1,2i} \Delta \ln CO_{2t-1} + \sum_{i=0}^{q_{12}} \mu_{1,3i} \Delta \ln GOV_{t-1} \\ & + \sum_{i=0}^{q_{13}} \mu_{1,4i} \Delta \ln INF_{t-1} + \sum_{i=0}^{q_{14}} \mu_{1,5i} \Delta \ln MS_{t-1} + \sum_{i=0}^{q_{15}} \mu_{1,6i} \Delta \ln TRADE_{t-1} \\ & + \theta_1 ECT_{1,t-1} + e_{1,t} \end{aligned} \quad (6)$$

3.3 Empirical model for second phase

This study also incorporates the green total factor productivity (GTFP) as another measure of economic efficiency in Malaysia. GTFP measures the level of output at a certain level of input in the qualitative aspect, through plugging the estimated regressor parameters into the GTFP model to compute productivity factors by including environmental and technology impacts associated with production (Syed & Alola, 2023).

Following Ahmed (2020), Elfaki and Ahmed (2024), and Syed and Alola (2023), the production function for this study is based on the traditional form as expressed in the Equation (7).

$$GDP_T = f(LABOR_t, CAPITAL_t, CO_{2t}, GLOBAL_t, \mu_t) \quad (7)$$

where t refers to time, GDP is real gross domestic product (GDP) and represents aggregate output, $LABOR$ is the labour force, and $CAPITAL$ is gross capital. CO_2 refers to the carbon dioxide emissions, which include the negative impacts of pollutant emissions. $GLOBAL$ refers to the globalisation index that includes the positive impacts of globalisation variables. While μ is residual and a proxy for GTFP as the progress of technology indicators of globalisation.

According to Ahmed and Elfaki (2023) and Elfaki and Ahmed (2024), the comprehensive growth theory illustrating the relationships among labour forces, gross capital, CO_2 , globalisation, and GDP is represented in the Equation (8).

$$\Delta \ln GDP_t = \alpha + \beta \Delta \ln LABOR_t + \gamma \Delta \ln CAPITAL_t + \rho \Delta \ln CO_{2t} + \varphi \Delta \ln GLOBAL_t + \mu_t \quad (8)$$

where α indicates constant, β represents the labour force, γ represents gross capital; ρ represents carbon dioxide emissions (CO_2), φ represents globalisation, μ indicates the residual term, $\ln$ indicates the logarithm to convert the series and Δ indicates the proportional change rate.

Next, the calculation of the growth rates for productivity factors by converting Equation (8) into the fundamental growth measurement framework, where the constant is excluded from productivity growth calculations (Ahmed, 2020). The extended framework follows Elfaki and Ahmed (2024) and Syed and Alola (2023) as in Equation (9).

$$\Delta \ln GTFP_t = \Delta \ln GDP_t - [\beta \Delta \ln LABOR_t + \gamma \Delta \ln CAPITAL_t + \rho \Delta \ln CO_{2t} + \varphi \Delta \ln GLOBAL_t] \quad (9)$$

where $\Delta \ln GTFP$ signifies GTFP growth rate, $\Delta \ln GDP$ denotes the gross domestic product, $\beta \Delta \ln LABOR$ denotes the labour force contribution; $\gamma \Delta \ln CAPITAL$ denotes the gross capital contribution, $\rho \Delta \ln CO_2$ denotes the carbon dioxide emissions contribution and $\varphi \Delta \ln GLOBAL$ denotes the globalisation contribution.

3.4 Data sources

This study utilises yearly data spanning from 1970 to 2018 for all variables. In this study, we measure Malaysia's economic efficiency based on the production of two inputs and one output. The inputs used are the total labour force and gross capital formation in USD, at current prices in millions. The output data used is the Gross Domestic Product (GDP) in USD, at current prices in millions and market price in volumes.

Data on Malaysia's economic efficiency, carbon dioxide (CO₂) emissions, government spending, inflation, money supply, and trade openness were primarily obtained from published reports. The details of the variables, their data sources, and measurement units are presented in Table 1.

Table 1: Variables, sources of data and measurement units

Variables	Sources	Measurement Units
EFFC	Department of Statistics Malaysia/Bank Negara Malaysia	Output/Input 1: efficient or < 1: less efficient
GDP	Department of Statistics Malaysia/Bank Negara Malaysia	Millions (USD)
CAPITAL	Department of Statistics Malaysia/Bank Negara Malaysia	Millions (USD)
LABOR	Department of Statistics Malaysia/Bank Negara Malaysia	Number of labors
CO ₂	Malaysia Energy Commission report/International Energy Agency (IEA)/Ministry of Water/Land and Natural Resources Malaysia/World Bank Open Data	Metric tons per capita
GOV	Department of Statistics Malaysia/ Bank Negara Malaysia/ World Bank Open Data	Millions (USD)
INF	Department of Statistics Malaysia/ Bank Negara Malaysia/ World Bank Open Data	CPI Index

Variables	Sources	Measurement Units
MS	Department of Statistics Malaysia/ Bank Negara Malaysia/ World Bank Open Data	Millions (USD)
TRADE	Department of Statistics Malaysia/ Bank Negara Malaysia/ World Bank Open Data	Millions (USD)
GLOBAL	KOF Global Index	Globalization Index

4. Empirical Results and Discussions

4.1 First phase: Quantitative analysis

Table 2 presents the descriptive statistics for the first phase of the variables used in the estimation of the regression of the economic efficiency model.

Table 2: Descriptive statistics of variables

Variables	Mean	Minimum	Maximum	Standard Deviation
EFFC	0.907	0.738	1.000	0.083056
CO ₂	4.575	1.352	8.530	2.437919
GOV	70101.47	2163.000	230960.5	75113.00
INF	68.767	23.400	120.700	28.45555
MS	485752.5	4838.600	1894517.0	565007.2
TRADE	0.820	0.105	1.544	0.527389

Source: Department of Statistics Malaysia

According to Table 2, Malaysia released a maximum of 8.530 metric tons per capita of carbon emissions in 2016. In fact, from 2013 until 2018, Malaysia's carbon emissions increased by more than 8.0 metric tons per capita compared to previous years. According to the World Bank Report, Malaysia has recorded a steady increase in carbon emissions from 1970 to 2018 - the study years. The population growth, high income and rapid growth of cities and urbanisation in Malaysia have led to an increase in energy demand for the production and transportation sector, with an alarming growth of carbon emissions caused by the escalating number of vehicles, factories, and power plants (Zaid et al., 2015).

This study used an efficiency score to determine if Malaysia is efficient in optimising the number of outputs produced with the lowest per-unit cost of production to promote economic growth. Malaysia achieved a maximum score value of 1.0 for efficiency, which demonstrates that a high economic efficiency could optimise the status of the economy, representing a higher productivity of high wages (Drennan & Brecher, 2012). This is due to Malaysia's rapid expansion in the service-based and industry-based economies in recent years.

The stability of the models between economic efficiency and its determinants is assessed using a diagnostic check as in Table 3 and Table 4.

Table 3: Stationary results based on ADF unit root test

Variables	Level (0)	First Difference (I)	Outcome
EFF	-2.654557	-5.410066*	I(1)
CO ₂	-0.385542	-8.086947*	I(1)
GOV	1.317388	-3.701809*	I(1)
INF	1.393207	-3.787535*	I(1)
MS	3.198574	-3.860241*	I(1)
TRADE	-0.470290	-7.078245*	I(1)

NOTE: * denotes significant level based on MacKinnon's critical value at 1%.

Table 4: Stationary results based on Philip-Perron unit root test

Variables	PP Statistic	PP Critical Value (5%)
(a) Stationary test at level		
EFF	-4.107997	-3.506374
CO ₂	-1.377894	-3.506374
GOV	2.695088	-3.506374
INF	-1.615008	-3.506374
MS	1.626944	-3.506374
TRADE	1.340390	-3.506374
(b) Stationary test at first difference		
EFF	-8.70138	-3.508508
CO ₂	-11.22394	-3.508508
GOV	8.036111	-3.508508
INF	-5.740171	-3.508508
MS	4.860241	-3.508508
TRADE	5.413528	-3.508508

Source: Author's own work

Results in Table 3 and Table 4 show that all variables achieved stationary status after the first differencing, and it can be concluded that these variables are $I(1)$ process.

The structures of the causal relationships between variables were analysed through the Granger causality approach. The Granger causality test is a statistical hypothesis test for determining whether one-time series is useful for forecasting another. If the probability value is less than any significant level, then the hypothesis would be rejected at that significant level. Table 5 shows the result of pairwise Granger Causality tests. When eight lags are applied, the results found that there is unidirectional causality running from CO_2 to EFFC, GOV to EFFC, MS to EFFC, INF to EFFC and TRADE to EFFC at the 1 % and 5% level of significance. Meanwhile, unidirectional causality running from CO_2 to EFFC, GOV to EFFC, MS to EFFC, INF to EFFC and TRADE to EFFC when nine lags were applied at the 5% and 10% levels of significance was revealed. Since the probability values are below the stated significance thresholds for these relationships, the null hypothesis is rejected.

Table 5: Pairwise Granger Causality tests

No. of Lags	Null Hypothesis	Obs.	F-Statistics	Prob.
8	lnCO2 does not Granger Cause lnEFFC	41	2.33671	0.0515
	lnEFFC does not Granger Cause lnCO2		0.91383	0.5219
	lnGOV does not Granger Cause lnEFFC	41	2.55296	0.0361
	lnEFFC does not Granger Cause lnGOV		1.49490	0.2110
	lnINF does not Granger Cause lnEFFC	41	2.31096	0.0554
	lnEFFC does not Granger Cause lnINF		0.81933	0.5797
	lnMS does not Granger Cause lnEFFC	41	2.41264	0.0455
	lnEFFC does not Granger Cause lnMS		0.85701	0.5643
	lnTRADE does not Granger Cause lnEFFC	41	3.17858	0.0133
	lnEFFC does not Granger Cause lnTRADE		0.35369	0.6346

No. of Lags	Null Hypothesis	Obs.	F-Statistics	Prob.
9	lnCO2 does not Granger Cause lnEFFC	40	2.08307	0.0798
	lnEFFC does not Granger Cause lnCO2		0.92992	0.5200
	lnGOV does not Granger Cause lnEFFC	40	2.84769	0.0231
	lnEFFC does not Granger Cause lnGOV		1.32711	0.2817
	INF does not Granger Cause lnEFFC	40	1.88757	0.1003
	lnEFFC does not Granger Cause INF		0.92676	0.5125
	lnMS does not Granger Cause lnEFFC	40	1.96085	0.0979
	lnEFFC does not Granger Cause lnMS		0.69867	0.7031
	lnTRADE does not Granger Cause lnEFFC	40	2.48416	0.0413
	lnEFFC does not Granger Cause lnTRADE		0.34867	0.9469

The results of the long-run relationship between two or more variables were estimated using the Johansen Cointegration Test and are presented in Table 6. Table 6 shows the results of the Cointegration Test. Both Trace and Maximum Eigenvalue statistics indicate that the null hypothesis of no cointegration can be rejected. This suggests the existence of a long-run equilibrium relationship between the variables.

Table 6: Johansen Cointegration test

	Statistic	Probability
<i>Trace Statistic:</i>		
None*	132.168	0.000
At most 1*	86.118	0.001
At most 2*	51.661	0.021
<i>Maximum Eigenvalue Statistic:</i>		
None*	46.050	0.009
At most 1*	34.457	0.042
At most 2*	27.885	0.045

NOTE: * * denotes rejection of the hypothesis at the 0.05 level

The main motivation of this study is to determine how CO₂ emissions affect Malaysia’s economic efficiency. For this reason, we use the log functional form, which can correct heteroscedasticity and multicollinearity problems between coefficients and the residuals. (Basu & Thibodeau,

1998; Ismail et al., 2020). Since there is a long-run relationship between the variables, the existence of a short-run relationship is presumed. Table 7 presents the results of the estimation regression.

Table 7: Estimation results of the first phase (short-run and long-run regression)

Variables	Coefficient	Standard Error	T-Stat	P-Value
<i>Short-run analysis:</i>				
Constant	3.4885**	1.768363	1.97	0.06
$\Delta \ln \text{EFFC}$	0.5910***	0.2717	2.17	0.04
$\Delta \ln \text{CO2}_t$	0.1331**	0.4104	3.24	0.05
$\Delta \ln \text{CO2}_{t-1}$	0.0800**	0.0405	1.98	0.06
$\Delta \ln \text{GOV}_t$	-0.0915	0.2013	-0.45	0.65
$\Delta \ln \text{GOV}_{t-1}$	0.4125**	0.1877	2.20	0.04
$\Delta \ln \text{INF}_t$	-0.0102**	0.0071	-2.10	0.02
$\Delta \ln \text{INF}_{t-1}$	0.0057	0.0061	0.65	0.55
$\Delta \ln \text{MS}_t$	-0.4480	0.3301	-1.05	0.29
$\Delta \ln \text{MS}_{t-1}$	-0.3979	0.3270	-1.06	0.30
$\Delta \ln \text{TRADE}_t$	0.3130*	0.1762	1.78	0.09
$\Delta \ln \text{TRADE}_{t-1}$	0.1846**	0.0898	2.05	0.05
<i>Long-run analysis:</i>				
$\ln \text{EFFC}$	0.7678	0.2651	2.90	0.01
$\ln \text{CO2}$	-0.1297***	0.0480	-2.70	0.01
$\ln \text{GOV}$	0.3585***	0.1308	2.74	0.01
$\ln \text{INF}$	-0.0603***	0.0131	-2.71	0.00
$\ln \text{MS}$	0.5817	0.1929	3.01	0.46
$\ln \text{TRADE}$	0.3848**	0.2002	1.92	0.07
Error Correction Term	-0.7678***	0.2651	-2.90	0.01
No. of observations			47	
Log-Likelihood			111.2891	
R-Squared			0.8223	
Adjusted R-Squared			0.4788	
Root MSE			0.0353	

NOTE: *, **, and *** refer to the tables that are significant at 10%, 5% and 1% level of significance, respectively.

Based on the result in Table 7, the error-correction term is negative and significant, which indicates the presence of long-run adjustments. The coefficient of 0.7678 suggests that the economic efficiency converged toward equilibrium 76 per cent in one quarter. It implies that it took more than approximately one quarter ($1/0.7678=1.3$) to eliminate the disequilibrium. Although this shows that economic slowdown is not a major issue since 76 per cent of disequilibrium is corrected within one quarter, an inefficient economy can affect prices, production and the labour market (Cotti & Drewianka, 2007; Fukuyama & Weber, 2004).

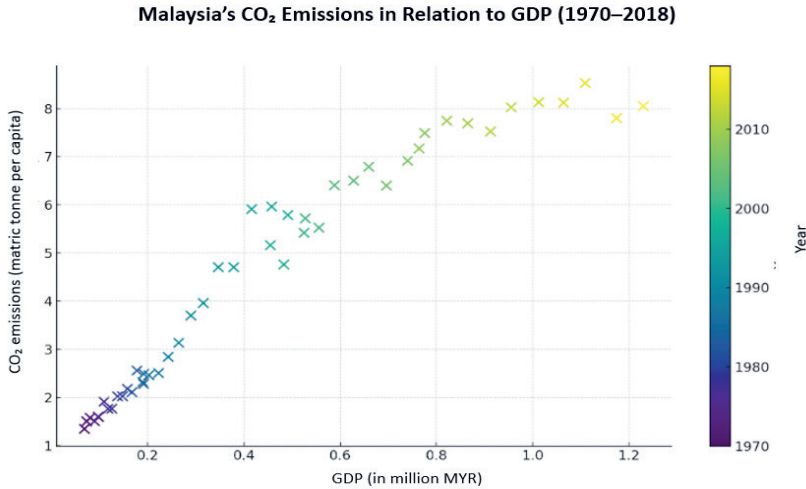
CO₂ emissions variable significantly affects economic efficiency. In the short run, the regression coefficient of CO₂ emissions is 0.1331, indicating that a 1 per cent increase in CO₂ emissions would increase economic efficiency by 0.1331 per cent in the short run. The increasing trend in CO₂ emissions due to increased production can contribute to the economic growth of a country. This finding supports the hypothesis that carbon dioxide has a positive impact on economic efficiency. This result is consistent with a recent study done by Begum et al. (2020). This is not surprising, given Malaysia's heavy reliance on its industrial sector for rapid growth, as the sector is the largest consumer of energy and the biggest contributor to carbon emissions. It is therefore reasonable to observe that higher CO₂ emissions can affect a country's economic efficiency through the expansion of inputs leading to higher output.

However, in the long run, the coefficient becomes negative at -0.1297, implying that a 1 per cent increase in CO₂ emissions would decrease economic efficiency by 0.1297 per cent. As production intensifies, more energy is consumed, resulting in excessive greenhouse gas (GHG) emissions through combustion (Ismail et al. 2020). These high levels of carbon dioxide emissions endanger air quality and public health in the long term. As reported by Bloom et al. (2001), illnesses caused by an unhealthy environment due to carbon dioxide emissions reduce workers' productivity and, hence, economic performance. As a result, CO₂ emissions will harm economic efficiency in the long run by negatively impacting worker health and thus worker productivity.

This pattern is illustrated by the comparative trend of Malaysia's CO₂ emissions and gross domestic product (GDP) from 1970 to 2018, as shown in Figure 1. In the earlier decades, both GDP and emissions were low, but as the economy continued to rise, emissions increased correspondingly.

Interestingly, in the more recent years, while GDP continued to rise, the rate of increase in CO₂ emissions began to moderate, suggesting early signs of decoupling between economic growth and environmental degradation.

Figure 1: Malaysia's CO₂ emissions and GDP from 1970 to 2018



Source: Author's build up

A positive and significant coefficient of government spending in both the short-run and the long-run results indicates that increased government spending can cause the economy to be more efficient. An increase in government spending can boost economic growth by increasing consumer purchasing power. This result is consistent with a recent study done by Ahuja & Pandit (2020), which reported a positive relationship between government spending and economic growth. Conversely, the coefficient of inflation shows a negative and significant result for both the long and short run. This suggests that higher inflation leads to an inefficient economy. High inflation is usually associated with a general decline in the macroeconomic performance and with a balance-of-payments crisis. This evidence supports the conclusions of Azam and Khan (2022), who reported a negative relationship between inflation and growth.

Surprisingly, the money supply coefficient is insignificant in the long run. This indicates that changes in money supply have no long-term impact on economic efficiency. One possible explanation for this situation is that the

performance of an economy tends to be more influenced by the productivity of economic agents (buyer and seller) and businesses rather than money supply (Raisova & Durcova, 2014). According to Jajri and Ismail (2010), an increase in productivity is necessary to stimulate economic growth and contribute to economic efficiency. On the other hand, in the long run, a positive and significant coefficient of trade openness shows that trade openness plays a substantial role in promoting the economy's positive performance. This is in line with Kong et al. (2021) and Keho (2017) studies, which found a positive relationship between trade openness and economic growth.

4.2 Second phase: Qualitative analysis

The first phase of the analysis represents the quantitative aspect, involving econometric procedures to estimate input quantities. Meanwhile, the second phase addresses the qualitative aspect, focusing on green total factor productivity (GTFP) calculations and highlighting quality contributions. Table 8 presents the summary estimation of the effects of CO₂ emissions and globalisation on economic growth. Besides that, the second phase encompasses substituting the estimated coefficients into the growth model to calculate the indicators' contributions and total factor productivity as in Equation (9). The result is presented in Table 9.

Table 8: Estimation results of the second phase (green total factor productivity)

Variables	Coefficient	Standard Error	T-Stat	P-Value
Constant	8.527***	0.5936	14.36	0.000
lnLABOR	0.2313***	0.1115	6.04	0.000
lnCAPITAL	0.0822***	0.0255	3.22	0.002
lnCO2	0.3136***	0.0541	5.79	0.000
lnGLOBAL	0.1003	0.1672	0.60	0.552

NOTE: *, **, and *** refer to the tables that are significant at 10%, 5% and 1% level of significance, respectively.

Table 8 shows that the positive and significant coefficient for CO₂ indicates that a 1 per cent increase in CO₂ emissions leads to a 0.31 per cent rise in GDP growth. This relationship suggests that GDP growth may

come at the cost of environmental quality in the early stages of economic development, supporting the hypothesis that environmental degradation intensifies as economies begin to expand. The labour force also has a positive association with economic growth, highlighting labour as a critical input in Malaysia’s emerging economy. Similarly, gross capital has a positive impact on growth. In contrast, the coefficient for globalisation is positive but statistically insignificant. Meanwhile, the residuals of the regression capture the indirect factors that influence productivity. These may include government interventions through green policy and technological innovations, reflecting the contribution of sustainable strategies that enhance productivity without an increase in emissions. Several studies by Elfaki and Ahmed (2024), Ahmed et al. (2023), and Zhang et al. (2023) support these findings.

Table 9: Indicators contributions and green total factor productivity (%)

GTFP	lnGDP	lnLABOR	lnCAPITAL	lnCO2	lnGLOBAL
0.0329	0.0578	0.0070	0.0066	0.0104	0.0008

Note: Statistics were calculated using Equation (8). Statistics showing in per centage.

The average growth rate of green total factor productivity (GTFP) is positive, as shown in Table 9. This is likely because GDP and CO₂ make big contributions, as well as labour, capital, and globalisation having positive effects. The increase in GTFP over this period reflects Malaysia’s rapid economic efficiency, driven by an abundant labour force and a surge of capital. While the positive contributions of all indicators support economic growth, they also slightly moderate the average GTFP growth rate, highlighting the need for an efficient, sustainable growth strategy. Although Malaysia has shown improvement, its growth in GTFP remains relatively slow compared to its closest neighbour, Singapore, which consistently ranks highest in the region due to its advanced clean technology adoption, energy efficiency programs, and strong environmental regulations (Ahmed, 2012). Therefore, to sustain GDP growth, it is essential for Malaysia to implement a plan that prioritises clean energy, environmental sustainability, and green growth initiatives.

4.3 Robustness

To validate the reliability of the findings, a series of robustness tests were conducted, including the use of alternative control variables, non-linear specifications, and exclusion of outlier years. Although the inclusion of variables such as energy consumption, financial investment, and population led to some instability in CO₂ emission coefficients, suggesting sensitivity to model specification, these were ultimately excluded from the main model to avoid multicollinearity. The non-linear model testing for the Environmental Kuznets Curve (EKC) yielded a U-shaped rather than the expected inverted U-shaped relationship, thus it was not adopted in the primary analysis. Moreover, excluding years of major economic shocks (such as the commodities shock in 1985–1986, Asian financial crisis in 1997–1998 and global financial crisis in 2008–2009) caused the long-run effect of CO₂ emissions to become statistically insignificant, highlighting sensitivity to extreme events. Despite these variations, the robustness tests confirm that the main conclusion remains consistent where CO₂ emissions play a significant association with economic efficiency, and the overall findings are not undermined by alternative model specifications or sample adjustments.

5. Conclusion and Policy Recommendation

This study combines quantitative and qualitative approaches to measure economic efficiency. The main objective of this study is to investigate the effect of CO₂ emissions on Malaysia's economic efficiency over the period 1970 to 2018 using the autoregressive distributed lag (ARDL) cointegration approach. The empirical results indicate that CO₂ emissions significantly affect economic efficiency both in the short- and long-run. In the short run, an increase in CO₂ emissions resulting from input expansion may boost output, and consequently, enhance economic efficiency. However, in the long run, CO₂ emissions will have a detrimental effect on workers' health and hence productivity, leading to a decrease in economic efficiency.

Following the significant findings on the effect of CO₂ emissions in this study, we make the following policy recommendations: First, to ensure that there is no negative effect on economic efficiency in the long run, the government should find an alternative source of clean energy that incorporates renewable energy innovation techniques such as solar

and wind power, which can reduce greenhouse gas emissions. Second, governments must assist in the incubation of clean energy practices in the public and private sectors through green energy policies and renewable energy programs such as the 'Energy Star Program' to encourage efficient and clean technologies. Third, in order to ensure a long-term positive impact on economic efficiency, as well as to achieve carbon neutrality by 2050, the Government should implement a carbon pricing scheme. Carbon pricing can take the form of a carbon tax or a permit-based emission trading system (ETS). The selection of the most appropriate carbon pricing instrument for Malaysia should be guided by the country's national climate objectives and broader economic and investment policies. Using carbon pricing approaches across Asia as benchmarks can help determine the optimal carbon pricing level, which involves striking a balance between environmental effectiveness, economic impact, industrial competitiveness, and social equity. Fourth, GTFP highlights the importance of adopting sustainable green growth strategies to improve Malaysia's economic efficiency. Accordingly, national development plans, frameworks, and models must prioritise green-oriented Foreign Direct Investment (FDI) to attract environmentally sustainable industries; guide urbanisation through smart and eco-friendly infrastructure planning; enhance capital investment and upskill the labour force in green sectors; advance digitalisation to boost resource efficiency; and strengthen financial institutions to expand access to green credit.

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CRediT author statement

Nur Hafizah Ismail: Formal analysis; Writing - original draft preparation and editing. **Mohd Zaini Abd Karim:** Conceptualisation; Methodology. **Mukhriz Izraf Azman Aziz:** Data collection/curation. **Muhammad Azam Khan:** Writing - review and editing. **Kashif Abbass:** Visualisation

References

- Abidin, Z.A. (2015). The inventory of greenhouse gases (GHG) in Malaysia. Retrieved from https://www-iam.nies.go.jp/aim/aim_workshop/aimws_07/presentation/s03_abidin_ppt.pdf
- Ahmad, E.M. (2012). Green TFP intensity impact on sustainable East Asian productivity growth. *Economic Analysis and Policy*, 42(1), 67-78. [https://doi.org/10.1016/S0313-5926\(12\)50005-6](https://doi.org/10.1016/S0313-5926(12)50005-6)
- Ahmed, E.M. (2020). Modelling green productivity spillover effects on sustainability. *World Journal of Science, Technology and Sustainable Development*, 17(3), 257–267. <https://doi.org/10.1108/WJSTSD-01-2020-0009>
- Ahmed, E.M., & Elfaki, K.E. (2023). Green technological progress implications on long-run sustainable economic growth. *Journal of the Knowledge Economy*, 15, 6860–6877. <https://doi.org/10.1007/s13132-023-01268-y>
- Ahuja, D., & Pandit, D. (2020). Public expenditure and economic growth: Evidence from the developing countries. *FIIIB Business Review*, 9(3), 228-236. <https://doi.org/10.1177/2319714520938901>
- Azam, M., & Khan, S. (2022). Threshold effects in the relationship between inflation and economic growth: Further empirical evidence from the developed and developing world. *International Journal of Finance & Economics*, 27(4), 4224-4243. <https://doi.org/10.1002/ijfe.2368>
- Azmi, M., & Tokai, A. (2016). Environmental risk trade-off for new generation vehicle production: Malaysia case. *Journal of Sustainable Development*, 9(6), 132-145. <https://doi.org/10.5539/jsd.v9n6p132>
- Babatunde, K.A., Said, F.F., & Md Nor, N.G. (2018). Reducing carbon dioxide emissions from Malaysian power sector: Current issues and future directions. *Jurnal Kejuruteraan*. 1(6), 59-69. <https://doi.org/10.17576/jkukm-2018-si1%286%29-08>

- Balezentis, T., Blancard, S., Shen, Z., & Streimikiene, D. (2020). Analysis of environmental total factor productivity evolution in European agricultural sector. *Decision Sciences*, 52(2), 325-534. <https://doi.org/10.1111/deci.12421>
- Banker, R.D., & Morey, R. (1986). Efficiency analysis for exogenously fixed inputs and outputs. *Operations Research*, 34, 513-521. <https://www.jstor.org/stable/170597>
- Barro, R.J. (2013). Inflation and economic growth. *Annals of Economics and Finance*, 14(1), 121-144.
- Barro, R.J. (1996). Determinants of economic growth: A cross-country empirical study. *National Bureau of Economic Research (NBER) Working Paper 5698*. Retrieved from <https://www.nber.org/papers/w5698>
- Barro, R.J., & Sala-i-Martin, X. (1995). *Economic growth*. McGraw-Hill.
- Basu, S., & Thibodeau, T.G. (1998). Analysis of spatial autocorrelation in house prices. *The Journal of Real Estate Finance and Economics*, 17, 61-85. <https://doi.org/10.1023/A:1007703229507>
- Begum, R.A., Raihan, A., & Said, M.N.M. (2020). Dynamic impacts of economic growth and forested area on carbon dioxide emissions in Malaysia. *Sustainability*, 12(22), 9375. <https://doi.org/10.3390/su12229375>
- Bekar, S.A. (2018). The relationship between CO₂ emission and economic growth in Turkey: 1977-2014. *International Journal of Economic and Administrative Studies*, 193-206.
- Bloom, D.E., Canning, D., & Sevilla, J. (2001). The effect of health on economic growth: Theory and evidence. *National Bureau of Economic Research (NBER) Working Papers 8587*. Retrieved from <https://www.nber.org/papers/w8587>
- Borhan, H., Ahmed, E.M., & Hitam, M. (2011). The impact of CO₂ on economic growth in Asean 8. *Procedia-Social and Behavioral Sciences*, 35, 389-397. <https://doi.org/10.1016/j.sbspro.2012.02.103>
- Buthelezi, E.M. (2023). Impact of money supply in different states of inflation and economic growth in South Africa. *Economies*, 11(2), 64-86. <https://doi.org/10.3390/economies11020064>
- Cao, J. (2007). Measuring green productivity growth for China's manufacturing sectors: 1991-2000. *Asian Economic Journal*, 21(4), 425-451. <https://doi.org/10.1111/j.1467-8381.2007.00265.x>
- Chandana, A., Adamu, J., & Musa, A. (2020). Impact of government

- expenditure on economic growth in Nigeria, 1970-2019. *CBN Journal of Applied Statistics*, 11(2), 139-174. <http://dx.doi.org/10.33429/Cjas.12121.6/6>
- Chia, R.C.J., & Lim, S.Y. (2015). Malaysian stock price and macroeconomic variables: Autoregressive Distributed Lag (ARDL) bound test. *Kajian Malaysia*, 33(1), 85-103.
- Choudhury, T., Kayani, U.N., Gul, A., Haider, S.A., & Ahmad, S. (2023). Carbon emissions, environmental distortions, and impact on growth. *Energy Economics*, 126, 107040. <https://doi.org/10.1016/j.eneco.2023.107040>
- Cotti, C.D., & Drewianka, S. (2007). Labor market inefficiency and economic restructuring: Evidence from cross-sectoral data. *Southern Economic Journal*, 74(1), 214-238. <https://www.jstor.org/stable/20111961>
- Churchill, S.A., Yew, S.L., & Ugur, M. (2015). *Effects of government education and health expenditures on economic growth: A meta-analysis*. Greenwich Political Economy Research Centre, No: GPER21. Retrieved from https://gala.gre.ac.uk/id/eprint/14072/1/GPERC21_Churchill_Yew_UgurF.pdf
- Dahmus, J.B., & Gutowski, T.G. (2005). Efficiency and Production: Historical Trends for Seven Industrial Sectors. Paper presented at the 3rd Biennial Conference of the US Society for Ecological Economics, Tacoma, Washington on July 20-23, 2005.
- Department of Statistic Malaysia (DOSM). *Statistic Report 2015-2020*. Malaysia.
- Dinh, D.V. (2020). Optimal inflation threshold and economic growth: Ordinal regression model analysis. *Journal of Asian Finance, Economics and Business*, 7(5), 91–102. <https://doi.org/10.13106/jafeb.2020.vol7.no5.091>
- Drennan, M., & Brecher, C. (2012). Does public transit use enhance the economic efficiency of urban areas? *Journal of Transport and Land Use*, 5(3), 53-67. <https://www.jstor.org/stable/26201701>
- Du, Y., Lie, Y., Hossain, M.A., & Chen, S. (2022). The decoupling relationship between China's economic growth and carbon emissions from the perspective of industrial structure. *Chinese Journal of Population, Resources and Environment*, 20(1), 49-58. <https://doi.org/10.1016/j.cjpre.2022.03.006>

- Elfaki, K.E., & Ahmed, E.M. (2024). Digital technology adoption and globalization innovation implications on Asian Pacific green sustainable economic growth. *Journal of Open Innovation: Technology, Market, and Complexity*, 10(1), 100221. <https://doi.org/10.1016/j.joitmc.2024.100221>
- Ekinci, R., Tüzün, O., & Ceylan, F. (2020). The relationship between inflation and economic growth: Experiences of some inflation targeting countries. Financial Studies. In Romanian Academy, National Institute of Economic Research (INCE), *Victor Slăvescu Centre for Financial and Monetary Research, Bucharest*, 24, 1(87), 6-20.
- Farrell, M.J. (1957). The measurement of productive efficiency. *Journal of the Royal Statistical Society Series A*, 120(3), 253-281. <https://doi.org/10.2307/2343100>
- Fukuyama, H., & Weber, W.L. (2004). Economic inefficiency measurement of input spending when decision-making units face different input prices. *Journal of the Operational Research Society*, 55(10), 1102-1110. <https://doi.org/10.1057/palgrave.jors.2601750>
- Ghosal, V., Stephan, A., & Weiss, J. F. (2019). Decentralized environmental regulations and plant-level productivity. *Business Strategy and the Environment*, 28(6), 929-1284. <https://doi.org/10.1002/bse.2297>
- Halkos, G.E., & Tzeremes, N.G. (2013). Renewable energy consumption and economic efficiency: Evidence from European countries. *Journal of Renewable and Sustainable Energy*, 5(4), 41803. <https://doi.org/10.1063/1.4812995>
- Ismail, N.H., Nayan, S., Kadir, N. & Mat Yusoff, M.Y. (2020). Causal link in economic growth, energy consumption and carbon dioxide (CO₂) emission: Evidence from selected Southeast Asia countries. *Journal of Emerging Economies and Islamic Research*, 8(2), 1-12.
- Iticha, M.D. (2020). Review on determinants of economic efficiency of smallholder maize production in Ethiopia. *International Journal of Agricultural Economics*, 5(4), 2020, 123-132. <https://doi.org/10.11648/j.ijae.20200504.15>
- Jajri, I., & Ismail, R. (2010). Impact of labor quality on labor productivity and economic growth. *African Journal of Business Management*, 4(4), 486-495.
- Kalirajan, K.P. (1989). On measuring economic efficiency. *Journal of Applied Econometrics*, 5, 75-85. <https://doi.org/10.1002/jae.3950050106>
- Kao, C., & Hwang, S. (2021). Measuring the effects of undesirable outputs

- on the efficiency of production units. *European Journal of Operational Research*, 292(3), 996-1003. <https://doi.org/10.1016/j.ejor.2020.11.026>
- Keho, Y. (2017). The impact of trade openness on economic growth: The case of Cote d'Ivoire. *Cogent Economics & Finance*, 5(1), 1-14. <https://doi.org/10.1080/23322039.2017.1332820>
- Khan, I., Zhong, R., Khan, H., Dong, Y., & Nuța, F.M. (2024). Examining the relationship between technological innovation, economic growth and carbon dioxide emission: Dynamic panel data evidence. *Environment, Development and Sustainability*, 26, 18161–18180 (2024). <https://doi.org/10.1007/s10668-023-03384-w>
- Kong, Q., Peng, D., Ni, Y., Jiang, X., & Wang, Z. (2021). Trade openness and economic growth quality of China: Empirical analysis using ARDL model. *Finance Research Letters*, 38, 101488. <https://doi.org/10.1016/j.frl.2020.101488>
- Li, T., & Liao, G. (2020). The Heterogeneous impact of financial development on green total factor productivity. *Frontiers in Energy Research*, 8(29), 1-9. <https://doi.org/10.3389/fenrg.2020.00029>
- Liou, J.L., Chiu, C. R., Huang, F.M., & Liu, W.Y. (2015). Analyzing the relationship between CO₂ emission and economic efficiency by a relaxed two-stage DEA model. *Aerosol and Air Quality Research*, 15, 694–701. <https://doi.org/10.4209/aaqr.2014.04.0074>
- Liu, W.B., Meng, W., Li, X.X., & Zhang, D.Q. (2010). DEA models with undesirable inputs and outputs. *Annals of Operations Research*, 173, 177-194. <https://doi.org/10.1007/s10479-009-0587-3>
- Meireles, M. (2023). Production Economics and Economic Efficiency. In: Macedo, P., Moutinho, V., Madaleno, M. (eds) *Advanced Mathematical Methods for Economic Efficiency Analysis*. Lecture Notes in Economics and Mathematical Systems, 692. Springer. https://doi.org/10.1007/978-3-031-29583-6_2
- Mardani, A., Streimikiene, D., Cavallaro, F., Loganathan, N., & Khoshnoudi, M. (2019). Carbon dioxide (CO₂) emissions and economic growth: A systematic review of two decades of research from 1995 to 2017. *Science of The Total Environment*, 649, 31-49. <https://doi.org/10.1016/j.scitotenv.2018.08.229>
- Martinez-Zarzoso, I., Bengochea-Morancho, A., & Morales-Lage, R. (2019). Does environmental policy stringency foster innovation and productivity in OECD countries? *Energy Policy*, 134, 110982. <https://doi.org/10.1016/j.enpol.2019.110982>

- doi.org/10.1016/j.enpol.2019.110982
- Murillo-Zamorano, L. (2004). Economic efficiency and frontier techniques. *Journal of Economic Surveys*, 18(1), 33–77. <https://doi.org/10.1111/j.1467-6419.2004.00215.x>
- Noman, S.M.S., & Khudri, M.M. (2015). The effects of monetary and fiscal policies on economic growth in Bangladesh. *ELK Asia Pacific Journal of Finance and Risk Management*, 6(3), 21-34.
- Omri, A., Nguyen, D. K., & Rault, C. (2014). Causal interactions between CO₂ emissions, FDI, and economic growth: Evidence from dynamic simultaneous-equation models. *Economic Modelling*, 42, 382–389. <https://doi.org/10.1016/j.econmod.2014.07.026>
- Pesaran, H., Shin, Y., & Smith, R.J. (2001). Bounds Testing Approaches to the Analysis of Level Relationships. *Journal of Applied Econometrics*, 16, 289-326. <https://doi.org/10.1002/jae.616>
- Raisova, M., & Durcova, J. (2014). Economic growth: Supply and demand perspective. *Procedia Economics and Finance*, 15, 184-191. [https://doi.org/10.1016/S2212-5671\(14\)00476-6](https://doi.org/10.1016/S2212-5671(14)00476-6)
- Schandl, H., Hatfield-Dodds, S., Wiedmann, T., Geschke, A., Cai, Y., West, J., Newth, D., Baynes, T., Lenzen, M., & Owen, A. (2016). Decoupling global environmental pressure and economic growth: Scenarios for energy use, materials use and carbon emissions. *Journal of Cleaner Production*, 132, 45-56. <https://doi.org/10.1016/j.jclepro.2015.06.100>
- Schipke A. (2001) Economic Growth and Efficiency. In: Why Do Governments Divest? Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-56682-0_2
- Singpai, B., & Wu, D.D. (2020). An integrative approach for evaluating the environmental economic efficiency. *Energy*, 118940. <https://doi.org/10.1016/j.energy.2020.118940>
- Smaoui, H., & Nechi, S. (2017). Does sukuk market development spur economic growth? *Research in International Business and Finance*, 41, 136–147. <https://doi.org/10.1016/j.ribaf.2017.04.018>
- Stern, D.I. (2004). The rise and fall of the Environmental Kuznets Curve. *World Development*, 32(8), 1419-1439. <https://doi.org/10.1016/j.worlddev.2004.03.004>
- Succurro, M. (2021). Economic Performance. In: Marciano, A., Ramello, G.B. (eds) *Encyclopedia of Law and Economics*. Springer, New York, NY. https://doi.org/10.1007/978-1-4614-7883-6_208-2

- Syed, Q.R., & Alola, A.A. (2023). Chapter 7 - Measuring green economic growth. In Recent Developments in Green Finance, Green Growth and Carbon Neutrality. *Elsevier*, 149-170. <https://doi.org/10.1016/B978-0-443-15936-7.00005-0>
- Tan, C.C., & Tan, S. (2018). Energy consumption, CO₂ emissions and economic growth: A causality analysis for Malaysian industrial sector. *International Journal of Energy Economics and Policy*, 8(4), 254-258.
- Tan, C., Mohamed, A., Habibullah, M.S., & Chin, L. (2020). The impacts of monetary and fiscal policies on economic growth in Malaysia, Singapore and Thailand. *South Asian Journal of Macroeconomics and Public Finance*, 9(1), 114-130. Doi: <https://doi.org/10.1177%2F2277978720906066>
- Tamazian, A., & Rao, B. (2010). Do economic, financial and institutional developments matter for environmental degradation? Evidence from transitional economies. *Energy Economics*, 32(1), 137-145. <https://doi.org/10.1016/j.eneco.2009.04.004>
- Tone, K. (2001). A slacks-based measure of efficiency in data envelopment analysis. *European Journal of Operational Research*, 130(3), 498-509. [https://doi.org/10.1016/S0377-2217\(99\)00407-5](https://doi.org/10.1016/S0377-2217(99)00407-5)
- Wang, Z., He, W., & Chen, K. (2016). The integrated efficiency of economic development and CO₂ emissions among Asia Pacific Economic Cooperation members. *Journal of Cleaner Production*, 131, 765-772. <https://doi.org/10.1016/j.jclepro.2016.04.097>
- World Bank (2020). CO₂ Emissions (metric tons per capita). The World Bank Group.
- Wu, Y., Zhu, Q., & Zhu, B. (2018). Comparisons of decoupling trends of global economic growth and energy consumption between developed and developing countries. *Energy Policy*, 116, 30-38. <https://doi.org/10.1016/j.enpol.2018.01.047>
- Xiong, C., Yang, D., Huo, J., & Zhao, Y. (2017). The relationship between agricultural carbon emissions and agricultural economic growth and policy recommendations of a low-carbon agriculture economy. *Polish Journal of Environmental Studies*, 25(5), 2187-2195. <https://doi.org/10.15244/pjoes/63038>
- Zaid, S.M., Myeda, N.E., Mahyuddin, N., & Sulaiman, R. (2015). Malaysia's rising GHG emissions and carbon 'lock-in' risk: A review of Malaysian building sector legislation and policy. *Journal of Surveying, Construction*

- and Property*, 6(1), 1-13. <https://doi.org/10.22452/jscp.vol6no1.1>
- Zhang, J., Li, Z., Ali, A., & Wang, J. (2023). Does globalization matter in the relationship between renewable energy consumption and economic growth, evidence from Asian emerging economies. *Plos One*, 18(8), e0289720. <https://doi.org/10.1371/journal.pone.0289720>
- Zivin, J.G., & Neidell, M. (2012). The impact of pollution on worker productivity. *American Economic Review*, 102(7), 3652-3673. <https://doi.org/10.1257/aer.102.7.3652>