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The Relationship between Green Economic Growth and Trade Openness: Empirical Evidence from Indonesia

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ABSTRACT

This study explores the relationship between green economic growth, regional trade openness, renewable energy consumption, and CO2 emissions in the agglomeration area of Sumatra Island, Indonesia. Using panel data from 2010 to 2023, this research examines the region's efforts to reduce the environmental impact of fossil-based energy consumption by transitioning to renewable energy, supporting ecological resilience. This transition, however, requires significant time and financial investments. The Sumatra Island agglomeration, with its shared environmental characteristics, plays a crucial role in trade openness and presents opportunities for alternative financing mechanisms to ensure economic sustainability. Employing ARDL and VEC model analysis, this study highlights both short- and long-term relationships between regional trade openness and green economic growth, providing insights into the future economic prospects of the Sumatra Island agglomeration. The findings indicate that regional trade openness significantly influences green economic growth in a positive direction in both the short and long terms. The study recommends fiscal policies, including tax incentives for trade that supports the green economy and the implementation of carbon taxes to regulate CO2 emissions, to promote sustainable development in the region.

Keywords: *trade openness; renewable energy consumption; CO2 emission, green economic growth; autoregressive distributed lag; vector error correction model*

JEL Classification: C10, C32, Q51, Q56

INTRODUCTION

The Sumatra Island agglomeration area is located along the strategic trade route of the Malacca Strait, between Malaysia, Singapore, and Thailand, with maritime trade routes to India and passing through ALKI 1, which is a maritime trade route passing through the Karimata Strait, South China Sea, Indian Ocean, Sunda Strait, and Java Sea. Due to this strategic position, maritime trade has developed as a gateway for investment flows into the Sumatra Island agglomeration area. This trade openness can create opportunities for investments in green economic growth in the region, provided there is the appropriate transfer of technology aligned with the capacity and support of ecosystem services to mitigate further environmental degradation. International trade offers benefits for economic growth while also protecting the environment, generating additional revenue that can be used to prevent ecological pollution. (Appiah et al., 2022).

The growth of trade in the Sumatra Island trade agglomeration area has been increasing in line with the rise in Gross Regional Domestic Product (GRDP). This has a positive effect on the domestic economy, which requires strategies and policies to maintain regional economic

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conditions that are both growing and stable within the framework of economic development system stability (Nguyen et al., 2022). Through trade openness and regional cooperation as an alternative form of financing for regional development, it is important to also consider ecological principles, ensuring the preservation of the capacity and support of natural resource ecosystems. The dependence on spatial areas, which can lead to changes in renewable energy consumption patterns, can influence GDP and, in turn, increase the national economy (Chica-Olmo et al., 2020).

The economic activities in the agglomeration area of Sumatra Island have been rapidly growing, driven by the development of various industrial zones to support economic growth. The economic growth in this region is predominantly dominated by the mining and excavation sector, particularly in the provinces of Riau, North Sumatra, Lampung, Jambi, West Sumatra, and South Sumatra. Continuous large-scale exploration and exploitation of coal for industrial fuel accelerate environmental degradation and contribute to global warming. Socio-technical adaptation to rapidly changing environmental conditions is driven by global climate change and the challenges of rapid decarbonization (Swilling et al., 2022). Meanwhile, the global effort to reduce CO2 emissions continues, involving both developed and developing countries, including those in the agglomeration area of Sumatra Island. CO2 emissions from fossil fuel-based energy are regarded as one of the most dangerous and complex issues, sparking debates among scientists about climate change (Lin & Raza, 2019); (Karedla et al., 2021).

Regional and international trade play an important role in green economic growth by enabling technology transfer, improving renewable energy literacy, and supporting the shift to sustainable energy sources. Developed countries have targeted the energy transition by expanding investment in the use of production and implementing energy resources that are adaptive to the environment (Zhang et al., 2023). This challenge opens opportunities for open trade, including importing raw materials and spare part components for renewable energy supply products and exporting energy from renewable sources, as well as renewable natural resources for manufacturing and transportation.

The management of natural resources for renewable energy, a driving factor for environmentally based economic growth, has become an important issue in the trade agglomeration areas of Sumatra Island amid increasingly limited ecological conditions. With trade openness, there is a significant impact on carbon dioxide emissions, with the use of green energy to increase spending on research and development focused on renewable energy (Jóźwik et al., 2022). The transition from fossil-based energy to adaptive, environmentally friendly energy can reduce the negative impacts of global warming due to climate change. This ongoing climate change phenomenon has implications that can pose threats to both the world and specific regions, leading to various climate disasters (Zamora-Pereira et al., 2023). The continuous increase in the consumption of material goods drives environmental crises and the loss of biodiversity and natural resources, thus triggering climate change (Sartzetakis et al., 2023).

Several studies have explored the relationship between trade openness and a country's green economic growth. For instance, Sebri and Ben-Salha (2014) conducted an investigation comparing the impact of trade openness on green economic growth in BRICS countries, finding that it offers greater benefits than in other nations due to the transfer of environmentally friendly technologies through investments in the renewable energy sector. Similarly, Khan et al. (2021) found that trade openness contributes to a reduction in carbon emissions in developed countries while negatively affecting environmental quality in developing nations.

Given the growing need for economic growth and the urgency of preserving environmental resilience in Sumatra Island’s trade agglomeration area, the author is motivated to examine the relationship between trade openness and green economic growth despite numerous previous studies on this topic.

DATA AND METHODOLOGY

This approach to variable non-stationarity can result in spurious regressions. Variables that are stationary at both the first level and first difference can be utilized in Autoregressive Distributed Lag (ARDL) model simulations.

Table 1. Variables and Data Sources

Variable	Symbol	Definition	Source
Renewable Energy	lnRENEW	Renewable energy consumption (% of total final energy consumption) which is proxied by GRDP share	World Bank, 2017
Economic Growth	lnGRDP	Total Gross Regional Domestic Product	Indonesian Central Statistics Agency
Energy Use	lnEU	Primary energy consumption is proxied by the GRDP share	World Bank, 2017
CO_2 Emission	lnCO_2	CO2 (% of total final gas consumption) is proxied by GRDP share	World Bank, 2017
Trade Openness	lnTRD	Regional trade openness	Indonesian Central Statistics Agency

Source: Authors' Compilation (2025)

The unit root test is used to identify stochastic trends in the data. To study the relationship between variables, the following general equation is proposed:

$$lnGRDP_{it} = \omega_0 + \omega_1 lnRENEW_{it} + \omega_2 lnEU_{it} + \omega_3 lnCO2_{it} + \omega_4 lnTRD_{it} + e_{it} \quad (1)$$

Where: ω_0 is a constant and ω_{1-4} is the coefficient of the exogenous variable, and ε is the error factor. From equation (1) above, this model was first introduced by Pesaran et al. (2001). If the series is stationary at the first level and level of difference or both, the model can be used. If there is a long-term relationship between the variables under consideration, the long-term and short-term ARDL models are as follows:

$$\Delta lnGRDP_{it} = \alpha_0 + \alpha_1 lnGRDP_{it-1} + \alpha_2 lnRENEW_{it} + \alpha_3 lnEU_{it} + \alpha_4 lnCO2_{it} + \alpha_5 lnTRD_{it} + \sum_{i=1}^{n} \beta_1 \Delta lnGRDP_{it-1} + \sum_{i=1}^{n} \beta_2 \Delta lnRENEW_{it-1} + \sum_{i=1}^{n} \beta_3 \Delta lnEU_{it-1} + \sum_{i=1}^{n} \beta_4 \Delta lnCO2_{it-1} + \sum_{i=1}^{n} \beta_5 \Delta lnTRD_{it-1} + ECM_{it-1} + e_{it} \quad (2)$$

where β is volatility in the short term and the error correction term shows how quickly things return to a point of stability after the previous period experienced a shock. The error correction term usually lies between -1 and 0.

The first distinction between renewable energy, green economic growth, export-import trade openness, energy consumption and CO2 emissions is represented in equation (2), where t-i is the Akaike information criterion (AIC) that provides lag selection. For long term impacts α and β are used. The analysis technique used is the long-term and short-term ARDL models in order to evaluate long-term relationships

In the ARDL model equation shown in equation (2) is the period that describes the long-term and short-term responses; e is the error; α_1 to α_5 are variable coefficients in the long term; β_1 to β_5 are variable coefficients in the short term, ε_t is the residual obtained from cointegration estimates whose different equations are shown in equation (3):

$$\Delta lnGRDP_{it} = \varphi_0 + \sum_{i=1}^{n} \gamma_1 \Delta lnGRDP_{it-1} + \sum_{i=1}^{n} \gamma_2 \Delta lnRENEW_{it-1} + \sum_{i=1}^{n} \gamma_3 \Delta lnEU_{it-1} + \sum_{i=1}^{n} \gamma_4 \Delta lnCO2_{it-1} + \sum_{i=1}^{n} \gamma \Delta lnTRD_{it-1} + ECM_{it-1} + \delta e_{it-1} \quad (3)$$

Where: φ_0 represents the parameter coefficient, with γ_1 to γ_5 representing the short-term effect. The coefficient of the error correction term is described with the notation δ which will indicate a measure of how quickly the shock is corrected in the following period until it reaches a point of stability. The value of this influence coefficient is theoretically significant and negative e_{it-1} is the measure of instability in equation 3.

The ARDL model overcomes the shortcomings of the conventional ARDL model for evaluating variable interdependence. The ARDL model is used to estimate, analyze, and provide visualization of changes in the regression variables and their implications for the regression itself for short-term to long-term adjustments in order to keep all other variables in the equation constant. For the ARDL model to be applicable, variables must be stationary at the first difference level and integrated with the variable under evaluation.

RESULTS AND DISCUSSION

Analysis of Economic Growth Variable Movement

The economic structure of the trade agglomeration area of Sumatra Island, based on GDP consumption by the mining and quarrying sector, is influenced by the significant potential of natural mineral resources such as natural gas, coal, and petroleum, which are fossil fuel-based energy sources. These fossil fuels support industrial activities and transportation, including diesel trains and land transport. If these natural resources are explored extensively, it could lead to environmental disruption, ecosystem damage, and potential environmental degradation. At higher income levels, GDP is expected to reduce deforestation, meaning that an increase in GDP per capita will lead to a decrease in deforestation, particularly with strict environmental policies focusing on green economics to control natural resource exploitation (Sotamenou & Nehgwelah, 2024). The condition of economic growth, as reflected in GDP, is shown in Figure 1, with GDP values continually rising along with increased consumption of goods and services to meet the needs of the population. The highest GDP consumption is observed in the regions of Riau, North Sumatra, and South Sumatra.

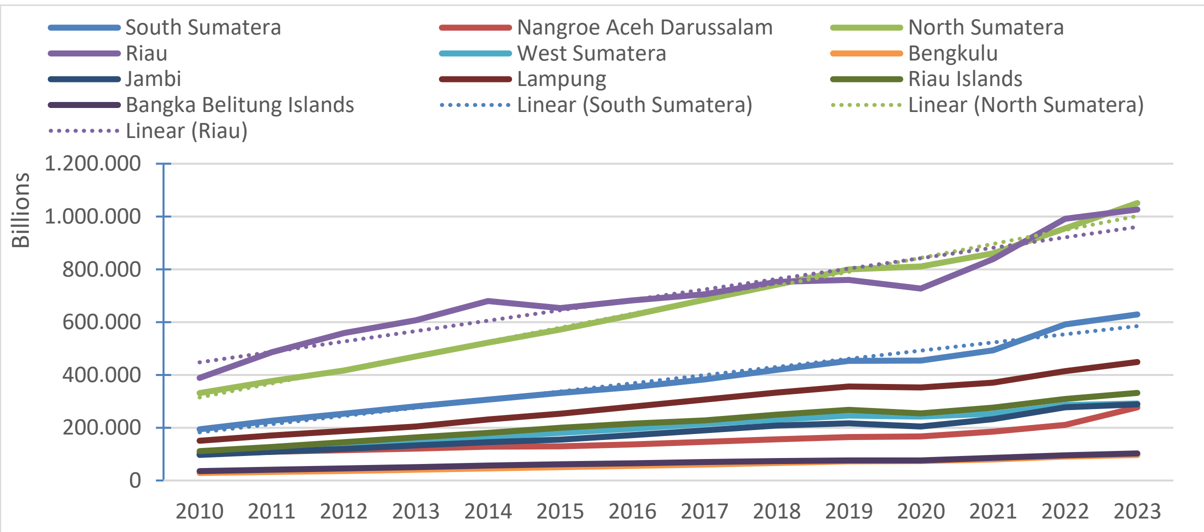

Figure 1. GRDP Growth Trend

Source: Indonesian Central Statistics Agency, (2025)

Analysis of Trade Openness Variable Movement

As shown in Figure 2, the trade value in the agglomeration area of Sumatra Island experiences fluctuations, in line with the need for regional development financing. This trade openness creates alternative opportunities for green economic growth. The influx of global trade flows into the region will stimulate the role and transfer of technology, such as operational equipment for industry and large production machinery. In Pakistan, various efforts have been made to mitigate the negative impact of foreign direct investment inflows on ecological pollution in relation to economic growth (Bakhsh et al., 2017). Meanwhile, the influence of globalization, trade, investment, and technological innovation has a negative impact on CO_2 emissions in Pakistan (M. K. Khan et al., 2019).

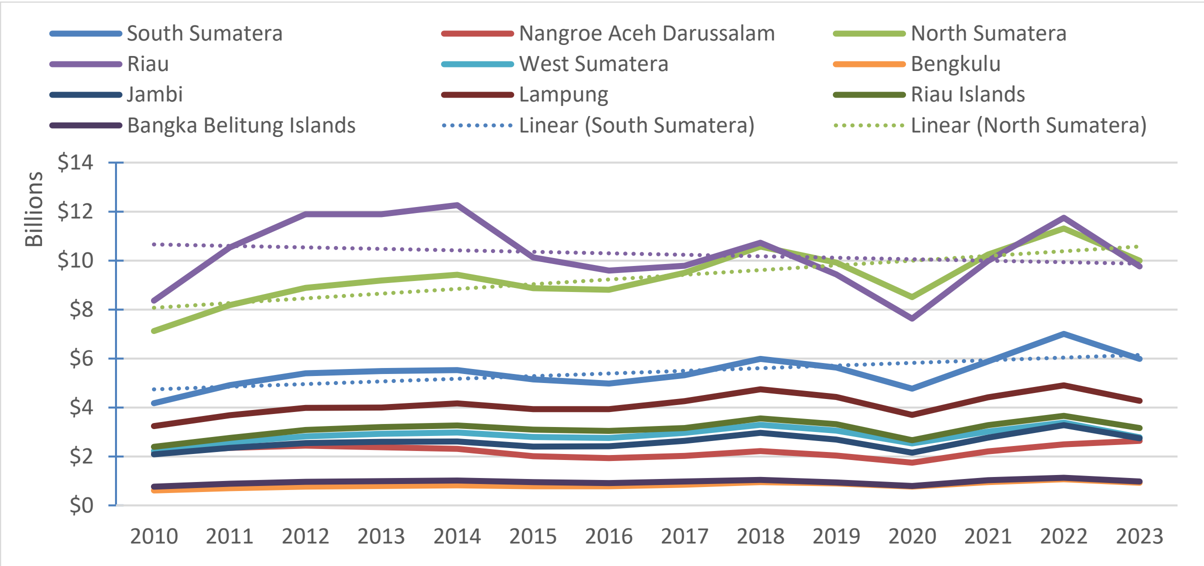

Figure 2. Regional Trade Value Trend

Source: Indonesian Central Statistics Agency, (2025)

Analysis of Renewable Energy Variable Movement

Renewable energy consumption in the trade agglomeration area of Sumatra Island remains highly fluctuating, although the trend in Figure 3 shows very slow progress. Only in the Riau region does the trend in renewable energy consumption show a decline, which is due to the continued dominance of fossil fuel energy use in the area. In China, over the long term, there has been a heavy reliance on carbon energy consumption, driven by abundant mineral and coal resources and high economic growth. This dependence on carbon consumption has led to a significant increase in CO_2 emissions (Wang et al., 2016). Green economic growth, combined with the flow of global trade, can economically increase renewable energy consumption, but CO_2 emissions remain quite high, even though the gradual adoption of renewable energy in developed countries, particularly in environmentally friendly industrial zones, continues to progress (Ashfaq et al., 2024).

Energy consumption highlights the relationship between total energy use, renewable energy consumption, and carbon emissions. Numerous studies have examined the determinants of carbon emissions in developing countries, with findings indicating that economic growth and energy consumption have a positive effect on carbon emissions in Southeast Asia. Carbon emissions are notably higher in Indonesia and Vietnam compared to other countries in the region. Research by Wang et al. (2016) explored the impact of energy consumption and economic growth on carbon emissions using OLS, fixed effects, Granger causality, and panel cointegration tests across seventy countries from 1995 to 2013. The study concluded that increased trade openness has fostered greater use of renewable energy. The analysis revealed a negative correlation between renewable energy consumption and economic growth. Furthermore, Ashfaq et al. (2024) examined the long-term relationship between economic growth, carbon emissions, and renewable energy consumption in a global panel.

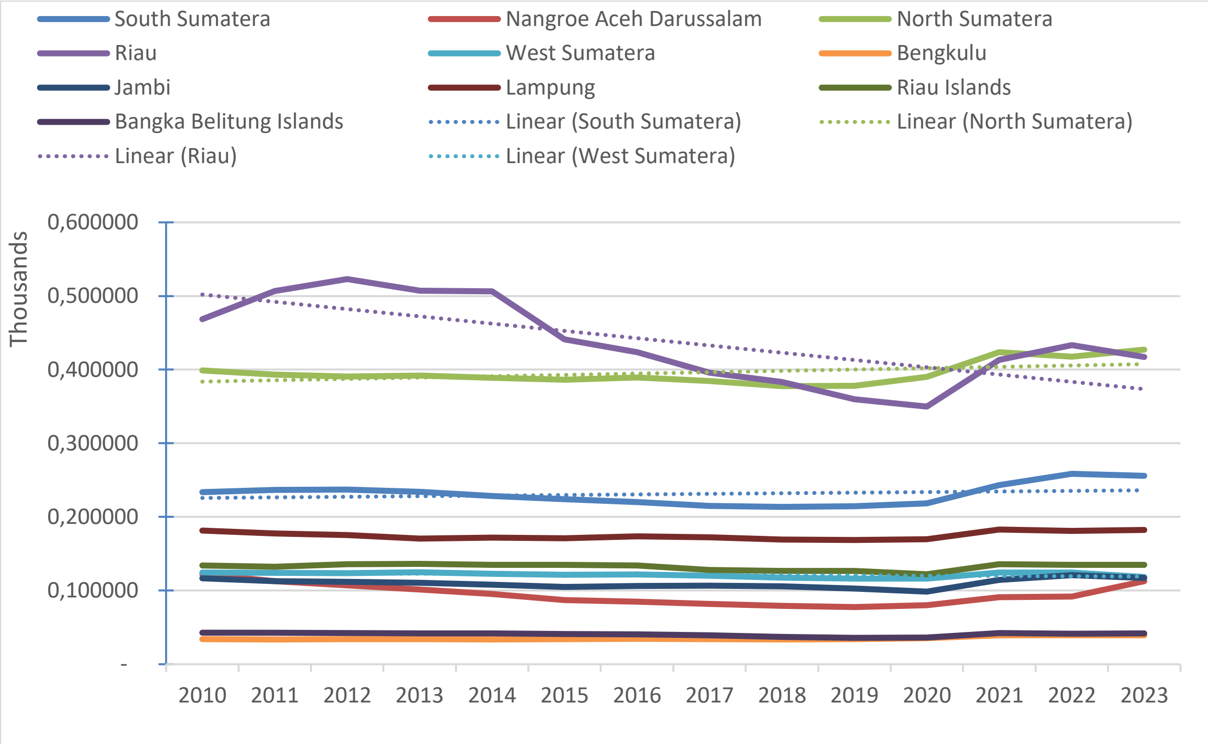

Figure 3. Renewable Energy Consumption Trend

Source: Indonesian Central Statistics Agency, (2025)

Analysis of CO2 Emissions Variable Movement

As shown in Figure 4, efforts to reduce CO2 emissions in the trade agglomeration area of Sumatra Island indicate a downward trend, although the downward movement remains very slow. Local governments have started to consider the environmental degradation impacts, such as increased air temperatures due to rapid growth. Green economic growth has become part of the policy adopted by local governments to reduce carbon consumption and mitigate the impacts of CO2 emissions. An empirical study in China, which divides the region into western and central parts with urbanization development, shows that the impact of urbanization linked to industrial development leads to relatively low energy efficiency, high CO2 emissions, and high energy consumption (Wang et al., 2016). The incomplete combustion of fossil fuel-based emissions is the most harmful to health, and there are complex issues that trigger climate change (Lin & Raza, 2019).

The BRICST countries have entered an economic expansion phase, where there is a positive shock in growth that is unbalanced, with shocks negatively responding to CO2 emission reductions. This predicts an increased demand for energy by exploring alternatives to energy resource potential, aiming to shift the energy base from fossil fuels to a more environmentally friendly direction with a renewable ecological system. This shift makes energy efficiency in these countries more productive, helping to maintain environmental quality (A. Khan & Sun, 2024).

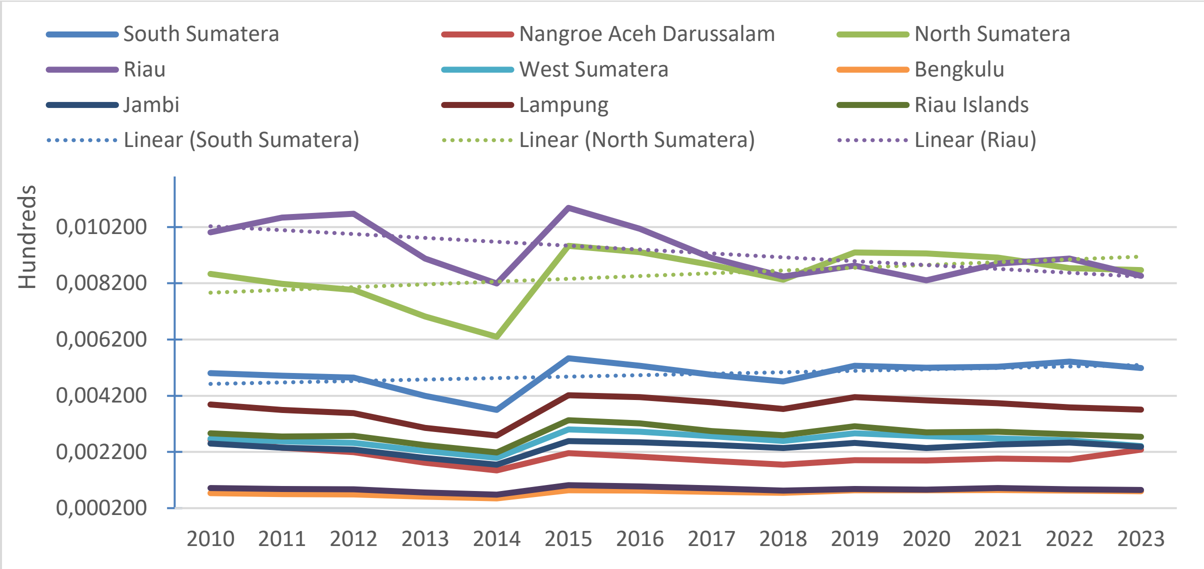

Figure 4. CO2 Emissions Trend

Source: Indonesian Central Statistics Agency, (2025)

Analysis of Primary Energy Variable Movement

Fossil-based primary energy consumption in the trade agglomeration area of Sumatra Island is still in use, but its consumption trend continues to fluctuate, as shown in Figure 5. This is due to the abundant mineral and coal resources in the region. A significant amount of time and investment is required to shift this energy conversion to renewable energy. Nevertheless, efforts have been made to reduce dependence on this primary energy consumption. An empirical study in China mediates the effects of development supported by innovation and appropriate technology transitions, which have contributed to reducing the negative impacts of environmental changes. As a result, development in China has become more environmentally friendly with high-quality standards (Chang & Lai, 2023).

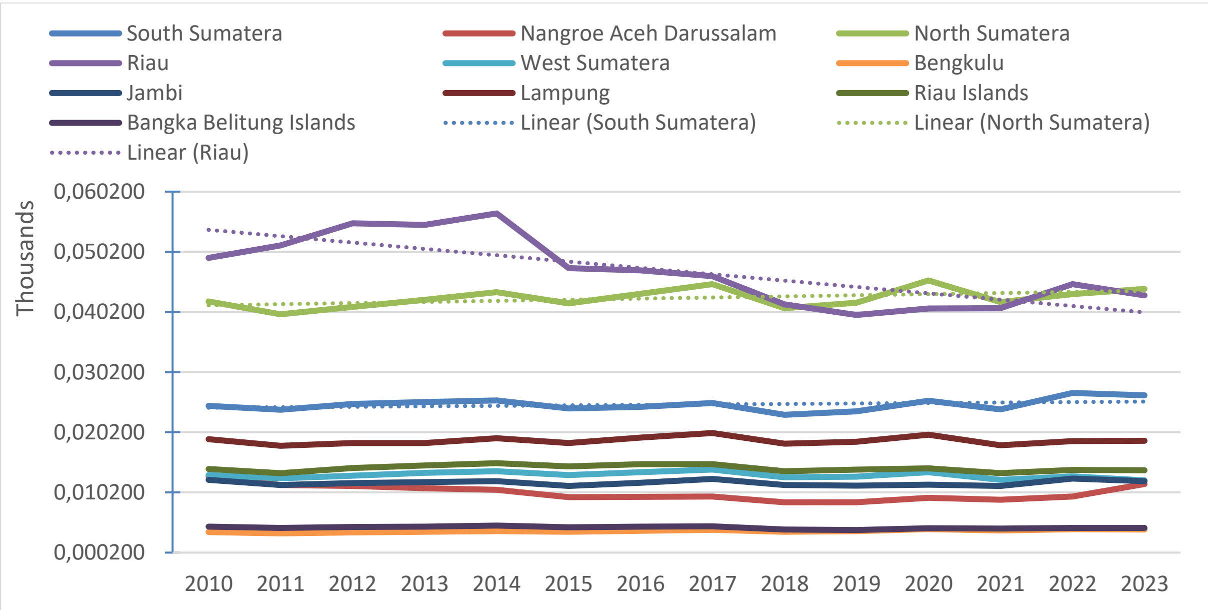

Figure 5. Primary Energy Consumption Trend

Source: Indonesian Central Statistics Agency, (2025) The use of fossil-based primary energy continues to play a supporting role in regional development and economic growth, contributing to the degradation of environmental ecosystem services. This study focuses on investigating the impact of economic growth on the degradation of environmental ecosystem services in Jordan (Jreisat, 2021). Empirical evidence from other studies shows that international trade cooperation is essential to reduce the negative effects of carbon emissions in order to maintain the resilience of cross-border growth against environmental ecosystem damage and other related negative spillover impacts. Therefore, governments must effectively achieve the goal of reducing carbon dioxide emissions by implementing fiscal spending functions focused on renewable energy (Udeagha & Ngepah, 2022).

Descriptive Statistical Analysis

The results of running data explain descriptive statistics based on Table 2 below, where the data is in natural logarithm form. This illustrates the means for export-import trade, green economic growth, use of renewable energy with a transition to CO2 emissions and energy consumption. The highest average values are the use of renewable energy (177.3338) and economic growth (19.04454); this shows that lnRENEW and lnGRDP have a relatively stable trend level. The standard deviation of all variables is positive, with the highest values for lnRENEW (133.7157) and lnEU (14.33357).

The relationship between the panel data variables is presented in Table 2. To assess the strength and direction of these relationships, the Pearson correlation test was employed. A value of 1 indicates a perfect relationship between the variables. Positive and negative signs represent the direction of the relationship: a positive sign indicates that an increase in one variable leads to an increase in another, while a negative sign indicates the opposite. The results shown in Table 2 reveal that the variables lnGRDP, lnRENEW, lnEU, lnCO2, and lnTRD exhibit positive correlations. Correlation analysis not only aids in understanding linear relationships between variables but also helps to identify the strength and direction of these relationships.

Table 2. Statistical Test Results Description

Description	lnGRDP	lnRENEW	lnEU	$lnCO_2$	lnTRD
Mean	32.96864	177.3338	19.04454	0.380193	21.85357
Median	33.00500	124.7985	13.62768	0.276365	21.84000
Maximum	34.59000	522.9640	56.57213	1.088361	23.23000
Minimum	30.98000	33.58876	3.399634	0.054741	20.23000
Std. Dev	0.859250	133.7157	14.33357	0.286951	0.805895
Skewness	-0.168188	1.021280	1.012083	0.998598	-0.159858
Kurtosis	2.372050	2.875933	2.842959	2.777458	2.204672
Jarque-Bera	2.960243	24.42678	24.04447	23.55686	4.286133
Probability	0.227610	0.000005	0.000006	0.000008	0.117295
Sum	4615.610	24826.73	2666.235	53.22702	3059.500
Sum Sq. Dev	102.6252	2485304.	28557.72	11.44538	90.27581
Observations	140	140	140	140	140
Multicolinearity					
lnGRDP	1.000000	-			
lnRENEW	0.848273	1.000000	-		
lnEU	0.850768	0.996971	1.000000	-	
$lnCO_2$	0.858242	0.983044	0.982979	1.000000	-
lnTRD	0.950352	0.917157	0.916928	0.908464	1.000000

Source: Authors' calculation based on output E-Views 13 (2025)

Panel Unit Root Test

Before estimating with the ARDL model, several econometric requirements must be met, such as testing data stationarity with the unit root test using the Augmented Dickey-Fuller test criteria (ADF-Test), specifically the ADF-Fisher Chi-square and ADF-Choi Z-stat methods. This test was developed by (Levin et al., 2002). The test results indicate that the data is not stationary, with homogeneity (null hypothesis) and heterogeneity (alternative hypothesis).

From the data results, lnRENEW is stationary at the level, while lnGRDP, lnEU, lnCO2 and lnTRD are stationary at the first difference level. No variables are stationary at the second difference level. This is very relevant and has met the criteria for estimating the ARDL model. The complete results of the unit root testing can be seen in Table 3 below.

Table 3. Panel Unit Root Test

Variable	ADF-Fisher Chi-square		ADF-Choi Z-stat		Information
	t-Statistic	Prob	t-Statistic	Prob	
$\Delta\ (lnGRDP)$	35.2897	0.0186	-1.88638	0.0296	stationary
$\Delta\ (lnRENEW)$	31.9372	0.0440	-1.89680	0.0289	stationary
$\Delta\ (lnEU)$	82.1643	0.0000	-6.01017	0.0000	stationary
$(lnCO2)$	38.0914	0.0086	-3.17800	0.0007	stationary
$(lnTRD)$	64.3103	0.0000	-5.31077	0.0000	stationary

Source: Authors' calculation based on output E-Views 13 (2025)

Lag Order Selection Criteria

The criteria and determination of the optimum lag in this research model were carried out to see the optimum lag length for each dynamic variable in the model equation. The optimum lag length was determined following the approach by Papers (1994), using one of the information criteria methods such as the Akaike information equation criterion (AIC) and the Schwarz information criterion (SC). The test results are seen in Table 4 below.

Table 4. Lag Order Selection Criteria

Lag	LogL	LR	FPE	AIC	SC	HQ
0	-291.6898	NA	0.013572	9.889659	10.06419	9.957927
1	73.46518	657.2789	1.62e-07	-1.448839	-0.401667	-1.039233
2	320.5354	403.5481	1.01e-10	-8.851181	-6.931365	-8.100235
3	570.2260	366.2128	5.88e-14	-16.34087	-13.54841	-15.24858
4	667.9838	127.0852	5.68e-15	-18.76613	-15.10102	-17.33250
5	760.0093	104.2955	7.09e-16	-21.00031	-16.46256	-19.22535
6	825.5669	63.37238*	2.34e-16	-22.35223	-16.94184*	-20.23593
7	863.6254	30.44678	2.22e-16*	-22.78751	-16.50448	-20.32987
8	901.7834	24.16673	2.58e-16	-23.22611*	-16.07043	-20.42713*

Source: Authors' calculation based on output E-Views 13 (2025)

Table 4 shows that the lag order selection criteria, based on the Akaike Information Criterion (AIC), has the smallest value (-23.22611) at the optimum lag of 8.

Cointegration Test

According to Hatemi-J (2020), hidden cointegration in cross-sectional data is examined within the Pedroni cointegration framework. To ensure the robustness of the findings, multiple variables are tested for cointegration following Kouton (2019), based on the stationarity properties of the residuals. The test results presented in Table 5 indicate that the null hypothesis is rejected, leading to the conclusion that hidden cointegration exists.

Table 5. Hatemi J's Hidden Cointegration in Pedroni's Framework

Pedroni-cointegration	Statistic	P-Value	Weighted Statistic	P-Value
Alternative hypothesis: common AR coefs (within-dimension)				
Panel v-Statistic	-1.954840	0.9747	-1.916088	0.9723
Panel rho-Statistic	2.869215	0.9979	2.880170	0.9980
Panel PP-Statistic	3.523847	0.9998	3.490641	0.9998
Panel ADF-Statistic	4.347007	1.0000	4.225725	1.0000
Alternative hypothesis: common AR coefs (between-dimension)				
Group rho-Statistic	4.039067	1.0000		
Group PP-Statistic	3.036694	0.9988		
Group ADF-Statistic	4.846516	1.0000		

Source: Authors' calculation based on output E-Views 13 (2025)

ARDL Model Test Results

To determine the optimal lag length for this research variable, the Akaike Information Criterion (AIC) is used, which is shown in Figure 6. The chosen maximum lag length is 1 (ARDL(1, 1, 1, 1, 1)) for various model variations. Table 6 also shows the results of the ARDL bound test, where the estimated F-statistic value exceeds the critical limit value for I(0) and I(1), surpassing 5,840 at the 1 percent significance level in the cross-section data. This means that the null hypothesis is rejected, indicating the presence of cointegration in the model.

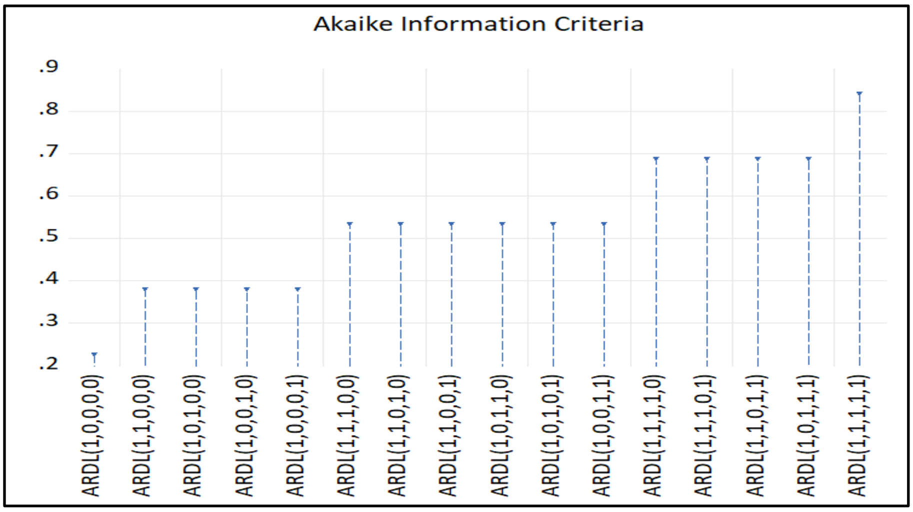

Figure 6. Akaike Information Criteria

Source: Authors' calculation based on output E-Views 13 (2025)

Table 6. ARDL Bound Test Model Results

ARDL Bound Test Model Results					Lag Max	
$lnGRDP_{it} = f(lnRENEW_{it}, lnEU_{it}, lnCO2_{it}, lnTRD_{it})$					1,1,1,1,1	
Criteria	10%		5%		1%	
	I(0)	I(1)	I(0)	I(1)	I(0)	I(1)
Critical Bound Value	2.525	3.560	3.058	4.223	4.280	5.840

Source: Authors' calculation based on output E-Views 13 (2025)

Table 6 presents the results of the ARDL Bound test model. Statistically, the cross-section shows the F-statistic value above the critical bound values at the 10 percent, 5 percent and 1 percent levels, both at level and at the first difference. This indicates that the studied variables influence the performance of the dependent variable in regional economic growth in Sumatra.

ARDL Model Short-Run and Long-Run Estimation

The testing of the ARDL model estimates for both short-run and long-run periods, along with detailed analysis, is presented in Table 7. The dependent variable is economic growth (lnGRDP), and the results show that the Error Correction Term (ECT) coefficient is negative (-0.020305) with a significant confidence level of 1 percent. This indicates a model imbalance in the long term, which has been corrected through adjustments from the short run to the long run, achieving a stability rate of 2.03 percent in the current conditions. The results of testing the ARDL and VEC models in the short term show that the dependent variable, lnGRDP, has a significant influence at lag 1. The lnRENEW variable shows a positive and insignificant coefficient, while lnEU has a positive and significant relationship influence at lag 1. The lnCO2 variable shows a negative and significant influence at lag 0, while lnTRD has a positive and significant relationship influence at lag 1.

Table 7. Long-Run and Short-Run Estimation Results of the ARDL Model

Dependent variable: lnGRDP	**Coefficient**	**Std-Error**	**t-Statistic**	**Prob**
Long-Run Estimation				
$lnRENEW$	0.069259	0.031342	2.209743	0.0291
$lnEU$	-0.645877	0.272261	-2.372273	0.0193
$lnCO2$	-3.032861	1.589536	-1.908017	0.0589
$lnTRD$	3.628636	0.972459	3.731404	0.0003
Short-Run Estimation				
$\Delta lnRENEW$	0.002177	0.001501	1.450214	0.1497
$\Delta lnEU$	0.451643	0.133673	3.378724	0.0010
$\Delta lnCO2$	0.011085	0.004105	2.700331	0.0080
$\Delta lnTRD$	0.170402	0.025278	6.741248	0.0000
ECT_{it-1}	-0.020305	0.004770	-4.256604	0.0000

Source: Authors' calculation based on output E-Views 13 (2025)

Table 7 presents the results showing that the relationship between the elasticity of economic growth in the short-run and long-run periods and exogenous factors is a key characteristic shown in open export-import trade. In the short run, cointegration is negative and significant. This research indicates that, in the long run, the relationship between export-import trade and the use of new renewable energy is significant and profitable, while in the short run, export-import trade has a positive impact. The use of new renewable energy in short-run periods can cause losses and is very rare when associated with other variables. The increase in export-import trade of 3.628636 percent, in the long run, was influenced by short-run gains of 0.170402 percent in regional economic growth in Sumatra.

Diagnostic Test

The results of the diagnostic statistical tests of the data used include autocorrelation tests using the Lagrange multiplier test. The results show that the null hypothesis is rejected, indicating no autocorrelation from the remaining lag one that is determined. The next test is the heteroscedasticity test with cross-product. The heteroscedasticity test of the null hypothesis shows that the null hypothesis is rejected, which means that there is no heteroscedasticity and no specification error. Then, the normality test using the Jarque-Bera test shows that the null hypothesis is accepted, which means that the observed sample size is normally distributed in Figure 7.

Heteroskedastisitas Test

Table 8 shows the results of the heteroscedasticity test which aims to test whether the ARDL model has a constant residual variance. Based on the p-value, it can be seen that most of the variables are not significant at the 5 percent confidence level, indicating that there is no serious heteroscedasticity problem. This indicates that the ARDL model meets the homoscedasticity assumption, where the variance of the error is constant and there is no indication that the error depends on the independent variable.

Tabel 8. Heteroskedasticity Test Results of the ARDL Model

Dependent Variable: ABS(RESID)				
Variable	**Coefficient**	**Std. Error**	**t-Statistic**	**Prob.**
C	0.070724	0.058000	1.219389	0.2252
$lnRENEW$	-4.06E-05	8.53E-05	-0.476459	0.6347
$lnEU$	0.000925	0.000782	1.182439	0.2395
$lnCO2$	-0.016841	0.015381	-1.094922	0.2758
$lnTRD$	-0.002887	0.002776	-1.040279	0.3004
Test statistics				
Serial Correlation (LM test)	Breusch-Godfrey		1.232294	0.1616
Ramsey Reset Test			0.260679	0.8009

Source: Authors' calculation based on output E-Views 13 (2025)

Normality Test

The results of the normality test using the Jarque-Bera Test showed a test statistic of 0.385 with a probability (p-value) of 0.824. In normality testing, the null hypothesis (H0) tested is that the data follows a normal distribution. If the p-value is greater than the commonly used significance level (alpha 0.05), then the null hypothesis cannot be rejected, meaning the data does not have enough evidence to state that the distribution is not normal.

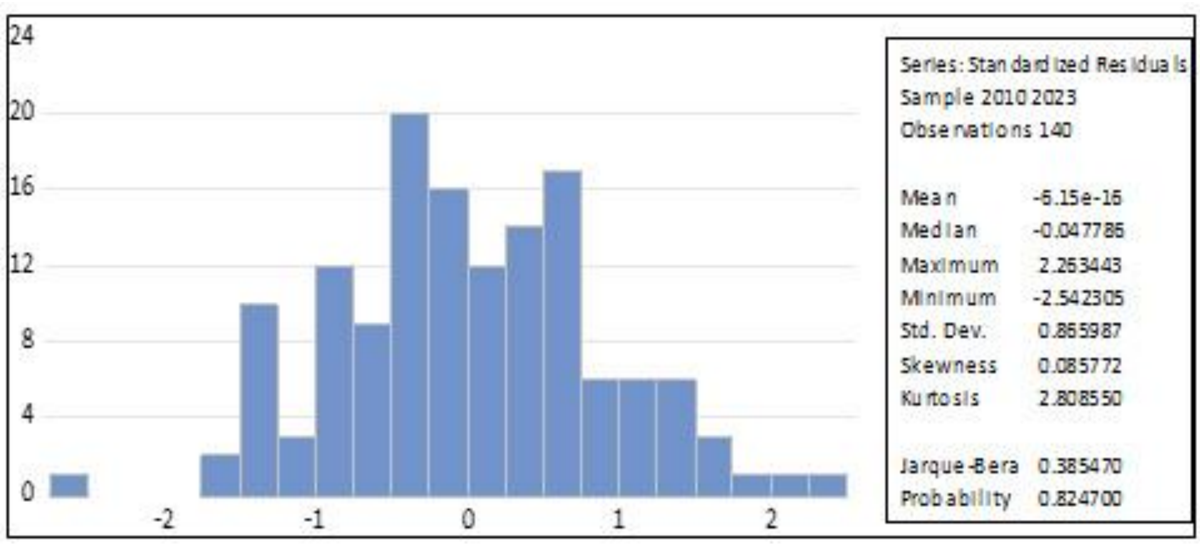

Figure 7. Histogram Normality Test

Source: Authors' calculation based on output E-Views 13 (2025)

CUSUM and cusum of Squares Test

Then, the CUSUM test is conducted to assess the stability of the long-run relationship in the ARDL model estimation. It continuously calculates the regression coefficient and residual within a specified boundary level. Normally, boundary-level identification involves constructing graphs representing various recursive statistics as a function of sequential transition variables. This is a common method applied in practice to determine the level of a significant boundary. Figure 8 shows the Cumulative SUM of Recursive Residue (CUSUM) from the ARDL stability test results. All desired lines are in critical threshold, and none cross it along the curve. Figure 8 provides evidence of the stability of the ARDL model estimation results.

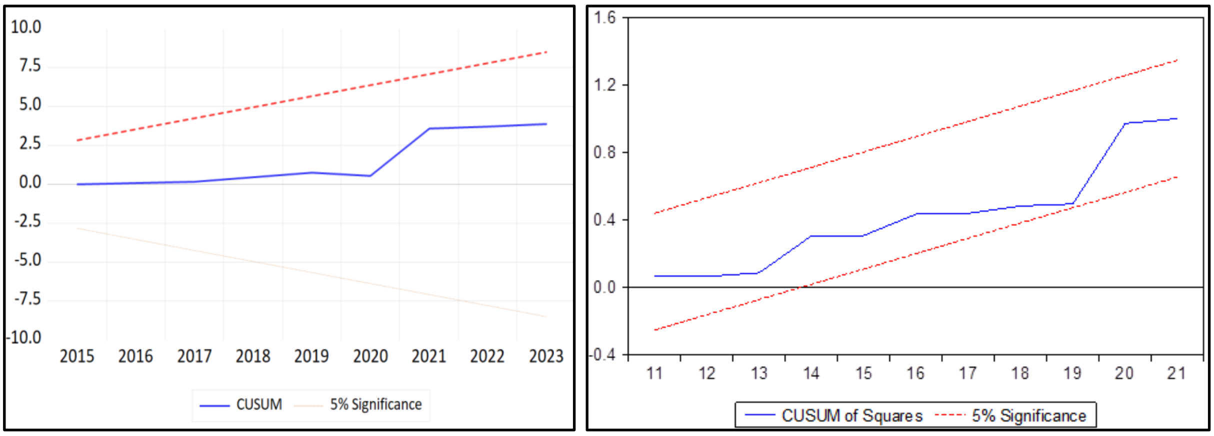

Figure 7. CUSUM and CUSUM of Squares Test

Source: Authors' calculation based on output E-Views 13 (2025)

Discussion

Empirical Results of Renewable Energy

The results of the ARDL model testing estimates for the short and long-term periods in Table 7 show the presence of an error correction term (ECT) indicating the adjustment of the short-run model to the long-run relationship, with a negative value of -0.020305. This means that a 2.03 percent adjustment is expected due to shocks from other variables in the previous period, which will gradually be corrected as time progresses, reflecting the influence of other variables in the study.

In the short-term period, the energy transition towards renewable energy usage value (lnRENEW) in the Sumatra Island trade agglomeration area shows a positive but insignificant impact. The coefficient of 0.002177 indicates that a 1 percent increase in economic growth can raise the performance of renewable energy usage value by 0.002177 percent. This is evident in the development of the Sei Mangkei Special Economic Zone in North Sumatra, which includes various requirements for achieving green economic sovereignty. The concept of developing this special economic zone will help avoid pollutant production, which could have negative environmental impacts. This is also supported by the findings of studies by (Ali et al., 2022); (Taher, 2020); (Degbedji et al., 2024).

Local governments, which have policy authority over the trade agglomeration areas, can implement policies that promote green economic sovereignty, such as providing regional fiscal incentives through tax relief to stimulate growth, while still considering environmental conditions. In trade agglomeration areas, special economic zones, and industrial zones, the imposition of carbon taxes on investors can be applied. This is supported by the views in the studies by (Appiah et al., 2022);(Karedla et al., 2021);(Sun et al., 2023). Supervision, monitoring, and evaluation of companies investing in the trade agglomeration areas of Sumatra Island can be carried out as a commitment from all parties to the environment by granting green and blue PROPER awards. This is also supported by research by Khan et al. (2021).

In the long term, the results of the study indicate a positive and significant impact of the transition to renewable energy usage on economic development (lnGRDP), with a coefficient of 0.069259. This means that a 1 percent increase in economic growth will lead to a 0.069259 percent increase in the consumption of renewable energy. The utilization of primary energy tends to have a negative and significant relationship with a coefficient of -0.645877, meaning that a 1 percent increase in economic growth in the long term will reduce the consumption of fossil-based primary energy by 0.645877 percent. This suggests that the trade agglomeration area in Sumatra Island is beginning to consider reducing the consumption of fossil-based primary energy and transitioning to environmentally adaptive renewable energy. However, this transition requires a long time, significant investment, as well as technology and knowledge transfer. This is supported by the research of Jóźwik et al. (2022) and Ozkan et al. (2023).

Empirical Results of Primary Energy

The utilization of primary energy, in this case, fossil-based energy, has a positive and significant effect, with a coefficient of 0.451643. This means that a 1 percent increase in economic growth will result in a 0.451643 percent increase in primary energy consumption. This illustrates that the use of primary energy still dominates in the trade agglomeration areas of Sumatra Island compared to the transition period to renewable energy, as the energy transition requires time, significant investment, and technology shifts. This is also supported by the research of Nguyen et al. (2022). The presence of significant natural resources in the trade agglomeration areas of Sumatra Island, such as minerals and coal scattered across regions like Riau, North Sumatra, Lampung, Jambi, and South Sumatra, supports regional economic activities. However, this can be mitigated by developing an environmentally adaptive industrial downstream. This aligns with the research by Taghizadeh-Hesary et al., (2021) and Jacques et al., (2023).

Empirical Results of CO2 Emissions

The use of fossil-based energy in transportation activities supports the trade agglomeration areas of Sumatra Island by utilizing carbon dioxide release technology from petroleum refining processes. This can reduce CO2 emissions compared to the release of CO2 from incomplete combustion processes in transportation. The shift from fossil-based energy to electric energy has also been introduced in public transportation in South Sumatra with the operation of the Light Rail Transit (LRT), a transportation technology powered primarily by electricity. This transition is being implemented gradually, considering that the shift from fossil-based energy to renewable energy requires time and the transfer of environmentally friendly technology, which requires significant investment. This aligns with the findings of Afshan et al. (2024), Chen et al. (2020) and Gao & Chen (2023). Efforts to reduce the use of fossil-based energy in industrial activities include utilizing hydropower plants that use river flows in the trade agglomeration areas of Sumatra Island to drive turbines and generate electricity. This ensures that economic growth activities in the trade agglomeration areas of Sumatra Island continue to grow, in line with Ashfaq et al. (2024).

CO2 consumption in the short term has a positive and significant relationship with economic development in the trade agglomeration areas of Sumatra Island, with a coefficient of 0.011085. This means that a 1 percent increase in economic growth will result in a 0.011085 percent increase in CO2 emissions. This indicates that in this area, with rapid economic growth, there is still a dependence on energy consumption that generates high CO2 emissions, as the region is rich in mineral and coal resources. This needs to be a concern for the government to ensure that the use of CO2-emitting energy is also efficient in supporting economic growth, as supported by the research of Zhang et al. (2023). Long-term CO2 consumption, on the other hand, shows a negative relationship and does not significantly impact economic development, with a coefficient of -3.032861, indicating that a 1 percent increase in economic growth will reduce CO2 consumption by 3.032 percent.

Empirical Results of Trade Openness

Trade openness in the region has a positive and significant impact on economic development in the trade agglomeration areas of Sumatra Island, with a coefficient of 0.170402. This indicates that a 1 percent increase in economic growth will result in a 0.170402 percent increase in regional trade value. This is supported by adequate regulations issued by the Ministry of Home Affairs, Regulation No. 22 of 2020, on Procedures for Regional Cooperation with Other Regions and Regional Cooperation with Third Parties. This system of trade openness provides opportunities for the region to engage in environmentally friendly technology transfer. China has evaluated trade openness and recommended that the government expand trade to reduce negative impacts and provide financial opportunities to promote renewable resources (Gao & Chen, 2023). This research is supported by Sun et al. (2019) and Taher (2020), who argue that renewable energy has a significant impact on green economic growth, as green economic growth is directly dependent on environmental regulatory policies, which in turn affect renewable energy consumption (Ashraf, 2023).

Trade openness in the Sumatra Island agglomeration areas provides opportunities for investors to invest; however, this must remain within the framework of regulations and policies set by the authorities, particularly in reducing environmental damage. Trade in this area is facilitated through several ports, including Belawan Port in North Sumatra, Dumai Port in Riau, Meulaboh Port in Nangroe Aceh Darussalam, Panjang Port in Lampung, Boom Baru Port in South Sumatra, and the Batam Authority area in the Riau Islands, which has direct trade authority with Singapore. Direct trade has a positive impact on economic growth in this area, but these results are not in line with the results of the study (Sheikh et al., 2020).

Meanwhile, the impact of trade openness in the long term has a positive and significant effect on economic development in the trade agglomeration areas of Sumatra Island, with a coefficient of 3.628636. This means that a 1 percent increase in economic growth will result in a 3.628636 percent increase in regional trade performance. International trade and the influx of economic globalization are closely linked, and due to this interconnection, they can help mitigate the negative effects of carbon emissions (Ali et al., 2022). During this transition period, the development of energy infrastructure connectivity networks and renewable energy technology continues to progress in line with the modernization of the 4.0 industrialization era. Meanwhile, the use of fossil energy is still dominant, as fossil energy reserves in the trade agglomeration areas of Sumatra Island are relatively large.

In the era of trade openness, export and import activities, along with investments that bring in goods and services, also influence the consumption of renewable energy (Sotamenou & Nehgwelah, 2024; Sun et al., 2023). Previous studies have emphasized that the negative impact of trade openness on export-import activities and investments, which leads to an increase in value-added production, has not been accompanied by internal controls and environmental risk management. This is due to the pollution generated and the failure to consider environmental degradation, which can hinder the utilization of renewable energy and lead to continuous environmental damage. Overall, this study aligns with existing literature. For example, research by Khan & Sun (2024) and Khan et al. (2021) found that international trade openness can result in a decrease in demand for primary fossil energy consumption. This is because trade openness encourages the transfer of innovation, technology literacy, and knowledge about the importance of sustainable green economies, which can reduce the demand for primary energy and promote the adoption of renewable energy.

The transition to renewable energy has not yet reached an optimal point, with various challenges that continue to be managed to replace environmentally harmful fossil energy sources (Taghizadeh-Hesary et al., 2021; Dzwigol et al., 2023). The establishment of regulatory policy controls in the environmental sector serves as a regulatory tool when granting investment permits, controlling impacts by monitoring environmental quality standards, and conducting evaluations in case of violations in the implementation of environmentally friendly investment policy principles, which are based on strategic environmental assessments that consider ecological values as well as the capacity and environmental support capacity. The adoption of renewable energy is faced with both technical challenges and opportunities, such as the significant utilization of natural gas in Nangroe Aceh Darussalam, which could lead to fluctuations during the energy transition. The transition to energy through the current electricity system also presents the opportunity for two-phase fluctuations, preventing the occurrence of a dual burden.

This situation can result in a return to the use of fossil-based energy, which is easier to manage but can lead to increased CO2 emissions and have negative long-term impacts, as supported by research from Zamora-Pereira et al. (2023), Jacques et al. (2023), and Sartzetakis et al. (2023). The long-term consequences of CO2 emission reductions indicate that investing in and transitioning to renewable energy sources can be an effective solution to address climate change and reduce the global carbon impact. These findings highlight the importance of promoting sustainable policies and practices that support the use of renewable energy as a strategic step in mitigating climate change. This conclusion is supported by research from Ozkan et al. (2023), where the development of electricity infrastructure and the transfer of technology for new renewable energy sources play a crucial role and represent a sensible course of action (Jreisat, 2021); (Ashraf, 2023).

For local governments with authority in the Sumatra Island trade agglomeration area, a special regulatory policy is needed for investment or strong cooperation between the government and business entities in the field of trade openness. This policy should consider green economic development as a criterion and requirement in the audited aspects and environmental sustainability performance assessments. Multilateral cooperation with developed countries that have implemented environmentally friendly economic development will have the potential to utilize environmentally friendly energy and play an important role in reducing CO2 emissions, as these countries have advanced economies. Local governments in this area are conducting regulatory studies to increase renewable energy consumption by providing subsidies for blue and green certification, as well as reducing carbon taxes to encourage renewable energy (Sun et al., 2023). The implications of regional policies in the Sumatra Island trade agglomeration area that can be applied from this research are that regional governments must adopt more intensive planning, regulation, monitoring, and internal control policies in implementing trade openness or cooperation in this area.

CONCLUSION

Sustainable regional development, guided by green economy principles, fosters innovation and renewable energy technology literacy. It serves as a driving factor to stimulate the region's macroeconomic growth during environmentally friendly phases of study and implementation, amid global challenges of climate change in several areas. Negative impacts and environmental degradation have become strategic issues in the trade agglomeration areas of Sumatra Island, particularly in regions with growth based on mining, excavation, and wetland agriculture sectors. This study highlights the importance of renewable energy for economic sovereignty and environmental ecosystem services, as it can be used as a policy tool in the non-biological natural resources sector, which significantly relates to energy transition policies in the region.

Using the ARDL and VEC model analysis approaches, this study shows that the relationship between green economic growth variables and new renewable energy, primary energy consumption, CO_2 reduction, and trade openness significantly impacts environmentally friendly economic growth. The time series from 2010 to 2023, with panel data from 10 provincial regions in the Sumatra Island trade agglomeration areas, reveals how renewable energy utilization in this region, in the long term, is influenced by renewable energy usage implications through trade openness mechanisms or regional, bilateral, and multilateral cooperation with developed countries. This study contributes significantly to climate change risk mitigation efforts by controlling environmental performance against the impact of rising global temperatures, reducing the harmful CO_2 emissions that threaten environmental health.

Government cooperation with business entities in the field of green economic development through trade openness, both internationally and regionally with developed countries, can encourage the utilization of renewable and environmentally friendly energy sources, reduce the consumption of fossil-based primary energy, reduce CO_2 emissions, and pave the way for the divestment of pollutant sources for the environmental ecosystem. The future and energy transition in regional development in the Sumatra Island trade agglomeration areas, through the sustainability of environmental ecosystem services within the regional trade cooperation scheme, can promote inclusive and environmentally friendly economic development. The regulatory policy framework in the areas of trade, regional cooperation, and investment is directed at utilizing environmental ecosystem services efficiently, considering the limited non-biological resources and enhancing the added value of renewable energy utilization in the Sumatra Island trade agglomeration areas.

Trade openness or regional cooperation that considers renewable energy utilization, reduction in fossil fuel primary energy consumption, and CO_2 emission reductions can provide insights for potential investors looking to invest in the Sumatra Island trade agglomeration areas, serving as an alternative financing option for green economic development to mitigate ecological pressure. The findings indicate that trade openness in the Sumatra Island trade agglomeration areas contributes positively and significantly, both in the short and long term. This suggests that trade openness in this area could become an alternative driver for sustainable, environmentally friendly green economic development, enhancing the efficient and productive use of resources according to the environmental carrying capacity and support capacity of the region.

This study demonstrates that the Sumatra Island trade agglomeration areas, with abundant mineral and coal resources, are gradually shifting towards renewable energy utilization. The research also explains that investment or cooperation between the government and business entities in the renewable energy service sector is still in its early stages, and the transition from conventional energy use—specifically fossil-based fuels—to renewable energy will take time, significant investment, technological shifts, and knowledge literacy. These factors positively influence the sustainable use of environmental ecosystem services. Wise economic development in utilizing environmentally friendly energy will increase productivity, create ecosystem stability, improve public health, and enhance community welfare.

Environmental ecosystem degradation, currently occurring due to massive natural resource exploration without control, and the extraction of resources without considering ecological carrying and support capacity, can lead to flooding, landslides, and increased global temperatures. These empirical issues highlight the importance of considering renewable energy utilization in this region and how the transition to renewable energy consumption plays a role in green economic development.

A limitation of this study is that the technology transfer variable was not included in the control variables. Therefore, we recommend that future research consider the use of technology transfer in subsequent studies. The gap and inequality between energy needs, renewable energy availability, and the use of technology transfer present new challenges for future research.

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