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Renewable Energy Use, CO2 Emissions, and Economic Growth in Thailand

Aerwadee Premashthira

Faculty of Economics, Kasetsart University, Bangkok, Thailand.

Corresponding author: fecoadu@ku.ac.th

Abstract

This study investigates the nexus among renewable energy consumption, CO_2 emissions, and economic growth in Thailand during the period 1995–2022. The study used the autoregressive distributed lag (ARDL) bound test, the vector error correction model (VECM), and the Granger causality test to analyze the linkages among variables. The developed ARDL model showed that a 1% change in renewable energy consumption and CO_2 emissions increased growth by 0.101% and 0.439%, respectively, in the long run. The causality tests identified a positive, unidirectional causal relationship of CO_2 emissions to economic growth in the short run, whereas in the long run, the model indicated bidirectional causality of renewable energy consumption and CO_2 emissions with economic growth, highlighting the challenge of balancing economic expansion with environmental concerns in Thailand. The results suggest that Thailand should efficiently implement renewable energy policies to enhance economic growth and contribute to sustainable development.

Keywords: renewable energy consumption, CO_2 emissions, growth, causality, ARDL model, Thailand**.**

1. Introduction

The consumption of renewable energy has increased in many countries due to its positive effects on the reduction of CO_2 emissions and pollution. Global concern for the environment has resulted in several countries implementing various subsidies and incentive policies to increase renewable energy production and consumption. Accordingly, an increase in renewable energy consumption can be considered as a substantial accelerating factor for economic development and for environmental sustainability. Economic growth contributes to the progress of renewable energy production and consumption, especially where research and development are less expensive, along with an increased demand through the higher income level of many consumers. These relationships have attracted attention in the past two decades, with the causal relationship examined between renewable energy consumption and economic growth.

In the past two decades, Southeast Asian countries have experienced remarkable economic growth, doubling the size of their economies. This growth has been accompanied by a rapid increase in energy demand, with imported fossil fuels meeting three-quarters of this demand, resulting in a nearly 35% rise in CO_2 emissions (IEA, 2022a). Southeast Asia is also highly susceptible to the adverse impacts of climate change, with Myanmar, the Philippines, and Thailand ranking among the top ten most at-risk countries. These challenges facing governments across Southeast Asia provide a strong incentive to prioritize renewable energy policies for enhancing energy security and reducing CO_2 emissions (IEA, 2022b).

Thailand is heavily dependent on imported energy, especially crude oil, which directly affects CO_2 emissions into the atmosphere and contributes to air pollution. The average ratio of Thailand crude oil imports-to-domestic demand for crude oil was nearly 90% in 2020–2022, with the value of the imported crude oil making up about 7.7% of GDP (Energy Policy and Planning Office, 2023). These concerns have resulted in a renewable energy policy aiming to decrease dependence on energy imports and to reduce the impact on the environment and communities. The Alternative Energy Development Plan (AEDP) 2015–2036 was developed and formulated to target renewable energy production and utilization to replace 30 percent of final energy consumption by 2036 in the forms of heat, electricity, and biofuels. In addition, it was expected to reduce greenhouse gas emissions equivalent to about 140 million tons of CO_2 (Energy Policy and Planning Office, 2016). Recently, alternative energy consumption reporting showed that renewable energy consumption in Thailand made up 13.27% of final energy consumption in 2022 (a slight increase from 12.9% in 2015), of which biomass accounted for 36.1%, followed by 26.3% for biofuels and 9.3% for solar energy (Department of Alternative Energy Development and Efficiency, 2023). These changes have led to energy security issues in Thailand, where the energy sector is one of the main sources contributing to the growth of the economy. Studies on the relationship between renewable energy and economic growth are important for their energy and environmental policy implications.

Recently, several studies have reviewed and found a nexus between renewable energy consumption and economic growth (Asiedu et al., 2021; Bouyghrissi et al., 2021; Li & Lee, 2022; Rahman & Velayutham, 2020; Tuna & Tuna, 2019). The findings from previous studies have shown varying results regarding the correlation between renewable energy consumption and economic growth. Some research indicated a positive correlation between renewable energy and economic growth (Asiedu et al., 2021; Karimi et al., 2021; Rahman & Velayutham, 2020). This suggests that an increase in the share of renewable energy consumption leads to a positive impact on economic growth in the countries under study. Some studies identified a unidirectional relationship

(Bouyghrissi et al., 2021; Li & Lee, 2022), indicating that renewable energy consumption has a one-way effect on economic growth, while the reverse relationship does not hold. Sari Hassoun et al. (2019) found that renewable energy consumption can lead to a reduction in both GDP and carbon dioxide emissions. Furthermore, Tuna and Tuna (2019) revealed that no causal relationship was found between renewable energy and economic growth variables in the ASEAN-5 countries, excluding the effects of CO_2 emissions. More importantly, few studies have been conducted to explore this link between renewable expansion and economic growth in Thailand. According to Fazal et al. (2020), renewable energy consumption positively impacts Thailand's economic growth without the effects of CO_2 emissions. However, the preliminary work of Boontome et al. (2017) studied the link including renewable energy and CO_2 emissions in Thailand, but the range of data in that study covered the period before the AEDP 2015-2036 alternative energy policy was applied.

Due to the presence of mixed conclusions in existing literature, this paper aims to clarify and contribute to the understanding of the relationship between renewable energy consumption and economic growth in Thailand while considering the effects of non-renewable energy and CO_2 emissions. The study applies time series methodologies based on stationarity, cointegration, and causality. The results might improve the design and implementation of appropriate energy policies in Thailand while providing valuable insights for policymakers, researchers, and stakeholders across Southeast Asian countries facing similar energy and environmental challenges.

The remainder of this paper is structured as follows: Section 2 reviews the literature and other relevant published studies. Section 3 includes the analytical model, data, and methodology. Section 4 presents the results of the study and discussion. The last section concludes the research with policy implementations.

2. Literature Review

A large body of research literature explores the energy and growth nexus. This nexus indicates a close relationship between economic growth and energy consumption, as higher economic development requires more increased energy usage, and more efficient energy use requires a higher level of economic development (Azlina et al., 2014; Belke et al., 2011; Borozan, 2013; Kasperowicz & Streimikiene, 2016; Litavcová & Chovancová, 2021; Liu & Liang, 2019; Magazzino, 2015, 2016; Mahalingam & Orman, 2018; Mele, 2019; Mukhtarov et al., 2017; Pachiyappan et al., 2021; Saldivia et al., 2020). The increasing importance of renewable energy sources has generated significant attention to analyzing relationships between economic growth and renewable energy consumption. Thus, research on the causal relationship between renewable energy and economic growth has been growing in recent decades. Several studies have investigated this nexus based on several factors, such as the price of oil, trade openness, environmental degradation, CO_2 emissions, financial development, and R&D expenditures.

Recent causality research on renewable energy consumption and economic growth can be classified into four different categories of causal relationship: unidirectional causation from consumption of renewable energy to economic growth (a growth hypothesis), causality from economic growth to energy consumption (a conservation hypothesis), bidirectional causation (a feedback hypothesis), and no causality or neutrality (Magazzino, 2015). A summary of studies on the nexus between renewable energy and economic growth is presented in Table 1. Most of the papers examined the relationships among GDP, non-renewable energy, and renewable energy. The key findings in the last column focus on the relationship between GDP and energy variables as well as CO_2 emissions in the short term and long term. However, the use of different variables, methodologies, countries, and periods has resulted in inconsistent outcomes.

The ‘growth hypothesis’ assumes energy as a significant input in the growth process, with a one-way causality from energy consumption to economic growth. In this context, Bhattacharya et al. (2016) found that implementing energy conservation policies is believed to have a negative impact on economic growth. Their study confirms the evidence of long-run dynamics between renewable energy and economic growth. This relationship is also found in Xie et al. (2022), who researched the growth hypothesis or unidirectional causality from renewable energy consumption to economic growth. Their study examined the influence of renewable energy on the economic growth of the N-11 countries (a group of developing economies) and only focused on the long-run coefficients. The estimated results revealed the validity of the renewable energy-led growth hypothesis. Bouyghrissi et al. (2021) found a significant causality between renewable energy consumption and economic growth and between economic growth and CO_2 emissions in Morocco. In Thailand, Fazal et al. (2020) used data from 1990 to 2018 and found the long-run result in which renewable energy positively impacted Thailand’s growth. Rahman and Velayutham (2020) identified the long-run positive impacts of renewable and non-renewable energy consumption and fixed capital formation on economic growth in five South Asian countries over the period 1990–2014.

On the other hand, the ‘conservation hypothesis’ suggests that economic growth drives energy consumption. Consequently, an increase in real GDP causes an increase in energy consumption (Magazzino, 2016). Several studies concluded there was unidirectional causality from economic growth to renewable energy consumption (the conservation hypothesis). Li and Lee (2022) confirmed the crucial role of economic growth in renewable energy capacity development and apparent long-term causality. Wang et al. (2021) used panel data at a regional level in China during 1997–2017 and found economic growth unidirectionally caused renewable energy consumption in the long run in China as a whole as well as in eastern and western China. Li and Leung (2021) found long-run causality between economic growth and renewable energy consumption in seven European countries for the period 1985–2018. Rahman and Velayutham (2020) also indicated short-run unidirectional causality running from economic growth to renewable energy consumption. Chontanawat (2020) supported the conservative hypothesis that economic growth drives energy use in Indonesia, Malaysia, and Thailand. Similarly, Destek and Aslan (2017) confirmed the conservation hypothesis for Colombia and Thailand in an investigation of 17 emerging economies. The same positive results for the conservation hypothesis were found by Alper and Oguz (2016) in eight countries of new EU member countries and by Azlina et al. (2014) for Malaysia in the long run.

The 'feedback hypothesis' implies a bi-directional relationship between energy consumption and economic growth. According to this hypothesis, changes in energy consumption will have a reverse effect on economic growth (Bhattacharya et al., 2016). The bidirectional causation or feedback hypothesis was confirmed by Zafar et al. (2019), where results from their long-run equilibrium indicate renewable energy has a positive impact on economic growth, and their heterogeneous causality analysis revealed a feedback effect, or bidirectional causal associations, among economic growth, renewable energy consumption, and non-renewable energy consumption in APEC countries. In addition, Asiedu et al. (2021) indicated a bidirectional causality between economic growth and renewable energy consumption, and there was a unidirectional causality between renewable energy and CO_2 emissions in 26

European countries.

The 'neutrality hypothesis' implies that energy consumption and economic growth are independent of each other and do not affect each other (Mathur et al., 2016). Some studies revealed the existence of no causality or neutrality, as shown by Tuna and Tuna (2019) and Boontome et al. (2017). Tuna and Tuna (2019) found that economic growth and renewable energy consumption were not generally related to growth in the ASEAN-5 countries. In addition, Boontome et al. (2017) explored the causal relationships between non-renewable and renewable energy consumption, CO_2 emissions, and economic growth in Thailand during 1971–2013 using a cointegration and causality model, with their Granger causality result indicating no causality between renewable energy and economic growth.

Table 1. Summary of studies on nexus between renewable energy, CO_2 emissions, and economic growth

Authors	Country	Period	Methodology	Variables	Key findings
Li and Lee (2022)	20 OECD countries in Europe	1993–2018	Panel data model	Renewable energy capacity, price of coal, price of natural gas	Y → Renewable energy capacity in LR
Xie et al. (2022)	N-11 countries	1990–2020	Non-parametric panel data approach	REC, industry value added, gross national expenditure, and trade openness	REC → Y in LR
Phadkantha and Yamaka (2022)	Thailand	1990–2019	Markov switching autoregressive distributed lag (MS-ARDL)	Labor force, non-renewable and renewable electricity consumption	Renewable electricity consumption → Y
Huang et al. (2022)	5 Asian countries (including Thailand)	1980–2018	Panel data technique	Trade, environmental degradation, governance, REC	Quality of governance → REC
Wang et al. (2021)	China	1997–2017	Panel data Model	REC, financial development	Y → REC in LR
Li and Leung (2021)	7 OECD countries in Europe	1985–2018	Panel data technique	REC, price of coal, price of natural gas, L, K	Y → REC in LR
Asiedu et al. (2021)	26 European Countries	1990–2018	Panel data technique	NREC, REC, CO_2 emissions	Y ↔ REC CO_2→ Y
Bouyghrissi et al. (2021)	Morocco	1990–2014	ARDL approach	NREC, REC, CO_2 emissions	REC → Y Y → CO_2
Chontanawat (2020)	4 Southeast Asian countries	1971-2017	Cointegration and causality model	EC, CO_2 emissions	Y → EC (Indonesia, Malaysia, Thailand) EC → Y (Philippines) EC → CO_2 in SR (Thailand)

Authors	Country	Period	Methodology	Variables	Key findings
Fazal et al. (2020)	Thailand	1990–2018	ARDL approach	REC, K, L	REC → Y in LR
Rahman and Velayutham (2020)	5 South Asian countries	1990–2014	Panel causality	NREC, REC, L, K, financial development	Y → REC in SR, REC → Y in LR
Zafar et al. (2019)	APEC countries	1990–2015	Panel data technique	NREC, REC, trade openness	REC → Y in LR Y ↔ REC
Tuna and Tuna (2019)	ASEAN-5 countries (including Thailand)	1980–2015	Symmetric and asymmetric causality	NREC, REC	No causality between REC and Y
Destek and Aslan (2017)	17 emerging market countries	1980–2012	Bootstrap panel causality	NREC, REC	Y → REC in Colombia and Thailand
Boontome et al. (2017)	Thailand	1971–2013	Cointegration and causality model	NREC, REC, CO_2 emissions	No causality between REC and Y NREC → CO_2
Alper and Oguz (2016)	8 EU countries	1990–2009	ARDL model	REC	Y → REC
Kyophilavong et al. (2015)	Thailand	1971–2012	Bayer and Hanck cointegration	Energy Consumption, Trade openness	EC → Y
Azlina et al. (2014)	Malaysia	1975–2011	Vector error correction	REC, income, energy use, CO_2 emissions	Y → REC in LR CO_2→ Y in SR and LR

Notes: Y = economic growth; EC = energy consumption; NREC = non-renewable energy consumption; REC = renewable energy consumption; L = labor; K = capital; SR = short run; LR = long run.

Various studies investigated the potential long-run connection between renewable energy and economic growth and its consequence to CO_2 emission. There are several articles that confirmed the validity of the growth hypothesis in the long term (Azlina et al., 2014; Li & Lee, 2022; Li & Leung, 2021; Wang et al., 2021). On the other hand, some of the reviewed articles support a long-run conservation effect that economic growth drives renewable energy consumption (Azlina et al., 2014; Fazal et al., 2020; Xie et al., 2022; Zafar et al., 2019). Additionally, a few articles explored the short-term causality with findings that also support the growth hypothesis in a short-term relationship (Azlina et al., 2014; Rahman & Velayutham, 2020).

Most of the above studies investigated causality in a group of countries by applying panel data, with only a few studies examining a single country using time-series data. From a methodological perspective, most of the time-series methods and panel data techniques included a vector autoregression (VAR) model, autoregressive distributed lags (ARDL), Granger causality, cointegration, and vector error correction (VEC). However, the empirical results of the nexus between renewable energy and economic growth still produced inconsistent outcomes due to differences in the choice of variables, methodologies, countries, and periods, as mentioned above.

3. Methodology

3.1 Data and Variables

The nexus between renewable energy and economic growth was investigated using four variables: economic growth (GDP), non-renewable energy consumption (NREC), renewable energy consumption (REC), and CO_2 emissions (CO_2). These variables were used to investigate the relationships between variables. The research data was obtained from an open dataset of the U.S. Energy Information Administration (EIA) for non-renewable energy consumption, renewable energy consumption, and CO_2 emissions, and from the World Bank and the Office of the National Economic and Social Development Board of Thailand for annual GDP information, with all data covering the period 1995–2022. The time period chosen reflects the implementation of renewable policies in several Southeast Asian countries and the first Thailand energy conservation plan that has been effective since 1995. Economic growth or GDP was measured based on GDP per capita (constant at USD 2015). NREC and REC were measured in kilograms of oil equivalent per capita. CO_2 emissions were measured in kilograms of CO_2 equivalent per capita. All variables were converted in logarithmic form to avoid the problem of heteroscedasticity.

3.2 Model and Methods

To investigate the nexus of NREC, REC, and CO_2 to economic growth (GDP), this study applied the ARDL approach, which is a cointegration method developed by Pesaran et al. (2001). The study proceeds as follows: 1) assess stationarity and cointegration properties of variables, 2) estimate the regression model, and 3) estimate causality relationships.

3.2.1 Unit Root Test

In this study, the augmented Dickey-Fuller (ADF) and Phillips Perron (PP) unit root tests were applied to determine the stationarity of a series (Shrestha & Bhatta, 2018), as shown in Equation (1):

$$\Delta X_t = \beta_0 + \beta_1 t + \delta X_{t-1} + \sum_{i=1}^{p} \alpha_i \Delta X_{t-i} + \varepsilon_t \qquad (1)$$

The null hypothesis of ADF is $\delta = 0$ against the alternative hypothesis of $\delta < 0$. If we reject the null, then the series is stationary at a level value or I (0). If the series is non-stationary, the ADF test is based on the difference series ΔX_t. If the series ΔX_t is stationary, the original series is said to be stationary at the first difference or I (1).

3.2.2 The Autoregressive Distributed Lag-error Correction Model Approach

The ARDL method uses an ordinary least square (OLS)-based model applicable to both non-stationary time series and times series with multiple levels of cointegration. This model takes a number of lags to effectively capture the data-generating process within a general-to-specific modeling framework. The ARDL process is appropriate for studying short-run and long-run relationships, as the error correction model (ECM) effectively combines short-run dynamics with long-run equilibrium without losing long-run information (Shrestha & Bhatta, 2018).

The standard form of model specification is presented in Equation (2):

$$GDP_t = \alpha_0 + \alpha_1 NREC_t + \alpha_2 REC_t + \alpha_3 CO2_t + \varepsilon_t \quad (2)$$

where GDP, NRENC, REC, CO_2, and ε represent GDP per capita, renewable energy consumption, non-renewable energy consumption, CO_2 emissions, and the residual term, respectively. Then, Equation (3) represents Equation (2) in logarithmic form (L):

$$LGDP_t = \beta_0 + \beta_1 LNREC_t + \beta_2 LREC_t + \beta_3 LCO2_t + \varepsilon_t \quad (3)$$

The ARDL approach for Equation (3) is presented in Equation (4):

$$\Delta LGDP_t = \beta_0 + \sum_{i=1}^{p} \beta_{0i}\, \Delta LGDP_{t-i} + \sum_{i=1}^{p} \beta_{1i}\, \Delta LNREC_{t-i} + \sum_{i=1}^{p} \beta_{2i}\, \Delta LREC_{t-i} +$$

$$\sum_{i=1}^{p} \beta_{3i}\, \Delta LCO2_{t-i} + \theta_0 LGDP_{t-1} + \theta_1 LNREC_{t-1} + \theta_2 LREC_{t-1} + \theta_3 LCO2_{t-1} + \varepsilon_t \quad (4)$$

where Δ denotes the difference operator, β_0 is the drift component, p represents lag length, and ε_t is the white noise. The first part of the equation with β represents the short-run dynamics of the model, and the second part with θ

represents the long-run relationship. The null hypothesis in the equation is $\theta_0 + \theta_1 + \theta_2 + \theta_3 = 0$, which means the non-existence of a long-run relationship.

The Schwarz information criterion (SC) was used in this study to select the optimal length. Next, the F statistic was calculated for the cointegration test of θ_i; if it exceeds the critical value upper limit, the null hypothesis of no long-run relationship (cointegration) between the variables is rejected. After that, the coefficients for the selected ARDL model were estimated. The error correction model (ECM) using the ARDL approach is given by Equation (5):

$$\Delta LGDP_t = \beta_0 + \sum_{i=1}^{p} \beta_{0i}\, \Delta LGDP_{t-i} + \sum_{i=1}^{p} \beta_{1i}\, \Delta LNREC_{t-i} + \sum_{i=1}^{p} \beta_{2i}\, \Delta LREC_{t-i} + \sum_{i=1}^{p} \beta_{3i}\, \Delta LCO2_{t-i} + \mu\, ECT_{t-1} + \varepsilon_t \quad (5)$$

where ECT is the error correction term or long-run relationship, and μ is the speed of adjustment.

3.2.3 Granger Causality Test

To determine causality relationships among economic growth, non-renewable energy consumption, renewable energy consumption, and CO_2 emissions, the VECM was used to estimate Granger causality. The Granger causality test determines the pattern of relationship between variables. Equations (6–9) show the VECM equations used in the current study:

$$\Delta LGDP_t = a_0 + \sum_{i=1}^{p} a_{1i}\, \Delta LGDP_{t-1} + \sum_{i=1}^{p} a_{2i}\, \Delta LNREC_{t-1} + \sum_{i=1}^{p} a_{3i}\, \Delta LREC_{t-1} + \sum_{i=1}^{p} a_{4i}\, \Delta LCO2_{t-1} + \mu_1\, ECT_{t-1} + \varepsilon_{1t} \quad (6)$$

$$\Delta LNREC_t = b_0 + \sum_{i=1}^{p} b_{1i}\, \Delta LNREC_{t-1} + \sum_{i=1}^{p} b_{2i}\, \Delta LGDP_{t-1} + \sum_{i=1}^{p} b_{3i}\, \Delta LREC_{t-1} + \sum_{i=1}^{p} b_{4i}\, \Delta LCO2_{t-1} + \mu_2\, ECT_{t-1} + \varepsilon_{2t} \quad (7)$$

$$\Delta LREC_t = c_0 + \sum_{i=1}^{p} c_{1i}\, \Delta LREC_{t-1} + \sum_{i=1}^{p} c_{2i}\, \Delta LGDP_{t-1} + \sum_{i=1}^{p} c_{3i}\, \Delta LNREC_{t-1} + \sum_{i=1}^{p} c_{4i}\, \Delta LCO2_{t-1} + \mu_3\, ECT_{t-1} + \varepsilon_{3t} \quad (8)$$

$$\Delta LCO2_t = d_0 + \sum_{i=1}^{p} c_{1i}\, \Delta LCO2_{t-1} + \sum_{i=1}^{p} d_{2i}\, \Delta LGDP_{t-1} + \sum_{i=1}^{p} d_{3i}\, \Delta LNREC_{t-1} + \sum_{i=1}^{p} d_{4i}\, \Delta LREC_{t-1} + \mu_4\, ECT_{t-1} + \varepsilon_{4t} \quad (9)$$

where Δ and ECT_{t-1} denote the first difference operator and the error correction term, respectively. If current and lagged values of X improve the prediction of the future value of Y, then it is said that X 'Granger causes' Y and the F-statistic is used for the rejection or non-rejection of the null hypothesis. The Granger causality test may explain unidirectional or bidirectional relationships if two variables are cointegrated. If two variables are not cointegrated, then one does not affect the other or neutrality.

4. Results and Discussion

4.1 Unit Root Test on Stationary of Variables

The unit root test results for the stationary series of all variables based on the Dickey-Fuller (ADF) and Phillips Perron (PP) tests are shown in Table 2. The variables in logarithmic form of economic growth (LGDP), non-renewable energy consumption (LNREC), renewable energy consumption (LREC), and CO_2 emissions (LCO2) were tested for the order of integration. The ADF and PP unit root test indicated non-stationary at level I(0) but stationary results for the series at the first difference I(1).

Table 2. Results of unit root tests

Variable	Level				1st difference			
	Dickey-Fuller test		Phillips-Perron test		Dickey-Fuller test		Phillips-Perron test	
	Intercept	Intercept and trend	Intercept	Intercept and trend	Intercept	Intercept and trend	Intercept	Intercept and trend
LGDP	-0.377	-1.999	-0.420	-2.198	-4.150***	-4.069***	-4.168***	-4.097***
LNREC	-0.771	-2.245	-0.777	-2.394	-3.403**	-3.382**	-3.557***	-3.643**
LREC	0.062	-2.353	0.199	-2.333	-4.980***	-5.237***	-4.981***	-5.237***
LCO2	-1.785	-1.290	-1.948	-1.253	-4.775***	-4.730***	-4.775***	-4.731***

Notes: ** Denotes a 5% significance level, and *** denotes a 1% significance level.

4.2 ARDL Cointegration Test

After determining whether stationary based on the unit root test, the cointegration or long-term relationship between variables was investigated based on the ARDL bound test approach. At first, the appropriate lag length of the ARDL model was chosen based on the Akaike information criterion (AIC). The lag result for the series showed that ARDL (2,2,1,1) was the optimal lag length based on the AIC.

Second, the ARDL bound testing was utilized to test the hypothesis of a long-term relationship (cointegration) between the series. The results of the ARDL bound testing for cointegration are reported in Table 3, indicating that the ARDL F-statistic (8.069) was greater than the upper critical value bound at the 1% significance level for I(0) and 5% significance level for I(1). Thus, the hypothesis of no-cointegration was rejected, so a long-term relationship exists between the variables in the model shown in Equation (3).

Table 3. Bound test result

Test statistic	k	Critical value bounds						P-value	
		10%		5%		1%			
F-statistic		I(0)	I(1)	I(0)	I(1)	I(0)	I(1)	I(0)	I(1)
8.069	3	3.061	4.443	3.862	5.496	5.952	8.218	0.003	0.011

After confirming the long-term relationship among the variables, the ARDL (2,2,1,1) model was estimated with the long-run and short-run parameters. The results of the short-run analysis are shown in Table 4, indicating a positive relationship between economic growth in lagged one period and economic growth at the 5% significance level. The non-renewable energy consumption in lagged one period was negatively associated with economic growth at a significant level of 1%. This finding implies that non-renewable energy in lagged one period was inefficient in accumulating economic growth in the short run, whereby a 1% increase in non-renewable energy consumption in lagged one period led to a decline in economic growth by 0.554% if all other variables remained constant. In addition, ECT (-1) or ECT_{t-1} in Equation (4) was negative (-0.8587) and significant at the 1% level, which indicated a long-term relationship between economic growth and all independent variables. The ECT variable's coefficient indicates a speed of adjustment between short-run dynamics and long-run equilibrium, implying that around 85.87% of the disequilibria resulting from the previous year’s shock converge back to the long-run equilibrium in the current year.

Table 4. Short-run coefficients estimation results of the ARDL model

Variable	Coefficient	Std. Error	t-statistic	P-value
LGDP (-1)	0.4001	0.1853	2.16	0.046**
ΔLNREC	-0.0281	0.1573	-0.18	0.861
LNREC (-1)	-0.5547	0.1562	-3.55	0.003***

ΔLREC	-0.0219	0.0341	-0.64	0.529
ΔLCO2	-0.0644	0.1573	-0.41	0.687
ECT (-1)	-0.8587	0.1810	-4.74	0.000***
R-squared	0.8368	Adj R-squared	0.7450	

The long-run coefficient estimation results for the ARDL model (Table 5) showed that all independent variables were significant at the 10% level for non-renewable energy consumption, at the 1% level for renewable energy consumption, and the 5% level for CO_2 emissions. Non-renewable energy consumption had a positive effect on economic growth in the long run. Assuming the other variables remain unchanged, a 1% increase in non-renewable energy consumption led to an increase of 0.334% in economic growth in the long run, implying that economic growth in Thailand was dependent on non-renewable energy consumption. This result was consistent with Nguyen and Le (2021) in Vietnam and with Bhattacharya et al. (2016) in 38 countries, where they noted that non-renewable energy consumption involved an increase in GDP in the long run.

Renewable energy consumption had a positive and significant impact on economic growth at the 1% level. An increase of 1% in renewable energy consumption increased economic growth by 0.101% in the long run. This finding was similar to the results of Bui Minh and Bui Van (2023), who found that renewable energy use impacted Vietnam's GDP level in the long term. Furthermore, Karimi et al. (2021) found a positive impact of renewable energy on Iran's economic activities. Fazal et al. (2020) reported that renewable energy consumption positively influenced Thailand's economic development. The long-run relationship between CO_2 emissions and economic growth was positive and statistically significant, with a 1% increase in CO_2 emissions driving economic growth by 0.439%, assuming the other parameters remained constant. Similar results were reported by Bouyghrissi et al. (2021) regarding a positive relationship between CO_2 emissions and economic growth.

Table 5. Long-run coefficients estimation results of the ARDL model

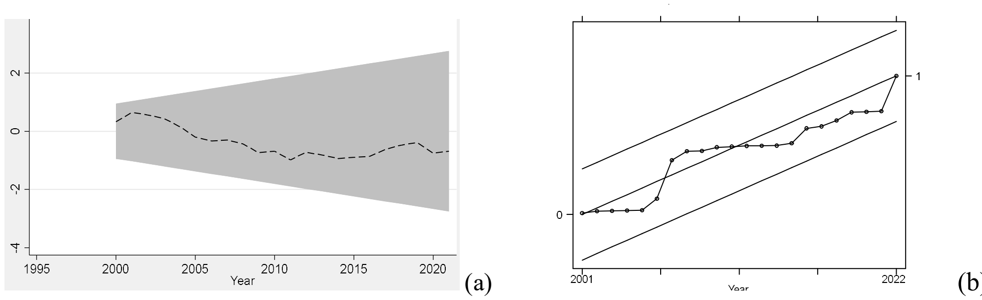
Variable	Coefficient	Std. Error	t-statistic	P-value
LNREC	0.3343	0.1763	1.90	0.076*
LREC	0.1013	0.0196	5.15	0.000***
LCO2	0.4396	0.2018	2.18	0.045**
C	1.7711	0.5674	3.12	0.007***

The diagnostic and stability tests in the model estimation are summarized in Table 6. The results of the Breusch-Godfrey LM test for serial correlation indicated no autocorrelation. Heteroskedasticity was tested based on the Breusch-Pagan test, which indicated no heteroskedasticity problem. Furthermore, the Jarque-Bera test indicated that the residuals in the model were normally distributed. The robustness of the ARDL model used in this study was supported by the cumulative sum of recursive residuals and the cumulative sum of squares of recursive residuals at 95% confidence intervals, as shown in Figure 1, with the plots confirming that the cointegration parameters were stable.

Table 6. Results of diagnostic tests

Test category	Diagnostic test	Statistic	P-value
Serial correlation	Breusch-Godfrey LM test	0.107	0.5743
Heteroskedasticity	Breusch-Pagan test	0.770	0.3791
Normality	Jarque-Bera test	0.136	0.9340

Figure 1. Plot of the cumulative sum of recursive residuals (a) and the cumulative sum of squares of recursive residuals (b) with 95% confidence intervals



4.3 Granger Causality Test

After confirming the existence of the ARDL cointegration relationship among variables, Granger causality tests were used to investigate the direction of causality in the short run and long run based on the vector error correction model (VECM) presented in Equations (6–9). The results of the VECM Granger causality tests are reported in Table 7. In the long run, the significance of the coefficients of the error correction terms for the economic growth, non-renewable energy consumption, renewable energy consumption, and CO_2 emissions equations indicated that long-run causality was significant at the 5%, 10%, 5%, and 1% levels, respectively. These results indicated the existence of bidirectional long-run causality between economic growth and non-renewable energy consumption. Similarly, Mele (2019) and Chen et al. (2019) found a long-run bidirectional causality between energy use and economic growth in Brazil and in Central China, respectively. In the long run, a feedback effect or the bidirectional relationship also exists between economic growth and renewable energy consumption. This finding shows that economic growth and renewable energy consumption are interdependent. This evidence is consistent with Li and Leung (2021) for Europe, Bouyghrissi et al. (2021) for Morocco, and Zafar et al. (2019) for APEC. The relationship between economic growth and CO_2 is also bidirectional in the long run. Similarly, Chen et al. (2019) also found that bidirectional long-run Granger causality exists between economic growth and CO_2 in China.

The short-run causality analysis indicated a statistical significance of unidirectional short-run causality between economic growth and CO_2 emissions at the 10% level of significance. In addition, there was unidirectional causality from non-renewable energy consumption to economic growth at the 1% level of significance.

Table 7. Results of Granger causality tests

Dependent variable	Short run causality				Long run causality
	ΔLGDP	ΔLNREC	ΔLREC	ΔLCO2	ECT (-1)
ΔLGDP	-	0.1723 (0.456)	0.1051 (0.761)	0.3289 (0.074)*	-0.0018 (0.010)**
ΔLNREC	0.9382 (0.009)***	-	-0.0290 (0.703)	0.4150 (0.306)	-0.0027 (0.088)*
ΔLREC	1.330 (0.160)	-0.4658 (0.729)	-	-0.1692 (0.874)	-0.0083 (0.045)**
ΔLCO2	-0.0128 (0.950)	-0.4323 (0.137)	0.00424 (0.922)	-	-0.0043 (0.000)***

Notes: *, **, and *** denote 10%, 5%, and 1% significance levels, respectively. The P-values appear in parentheses.

The Granger causality test results for the short run showed that economic growth had a positive causal relationship to non-renewable energy consumption, implying that non-renewable energy consumption was accelerated by economic growth due to the high consumption level of fossil energy in general and a large amount of non-renewable energy consumption in the country. The results of this relationship were similar to those reported by Tuna and Tuna (2019) for the Philippines, Malaysia, and Singapore, by Magazzino (2015) for Italy, by Sharif et al. (2019) for a global study, and by Kyophilavong et al. (2015) for energy consumption and economic growth in Thailand.

The current results showed that CO_2 emissions had positive causal relationships with economic growth, implying that a change in CO_2 emissions had an impact on economic growth in the short run. An increase in CO_2 emissions resulted in an increase in economic growth, implying that reducing emissions resulted in a negative impact on economic growth. These results were similar to those reporting short-run causality running from CO2 emissions to GDP by Azlina et al. (2014) for Malaysia and Litavcová and Chovancová (2021) for Czechia, Germany, Romania, Slovakia, Slovenia and Ukraine.

5. Conclusions and Recommendations

This study explored the links among economic growth, renewable energy, non-renewable energy, and CO_2 emissions in Thailand during 1995–2022. The study applied time-series techniques and unit root tests to investigate the integration of variables, the ARDL bound test to examine the presence of cointegration, and VECM and Granger causality tests to analyze the linkages among variables. The empirical results showed the existence of cointegration among variables at the first different levels. The results of the ARDL short-run analysis showed negative relationships between non-renewable energy consumption and CO_2 emissions on economic growth. The VECM and Granger causality tests indicated bidirectional long-run causality between economic growth and renewable energy consumption and between CO_2 emissions and economic growth. Furthermore, the study results identified a positive unidirectional causal relationship between CO_2 emissions to economic growth and economic growth to non-renewable energy in the short run.

Regarding renewable energy consumption, the results do not support a short-run causal relationship between renewable energy consumption and economic growth. This suggests that renewable energy plays a relatively minor role in GDP, and consequently, it is unlikely to have a significant impact on economic growth. However, there was bidirectional causality between economic growth and renewable energy consumption in the long run. Thus, in the long run, the adoption of renewable energy sources will have a positive impact on economic growth because renewable energy sources could lead to reduced costs and increased efficiency in economic activity in the long term. This implies that because Thailand has been promoting renewable energy production, utilization, and consumption since its first energy conservation plan in 1995, it is contributing positively to the growth of its economy.

According to these results, it can be concluded that non-renewable energy consumption and CO_2 emissions are associated with a decrease in economic growth in the short run. This is largely due to Thailand's heavy dependence on fossil energy imports, which have increased from 65% of total energy consumption in 1995 to 79% in 2022. This increased dependence on fossil energy is directly linked to a rise in CO_2 emissions, from 2.62 metric tons per capita in 1995 to 3.74 metric tons per capita in 2022. Furthermore, the results indicated that an increase in non-renewable energy consumption and CO_2 emissions would be associated with an increase in economic growth in the long run. This suggests that the economic growth of Thailand could potentially be accelerated by an increase in fossil energy use and CO_2 emissions. The results indicate that, despite efforts, plans, and targets to reduce emissions and transition to renewable energy sources, Thailand has not successfully decoupled economic growth from non-renewable energy usage and CO_2 emissions. The results are also in line with the studies in Southeast Asia countries by Chontanawat (2020) in the case of the

Philippines and by Tuna and Tuna (2019) for non-renewable energy consumption and economic growth in Malaysia, Singapore, and the Philippines.

The results of this study should provide useful insights into the nexus between non-renewable energy consumption, renewable energy consumption, CO_2 emission, and economic growth and help policymakers make informed decisions about energy policies. The bidirectional causal relationship among these variables highlights the need for a holistic approach to energy and environmental policy in Thailand that accounts for the interactions among these variables. In addition, it is important to continue implementing policies that promote the use of renewable energy sources to decrease the country's energy dependence and reduce CO_2 emissions. However, the impacts of CO_2 emissions on economic growth could be mitigated by innovation and technological advancements in the long run. The widespread adoption of renewable energy technologies, such as biofuel, wind, and solar power, could promote economic growth in the long run. The results suggested that Thailand should efficiently implement renewable energy policies to enhance economic growth and contribute to sustainable development.

The results of this research highlight the interrelation between economic growth, renewable energy consumption, and CO_2 emissions. Further research could be conducted to investigate the specific types of renewable energy sources that are most effective in reducing CO_2 emissions in Thailand. This information could be used to inform policy decisions related to the promotion of renewable energy sources. Furthermore, extending the study to include other countries in the Southeast Asia region to investigate whether similar relationships exist would provide a broader understanding of the regional dynamics facing similar energy and environmental challenges.

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