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The Economic Growth with Low Carbon Emissions: Evidence from Indonesian 10 Provinces

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ABSTRACT

This study investigates potential measures to reduce CO2 emissions in Indonesia, focusing on ten provinces in Sumatra. The high dependency on fossil fuels has led to significant environmental issues, particularly CO2 emissions. The research examines potential ways to mitigate these emissions and evaluates whether they are influenced by economic activities across regions. Using panel data from 2017 to 2023, this quantitative descriptive study includes ten provinces in Sumatra and six in Java, employing spatial regression analysis. The variables analyzed are CO2 emissions, industrial agglomeration, GRDP of the manufacturing sector, GRDP of mining and quarrying, GRDP of agriculture, fisheries, and plantations, as well as GRDP of wholesale and retail trade, including vehicle repair. The findings reveal a positive Moran's I value for CO2 emissions, indicating a clustered pattern among the ten provinces in Sumatra over the study period. Industrial agglomeration, manufacturing GRDP, mining and quarrying GRDP, and GRDP in agriculture, fisheries, and plantations are positively and spatially correlated with CO2 emissions. Conversely, GRDP from wholesale and retail trade has a significant negative impact on emissions. Policy recommendations include reducing carbon emissions, promoting sustainable sectoral development, adopting green technologies, and conducting regular evaluations to ensure environmental and economic sustainability.

Keywords: Spatial Regression; Lissa; Economy; Renewable Energy; CO2 Emissions

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1. Introduction

Comprehending the progression of energy policies and low-emission plans in Indonesia necessitates an analysis of significant changes over the last 20 to 30 years. This period signified major transformations, including the change to an oil-importing nation in 2004 and the implementation of Law No. 30/2007, which emphasized renewable energy. These modifications emphasize the necessity to diminish dependence on fossil fuels and tackle greenhouse gas emissions. A historical analysis demonstrates how policy modifications and institutional frameworks influence the contemporary energy landscape, providing insights crucial for sustainable development [1]. Indonesian energy infrastructure relies on fossil fuels, with 96% of its energy mix coming from coal, oil and natural gas, while less than 4% comes from renewable energy sources [2]. Below is a representation of renewable and non-renewable energy consumption in Indonesia. **Figure 1** depicts the trajectory of the Employment to Total Population Ratio (ETT) and the Labor Force Participation Rate (KET) from 1990 to 2020. The ETT has consistently risen, signifying an expanding percentage of the workforce employed. Conversely, the KET has undergone variations, exhibiting a minor decrease in recent years. This indicates a possible decline in the labor force participation rate, potentially attributable to factors such as demographic shifts, educational levels, and economic circumstances. Additional investigation is required to comprehend the fundamental reasons of these changes and their ramifications for the labor market and overall economic growth.

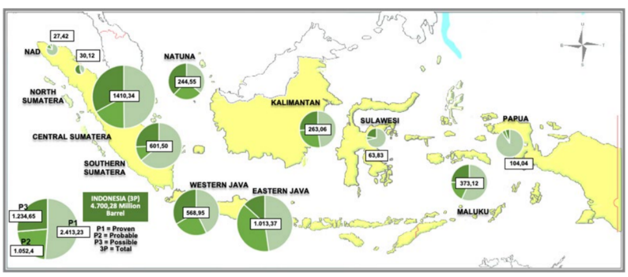

Figure 1. Conditions for the use of renewable energy and non-renewable energy in Indonesia.

Source: World Bank Indonesia Energy Data, 2023.

This reliance on fossil fuels has several implications: economic and urbanization demands, regional imbalance, energy security, environmental impact, and supply uncertainty. The rapid economic growth and urbanization in Indonesia have increased energy demand, and fossil fuels are currently seen as the quickest and cheapest solution to meet these needs [3]. Currently, the uneven distribution of energy resources creates inequality in energy access in each region and creates inequality in development [4]. The domestic production of energy is insufficient to meet the national demand, necessitating increased imports and creating a dependency on foreign energy sources [5]. Issues such as fuel shortages, distribution problems, and economic factors have led to periodic energy supply disruptions, impacting key sectors like industry, transportation, and public services. These factors highlight the need for Indonesia to diversify its energy sources and invest in renewable energy infrastructure to ensure sustainable and balanced energy management in the future [6]. Kyriakopoulos, et al. [7] also mentioned that climate mitigation and adaptation efforts are prioritized based on environmental, socio-economic, and agro-biological analyses.

Research from Kyriakopoulos and Sebos [8] stated how the interplay between economic growth and reduced carbon emissions is intricate yet crucial for sustainable development [8] followed up on the idea of how both of their essays converge on the notion that combating climate change necessitates coordinated efforts across all sectors, especially agriculture. They underscored the significance of policy frameworks such as "Coordinated Climate Action" in enabling this shift, accentuating sustainability, financial assistance, and strategic planning to attain low carbon emissions while promoting economic growth. This collaboration is essential for developing robust agricultural systems that can endure climate effects while enhancing overall economic stability. The findings from these studies function as a stimulus for additional investigation into cohesive strategies for climate change in agriculture. By focusing on these areas, future study can substantially aid in formulating effective methods that enhance sustainability and alleviate the effects of climate change on agricultural systems [9]. This upcoming study further provides an overview of the state of energy in Indonesia, focusing on the dominance of fossil energy in the country's energy infrastructure and the challenges faced in the development of renewable energy.

The essay emphasizes that coordinated mitigation and adaptation activities, coupled with stakeholder involvement, can facilitate economic growth in accordance with low carbon targets. This comprehensive strategy not only tackles climate change but also strengthens resilience in socio-economic systems, facilitating a sustainable future. The heavy reliance on fossil fuels in Indonesia has several negative environmental consequences, including higher carbon emissions and other pollutants, which affect public health and contribute to climate change. Due to the high and increasing level of non-renewable energy use every year, the increase in non-renewable energy in Indonesia can't be simply reduced. The support to enhance the increase in non-renewable energy in Indonesia can be improved by focusing on the infrastructure and facilities for energy access. The need for funding for the natural resource infrastructure is progressing [10]. Overview of the use of GDP per capita for energy facilities in Sumatra is presented in **Table 1**.

Table 1 illustrates a diverse allocation of GDP funds for energy infrastructure among Sumatra's provinces from 2018 to 2020. There is a considerable focus on natural resource infrastructure, indicating a prioritization of resource extraction or energy generation initiatives. This trend, along with variable funding annually, indicates a dynamic strategy for infrastructure development. While certain provinces, such as Aceh, witnessed a reduction in financing, others, like Riau Islands, demonstrated steady development. The diverse allocations may affect regional economic development, resource management, and infrastructural connectivity, hence influencing the entire economic landscape of Sumatra.

Additionally, supply uncertainty is a significant issue, with factors such as fuel shortages, distribution problems, and economic factors leading to periodic energy supply disruptions. These disruptions impact key sectors like industry, transportation, and public services, negatively affecting economic growth and societal well-being [11].

The domestic production of energy in Indonesia is insufficient to meet the national demand, necessitating increased imports. This insufficiency is due to the rapid economic growth and urbanization, which have significantly increased energy demand [12]. Therefore, the Indonesian government must take advantage of the great potential of renewable energy. The estimated production and ratio of new and renewable energy (EBT) can be seen in **Figure 2** below. **Figure 2** depicts the anticipated expansion of renewable energy sources in Indonesia from 2013 to 2050. It underscores the growing role of diverse renewable energy sources in the overall energy composition, particularly emphasizing geothermal and solar power. The anticipated increase in renewable energy usage is predicted to coincide with a decrease in dependence on fossil fuels. This transition to renewable energy sources corresponds with international initiatives to alleviate climate change and foster sustainable development. Nevertheless, obstacles such as initial capital expenditures and grid integration must be resolved to facilitate a seamless transition to a low-carbon energy future.

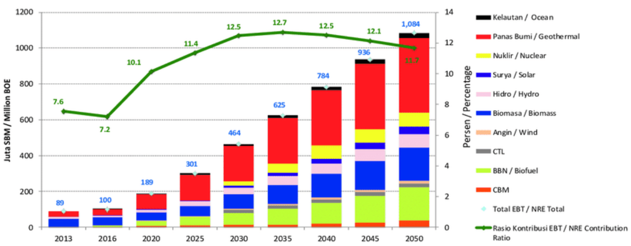

Figure 2. The estimated production and ratio of new and renewable energy (EBT).

Source: Researchgate.net.

The energy problem in Indonesia is complex and demands a comprehensive solution. One of the main problems is the high dependence on fossil energy, such as coal, petroleum, and natural gas. This dependence not only impacts the environment and public health, but also leaves the energy sector vulnerable to fluctuations in global energy prices. In addition, infrastructure for renewable energy sources such as solar, wind, and geothermal power also needs to be further developed to optimize its potential. Apart from that, there are still obstacles in the use of energy that is not yet optimal [13].

Dependence on fossil energy causes environmental problems, namely CO2 emissions. Studies are needed to identify opportunities that can be utilized in efforts to reduce carbon dioxide emissions. In addition, it is also

Table 1. Conditions for the use of GDP for energy infrastructure in Sumatra (in million Rupiah).

Province in Sumatra	Funding for Infrastructure					
	Natural Resource Infrastructure			Street		
Year	2018	2019	2020	2018	2019	2020
Aceh	0	602,370	599,200	1,184,210	411,369	525,000
North Sumatra	1,157,680	484,056	118,450	511,405	2,165,790	0
West Sumatra	520,704	699,750	57,500	965,000	1,182,000	1,199,000
Riau	83,000	1,396,660	6,250	342,515	480,500	314,600
Jambi	0	435,483	1,200	8,000	500,000	340,000
Bengkulu	81,234	443,272	84,397	453,341	100,000	0
South Sumatra	450,195	23,000	227,475	477,344	218,000	168,000
Lampung	200,000	1,124,052	31,000	598,903	275,923	199,223
Bangka Belitung Island	7,500	141,600	246,000	1,019,927	1,010,958	3,468,855
Riau Islands	841,306	344,030	295,298	69,676	46,423	522,241

Source: Public Affair Ministry Data, 2021.

important to investigate the possibility that the detected carbon dioxide emissions are impacts originating from other areas. Thus, this research is an important step in maintaining Indonesia's energy security and facing the global challenge of climate change. Therefore, this research focuses on researching the potential components of emission reduction in Indonesia.

2. Literatur Review

Research [14] using quantile panel regression tools resulted in FDI having a positive but insignificant effect on carbon dioxide emissions, energy consumption having a significant positive effect, but economic growth having a significant negative effect on carbon dioxide emissions. Then research [15] using an innovative causal analysis (IAA) accounting approach stated that energy consumption, financial development, and economic growth were the main contributors to CO2 emissions. Research [16] obtained results that the causality of the panel was unidirectional in the short and long term between variables, where the four variables showed the importance of the balance adjustment process. Research from [7] stated that findings underscore the need for a comprehensive approach to climate action planning that incorporates both adaptation and mitigation measures.

In terms of carbon, the spatial model, which is a combination of MGWPR and HR, has the advantages of both [17]. In contrast, the spatial variable coefficient autoregression (SAR) and variable error coefficient (SEM) models are some of the panel models of spatial variable coefficients that can be adapted to various types of studies. In contrast, these models simultaneously consider spatial correlation and heterogeneity. This shows an improvement over traditional regression models and spatial econometrics, in line with the topic of this study. Section 5 finds that the MGR-HR model is used by the benchmark model and the mediation effect model.

The level of energy consumption increases in direct proportion to the GDP growth rate and other economic indicators. Conversely, the great degree of energy use, tends to affect both the deterioration of environmental quality and air quality. These results suggest that, by limiting and optimizing the level of non-renewable energy usage, energy laws should be based on social fairness and environmental sustainability [18].

3. Research Methodology

The nature of this research is quantitative descriptive, conducted by collecting, analyzing, and interpreting secondary data in panel form from 2017–2023. Data were obtained from 10 provinces in Sumatra Island and 6 provinces in Java Island through the official website https://www.bps.go.id/id. The model options used are the *Spatial Error Model* (SEM) or *Spatial Autoregressive Moving Average (SARMA)* [19].

3.1. Spatial Error Model (SEM)

The first model where spatial dependency appears through errors, not systematic components. SEM assumes that errors at one location are correlated with errors at other locations, where the locations are adjacent. The spatial error regression model is generally explained as follows [20].

$$y_i = \beta_i X_i + \lambda W_{ij} u_i + \varepsilon \quad (1)$$

Where:

yi: response variable at location *i*

βi: parameter of regression coefficient

Xi: predictor variable at location *i*

Wij: element of the spatial weighting matrix W on row i column to *j*

ε: Error at location *i*

uj: Error in location *j*

λ: parameter koefisien spatial error

If the SEM Model is selected, then the specifications used in this study are as follows:

$$yi = \rho Wijyi + \beta 1AGGit + \beta 2PDRBI_{it} + \beta 3\ PDRBPP_{it} + \beta 4\ PDRBP_{it} + \beta 5\ PDRSP_{it} + \lambda Wijui + \varepsilon i \quad (2)$$

Where:

yi: CO2 Emissions

ρ: Parameter cophysin spatial lag

Wij: Element of spatial weighting matrix W on row i column *to j*

$\beta_{0.2..5}$: Regression coefficient parameter

AGG: Agglomeration of Manufacturing/Processing Industry

PDRBI: GRDP for the Manufacturing/Processing Industry Sector

PDBRPP: GRDP for the Mining and Call Sector

PDBRP: GRDP for Agriculture, Fisheries and Plantation Sector

GRDP: GDP of Large Trade and Retail Sector; Car and Motorcycle Reperation.

ε: *error term*

The hypotheses used in the spatial error regression significant test are as follows:

H0: λ = 0 (Insignificant parameter)

Ha: λ ≠ 0 (Significant parameter)

Decision making with the following criteria:

1. H0 is rejected which means Ha is accepted, if $Z_{counts} > Z_{table}$ or *p-value* < α = 5 percent, that the regression coefficient is significant so that it is feasible to use in the model.
2. H0 is accepted which means Ha is rejected, if $Z_{counts} < Z_{table}$ or *p-value* > α = 5 percent, that the regression coefficient is not significant, so it is not suitable for use in the model.

3.2. Spatial Autoregressive Moving Average (SARMA)

The general model of spatial regression or also commonly called *Spatial Autoregressive Moving Average (SARMA)* [20] as follows:

$$y = \rho Wy + X\beta + u \quad (3)$$

$$u = \lambda Wu + \varepsilon \quad (4)$$

Where:

y: vector variable dependent by sizes

X : matrix of independent variables

β: vector regression parameter coefficient with size *(K+0)* x 0

ρ: parameter of the spatial coefficient of lag of the dependent variable

λ: parameter of the spatial coefficient of lag on *error*

in, ε: vector *error*

W: weighting matrix

If the SARMA Model is selected, then the specifications used in this study are as follows:

$$yi = \rho Wijyi + \beta 1AGGit + \beta 2PDRBI_{it} + \beta 3\ PDRBPP_{it} + \beta 4\ PDRBP_{it} + \beta 5\ PDRSP_{it} + u = \lambda Wu + \varepsilon i \quad (5)$$

where:

yi: CO2 emission

ρ: Parameter cophysin spatial lag

Wij: Element of spatial weighting matrix W on row i column *to j*

$\beta_{0.2..5}$: Regression coefficient parameter

AGG:: Agglomeration of Manufacturing/Processing Industry

PDRBI: : GRDP for the Manufacturing/Processing Industry Sector

PDBRPP:: GRDP for the Mining and Call Sector

PDBRP: GRDP for Agriculture, Fisheries and Plantation Sector

GRDP: GDP of Large Trade and Retail Sector; Car and Motorcycle Repair ρ: Parameter of the spatial coefficient of lag of the dependent variable

λ: Parameter of the spatial coefficient of lag in *error*

u, ε: Vector *error*

W: Weighting matrix

4. Results

The research discusses Indonesia's energy infrastructure, which is heavily reliant on fossil fuels, with the largest energy consumption coming from electricity. The country faces challenges such as oil shortages and an addiction to fossil fuels. The purpose of this study is to determine the consequences of economic growth, fossil fuel consumption, renewable energy, technological innovation, agricultural productivity, and forest area on CO2 emissions in Indonesia. It also aims to provide policy recommendations to limit emissions and promote environmental sustainability. The research will be presented at an international seminar and published in a Scopus-indexed journal, with the hope of offering new insights and policy recommendations for energy and environmental policymakers in Indonesia. Some of the results are listed below.

4.1. Spatial Analysis of Moran's I CO2 Emission Result

The benefit of the local Moran's I Index is to determine the heterogeneity of local spatial elements, which explains the relationship between attribute values of a region and surrounding regions (**Table 2** mostly discusses The Moran I value from 2017 to 2023. The results of Moran's I for the variable CO2 emissions in the entire research period from 2017–2023 can be seen in **Table 2.** The Moran's I statistic, a spatial autocorrelation metric, is shown in Table 2 for CO2 emissions in 10 Sumatra Island provinces between 2017 and 2023. Spatial clustering, in which comparable emission levels are typically grouped spatially together, is indicated by positive Moran's I values. The table indicates spatial autocorrelation, with the majority of years displaying positive Moran's I values. This suggests that underlying spatial dynamics rather than chance determine Sumatra's CO2 emission distribution. These geographical patterns' relevance is further supported by the Z-score values, which show that the observed grouping is unlikely to be the result of chance. Visualizing the data on a map and investigating possible causes of the spatial autocorrelation, such as topography, economic activity, or policy interventions, would be helpful in order to better comprehend these spatial patterns.

The Moran I value from 2017 to 2023 shows a positive autocorrelation with the clustering pattern in CO2 emissions. The Z test is conducted to assess the existence of significant spatial relationships; if Z exceeds $Z\alpha/2$ or is less than $-Z\alpha/2$, it means that there is a significant relationship in the region at the α level. The critical value of α is 5%, namely $Z0.95 = 1.654$. Overall, the value of $Z(I) > Z0.95 > 1.654$ means that there is a statistically significant spatial relationship in CO2 emissions. Figure 3 which describes Moran's scatter diagram in the percentage of poor population data for 2017–2023 shows a distribution pattern into four categories: areas with high, low-high, low-low, and high-low values. Spatial pattern analysis was conducted to detect local clustering of CO2 emissions in ten provinces on Sumatra Island by observing the distribution patterns of thematic maps processed using the *Geoda Moran scatter plot*:

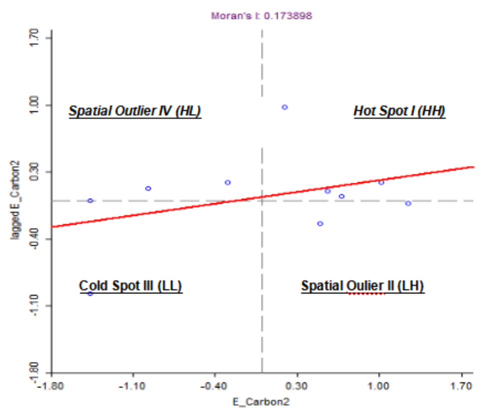

Figure 3. Moran scatter diagram.

Source: processed, Open Geoda, 2024.

Table 3 shows the Moran's Scatterplot visualizes the spatial autocorrelation of CO_2 emissions among 10 provinces on Sumatra Island, demonstrating the geographical relationship of each province's CO_2 levels with those of adjacent provinces. The scatterplot is segmented into four quadrants, each representing a unique spatial pattern.

Table 2. Moran's I CO2 emissions in 10 provinces on Sumatra Island in 2017–2023.

Year	Moran's I	E(*I*)	Z(I)	Z0.95
2017	0.5811	−0.1111	1.8211	1.654
2018	0.3451	−0.1111	1.6327	1.654
2019	0.2908	−0.1111	1.7718	1.654
2020	0.1384	−0.1111	1.7865	1.654
2021	0.1376	−0.1111	1.8900	1.654
2022	0.3883	−0.1111	1.6775	1.654
2023	0.4123	−0.1111	1.6623	1.654

Source: processed, Open Geoda, 2020.

Table 3. *Moran's Scatterplot* depicting patterns of CO2 in 10 provinces in Sumatra Island.

Moran's I Quadrant Percentage of CO2 Emission			
I , HH (High-High)	**II, LH (Low-High)**	**III, LL (Low-Low)**	**IV, HL (High-Low)**
West Sumatra North Sumatra Lampung South Sumatra	Aceh Bengkulu	Riau Islands	Bangka Belitung Islands Jambi Riau

1. Quadrant I (High-High): West Sumatra, North Sumatra, Lampung, and South Sumatra are provinces in this quadrant. The four provinces are known as areas with high CO2 emissions and are surrounded by zones with high observation values or called the Hot Spot quadrant.
2. Quadrant II (Low-High): Aceh and Bengkulu fall into this quadrant, where both have low levels of carbon dioxide (CO2) emissions, but are surrounded by areas with high observed values. Both provinces fall into the Spatial Outlier quadrant, which describes areas with low CO2 emissions surrounded by areas with high CO2 emissions.
3. Quadrant III (Low-Low) includes the Riau Islands, which has low CO2 emissions and is surrounded by low-observation areas. In this quadrant there is one Cold Spot area, which is an area with low emissions surrounded by neighbors with similar emission values.
4. Quadrant IV (High-Low) includes Bangka Belitung, Jambi, and Riau, characterized by high CO2 emissions surrounded by areas with low observation values. This quadrant shows three areas that are classified as Spatial Overseas, where high-emission areas are surrounded by neighboring areas with low emissions.

Figure 4 is the description of the *Moran's Scatterplot* in the year of study on the variable CO2 in 2017–2023. It has the same pattern and throughout the year of study, as well as it has a pattern that clusters and signifies that each region has the same characteristics. The LISA Cluster map can be seen as follows:

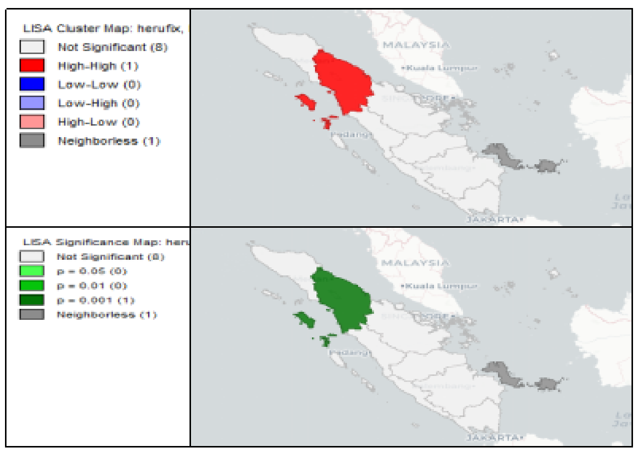

Figure 4. LISA Cluster map of CO2 emissions in 10 provinces in Pualau, Sumatra.

Source: Open Geoda, 2024.

LISA Cluster map depicts a grouping of CO2 emissions with an indication of a significant *High-high* area covering 1 region, namely North Sumatra. The *LISA significance map* at 0.001 significance has 1 North Sumatra region. Unequal percentages of CO2 emissions across provinces can affect the clustering or distribution of relationships between regions, which plays a role in how these regions influence each other. In North Sumatra, carbon dioxide (CO2) emissions show a clustering pattern and affect the surrounding areas. This phenomenon illustrates the existence of a spatial effect, where there is a two-way interaction: North Sumatra suffers from the consequences of carbon dioxide emissions from neighboring areas, while also influencing the level of emissions in the surrounding areas. This reflects the existence of a reciprocal relationship in the context of the spatial effects of carbon dioxide emissions between North Sumatra and the surrounding areas.

4.2. Selection of the Best Lagrange Multiplier (LM) Modeling in Spatial Analysis

***Lagrange Multiplier* (LM)**

Spatial models are selected using the Lagrange Multiplier (LM) for initial identification, which detects spatial effects via lag, error, or both. Spatial linkage tests were conducted using queen contiguity weighting. **Table 4** shows the results of the LM test. It is summarized in the table are as follows:

Table 4. Lagrange Multiplier (LM) Results.

Spatial Dependency Test	Value	P-Value
Moran's I (error)	3.9911	0.02165
Lagrange Multiplier (lag)	3.7542	0.00526
Lagrange Multiplier (error)	2.5854	0.10785
Lagrange Multiplier (SARMA)	5.9271	0.05163

Source: Geoda estimation results spatial regression data processed, 2024.

The LM test revealed spatial dependence in the model, with a value of 3.7542 and LM Robust P-value of 0.00526 < α = 0.05. This result indicates the need for a *Spatial Autoregressive Model* (SAR) or *Spatial Lag Model* (SLM). Then further testing was carried out comparing the classical regression and spatial regression models; the following are the results of the model comparison:

Table 5 presents a comparison that offers insights into the model's suitability, precision, and dependability in representing spatial phenomena. **Table 5** indicates the AIC value for the SAR model is –47.9824, with a Log Likelihood value of 30.9912 and an R^2 of 0.982725. These figures indicate that the SAR spatial model is superior to other spatial models.

Table 5. Comparison of classical regression models and spatial regression models.

Coefficient	OLS	SAR	SEM
R^2	0.974145	0.982725	0.991040
AIC	–45.9569	–47.9824	–53.3188
Log Likelihood	28.9784	30.9912	32.659421

Source: Geoda estimation results spatial regression data processed, 2024.

The use of the SAR modal to analyze spatial binding. **Table 6** is employed to examine geographical data in which the dependent variable is affected not only by its own predictors but also by the values of the dependent variable in adjacent or proximate places. The following are the estimation results of the Autoregressive Spatial Model.

The estimated calculation yields an R^2 of 0.9827, indicating that the model explains 98% of the variance in the dependent variable, with the remaining 2% influenced by external factors. The SAR Spatial Modeling shows a significant spatial lag coefficient (ρ), highlighting inter-regional dependency. The ρ value obtained is 0.0480, and the probability significance value is 0.0249 < α = 0.05, which means that the 10 provinces on Sumatra Island have the same characteristics, namely 0.0480. Below is a mathematical model of the Spatial Lag model:

$$\widehat{y_i} = -0.6159 \sum_{i=1, i\neq j}^{n} 0.0480 w_{ij} y_i + 0.8683_{AGG_i} + 0.2077_{PDRBI_i} + 0.5944_{PDRBPP_i} + 0.9414_{PDRBPPP_i} - 0.8983_{PDRBSP_i} \quad (6)$$

1. Industrial Agglomeration: The coefficient of large and medium industrial agglomeration, which is 0.8683, shows a positive and significant effect on carbon dioxide emissions. Every 1 percent increase in this variable will result in an increase in carbon dioxide emissions of 0.8683 Ton CO2e. In the context of provinces in Sumatra Island, if the value of large and medium industrial agglomeration increases by 1 percent, assuming the spatial weighting matrix (w) and residual (ɾ) remain constant, there will be an increase in carbon dioxide emissions of 0.8683 Ton CO2e.
2. GDP of the Manufacturing Industry: The Manufacturing Industry GDP coefficient is 0.2077. The interpretation of this figure is that every one million rupiah increase in Manufacturing Industry

Table 6. Results of Spatial Autoregressive Model (SAR) regression estimation.

Variable	Coefficient	Std. Error	Z-Value	P-Value
ρ	0.0480	0.02144	2.2417	0.0249
C	−0.6159	0.08618	−7.1462	0.0000
AGG	0.8683	0.09331	9.3051	0.0000
PDRBI	0.2077	0.06415	3.2384	0.0012
GRDPP	0.5944	0.08530	6.9689	0.0000
GRDPPPP	0.9414	0.1147	8.2020	0.0000
GRDP	−0.8983	0.1212	−7.4089	0.0000
R^2 = 0.982725				
Log likelihood: = 30.9912				
Akaike Info Criterion = −47.9824				
Significance α = 0.05%				

Source: Geoda estimation results Spatial regression data processed, 2024.

GDP will result in an increase in carbon dioxide emissions of 0.2077 Tons of CO2e. This indicates a direct relationship between the growth of the manufacturing sector and the increase in carbon footprint. In the context of provinces in Sumatra Island, if the Manufacturing Industry GDP in a province increases by 1 million rupiah, assuming the spatial weighting matrix (w) and residual (ṙ) remain constant, there will be an increase in carbon dioxide emissions of 0.2077 Ton CO2e.

3. Mining and Quarrying GDP: The coefficient of GRDP Mining and Quarrying is 0.5944 and has a positive and significant effect on carbon dioxide emissions. Every 1 million rupiah increase in this variable will result in an increase in carbon dioxide emissions of 0.5944 Ton CO2e. In the context of provinces in Sumatra Island, if the GRDP of Mining and Quarrying in a province increases by 1 million rupiah, assuming the spatial weighting matrix (w) and residual (ṙ) remain constant, then there will be an increase in carbon dioxide emissions of 0.5944 Ton CO2e.
4. GDP of Agriculture, Fisheries, and Plantations: The GDP coefficient of Agriculture, Fisheries and Plantations has a value of 0.9414 and shows a positive and significant effect on carbon dioxide emissions. An increase of 1 million rupiah in this variable will cause an increase in carbon dioxide emissions of 0.9414 Ton CO2e. In the context of provinces in Sumatra Island, if the GDP of Agriculture, Fisheries and Plantations in a province increases by 1 million rupiah, assuming the spatial weighting matrix (w) and residual (ṙ) remain constant, there will be an increase in carbon dioxide emissions of 0.9414 Ton CO2e.
5. GDP of Large Trade and Retail: The GDP coefficient for Wholesale and Retail Trade of −0.8983 shows a negative and significant effect. If there is an increase in the variable by 1 million rupiah, CO2 emissions will decrease by −0.8983 Ton CO2e. This applies if the value of Wholesale and Retail GDP in a province on Sumatra Island increases by 1 million rupiah, assuming the spatial weighting matrix (w) and residual (ṙ) remain constant, then CO2 emissions will decrease by −0.8983 Ton CO2e.

5. Discussion

Spatial autocorrelation with Moran's index makes it possible to trace the spatial relationship [21] between carbon emissions in Sumatra and neighboring regions. Thus, identifying how carbon emission patterns in Sumatra can affect the surrounding environment geographically, including more distant areas, both in terms of air pollution, climate change, and other impacts. The results show that there is a positive spatial autocorrelation of the variable Moran's I that has been calculated, this shows that the spatial dependence of carbon emission activities can have an impact on spillovers of effects on neighboring areas on the island of Sumatra. Moran's distribution of carbon emissions is mostly concentrated in quadrants and mostly cities of productive regions, and the number of low-carbon emission areas is increasing and continues to be agglomerated.

North and South Sumatra serve as the main axes in economic activity that contribute to carbon emissions in the Sumatra region. Both have significant roles in industry, transportation, and natural resources, which are the main drivers of carbon emissions on the island. Thus, the increase in carbon emissions in North and South Sumatra has a major impact not only on the local environment but also widely affects other surrounding regions as well as on a wider scale globally; this is also due to various sectoral economic activities [22]. A significant increase in TFP promotes high-quality economic growth.

Regional heterogeneity is crucial in achieving carbon-neutral growth, as it significantly impacts high-quality economic development. Policymakers should consider geographical relationships to avoid negative spillover effects and tailor policies that promote economic development while addressing regional differences [23].

Carbon emissions show spatial correlation. The environment directly and positively impacts carbon emissions. Environmental regulations indirectly affect carbon emissions by influencing economic spillover structures. **Figure 5** elucidates the importance of comparing interpolation methods in the analysis of CO_2 emissions across 10 provinces on Sumatra Island, since this is essential for enhancing the spatial representation and accuracy of emission data. This comparison is especially pertinent for policymakers, academics, and stakeholders in economics and energy to facilitate effective decision-making and policy development. The following is an analysis of the distribution and interpolation of carbon distribution in 10 provinces on the island of Sumatra:

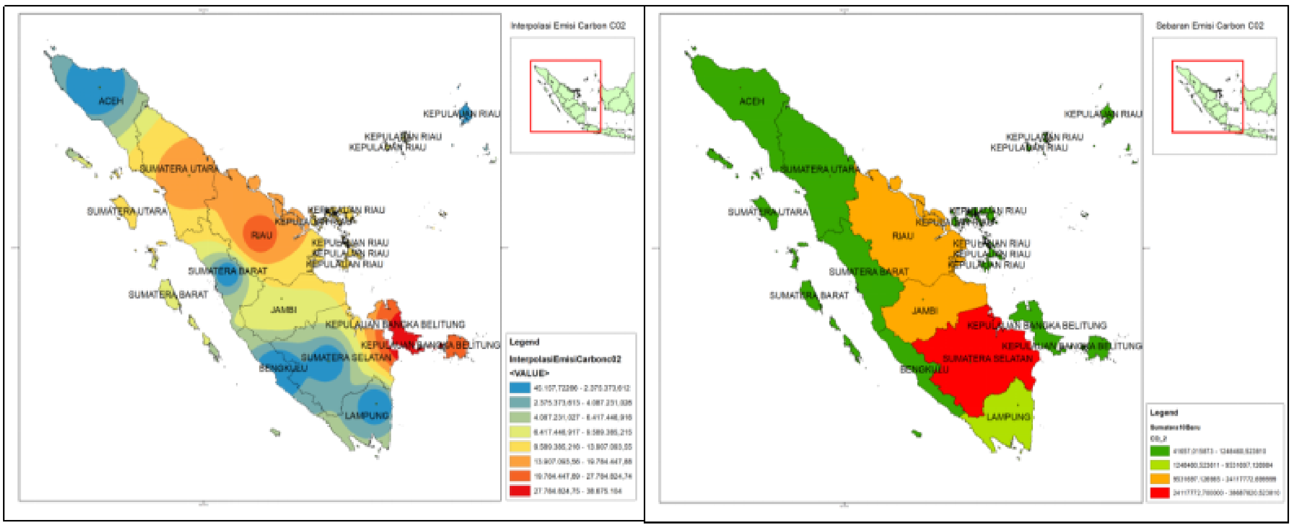

Figure 5. Comparison of interpolation and CO2 emissions in 10 provinces in Pulau, Sumatra.

Source: Open ArcGIS, 2024.

The figure above shows that South Sumatra, Riau, Jambi and Bangka Belitung have the highest carbon emissions and North Sumatra has a significant distribution pattern by spatial autocorrelation per metric ton, while Bengkulu, West Sumatra, Aceh, Lampung, and Riau Islands have low carbon emissions per metric ton. The highest carbon emissions (South Sumatra, Riau, Jambi and Bangka Belitung) suggest that the region may have large industrial activity, dense transportation, and may also rely on fossil energy resources. This can be due to the presence of large industrial sectors, such as mining or manufacturing, or high population mobility. On the other hand, low-carbon emission areas of Bengkulu, West Sumatra, Aceh, Lampung and Riau Islands may have smaller economic structures and fewer resources used, resulting in relatively low carbon emissions. It is important to note that carbon emissions are not limited to the region in which they are generated. This means that even though one region may have low carbon emissions, the impact of high carbon emissions in other regions can still be felt. It emphasizes the importance of cooperation between regions in reducing carbon emissions and tackling climate change globally.

In the overall spatial regression analysis, the analysis shows that economic growth and activity on the island of Sumatra have a significant influence on carbon emissions. Factors such as industrial agglomeration, GDP growth of manufacturing, mining, agriculture, fishing, plantations, and wholesale and retail trade all contribute to the increase in carbon emissions. This demonstrates the importance of sustainable economic management and carbon emission mitigation policies to limit negative consequences for the environment and human health [24]. CO2, dust, and NOx emissions are the main factors influencing economic growth and urbanization. This is a key issue in studying spatial relationships in the future, where the economic activity of a region greatly influences its impact on the surrounding environment.

The increase in industrial agglomeration sectoral in 10 provinces on the island of Sumatra has a spatially significant impact on the spread and formation of CO2 emissions [25]. Industry-specific agglomerations in special areas have a positive impact on carbon emissions; there is regional heterogeneity in the impact of industrial agglomeration on carbon emissions. There must be a role for the government of each regional administration and interregional communication in formulating governance policies for different environments regionally to drive future reductions in carbon emissions [26]. The clustering or concentration of manufacturing industries in a particular area has a significant impact on the level of carbon emissions in that area. Moreover, the effects of this industrial concentration are not only limited to the local location but also spread and affect the level of carbon emissions in the surrounding areas. This phenomenon shows that the environmental impact of the agglomeration of manufacturing industries has a wider reach than its original location. Agglomeration of diversified manufacturing industries exerts an influence on local carbon emissions. Industrial agglomeration impacts the economy of the region in groups, leading to a full concentration of carbon problems.

The GRDP of the Manufacturing Industry, the GRDP of Mining and Quarrying, and the GRDP of Agriculture, Fisheries, and Plantations spatially and significantly affect the distribution of carbon emissions between regions on the island of Sumatra. The balance of carbon emissions based on regions that depend on natural resources in the national emission volume has increased slightly, and emissions from cities are expected to peak [27]. A fairly consistent spatial pattern characterizes carbon emissions in resource-dependent cities, indicating significant spatial autocorrelation. Natural resources serve to increase carbon emissions in these cities if the level of economic development and the proportion of industry depend on them, with variations in the strength of these factors spatially. Huang, N. et al. [28] stated the changes in the agricultural sector, industrial development, and population migration to cities have had significant impacts. Modernization in agriculture, especially the excessive use of chemical fertilizers, has resulted in a decline in soil quality and environmental pollution, which ultimately disrupts the carbon balance at the regional level. The effects of increasing carbon emissions are very visible in several areas of the Comprehensive Economic Zone, especially in its center. This is due to the dominance of the manufacturing industry and other economic sectors in the region that produce high levels of carbon emissions [29].

6. Conclusions

CO2 emissions among 10 provinces on Sumatra exhibit a positive Moran's I, indicating a spatial relationship characterized by positive autocorrelation. This suggests that CO2 emissions in these provinces show a clustered pattern from 2017 to 2023. The analysis concludes that the transition to low-emission energy sources benefits environmental sustainability and promotes long-term economic prosperity. The results indicate a significant relationship between the adoption of renewable energy and a decrease in carbon emissions, aiding sustainable economic development. For a thorough comprehension of these effects, additional validation through cross-referencing with contemporary studies on low-emission development is advisable. Incorporating findings from empirical studies on analogous economic environments and technical influences would improve the precision of these conclusions and enrich the examination of renewable technology's contribution to energy transition strategies and economic results. Referencing recent case studies and meta-analyses in peer-reviewed literature would offer a more comprehensive and nuanced perspective, reflecting the latest developments and socioeconomic impacts. This improved methodology would augment the reliability of the findings and raise the paper's significance as a dependable resource for stakeholders in energy economics and sustainable development.

7. Suggestions

Provincial administrations, especially on Sumatra, must implement proactive carbon emission reduction strategies that comply with national and international climate obligations. These measures must encompass the establishment of quantifiable and time-sensitive emission reduction objectives, the shift to renewable energy sources, the enhancement of energy efficiency, and the incorporation of low-carbon policies into regional development plans. To foster sustainable economic growth, policy must incentivize ecologically sustainable sectors, like renewable energy, organic agriculture, and green industries, with investments in supporting infrastructure to augment their contribution to regional GDP. As well as proactive strategies, the government may evaluate and monitor the implemented policies periodically. An efficient monitoring system also needs to be developed to track the development of carbon emissions and the impact of policies taken.

Author Contributions

Conceptualization, H.W., U.C., and A.D.P.; methodology, H.W. and I.W.S.; software, A.D.P.; validation, H.W., U.C., T.A., and A.D.P.; formal analysis, H.W. and T.A.; investigation, H.W. and I.W.S.; resources, H.W.; data curation, A.D.P. and U.C.; writing—original draft preparation, H.W. and U.C.; writing—review and editing, U.C. and I.W.S.; visualization, A.D.P. and T.A.; supervision, H.W. and I.W.S.; project administration, H.W.; funding acquisition. All authors have read and agreed to the published version of the manuscript.

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Not applicable.

Data Availability Statement

Data supporting reported results can be accessed by sending an email request to our first author, Heru Wahyudi, at heru.wahyudifeb.unila.ac.id.

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Conflicts of Interest

The authors declare no conflict of interest.

References

[1] Madsuha, A.F., Setiawan, E.A., Wibowo, N., et al., 2021. Mapping 30 years of sustainability of solar energy research in developing countries: Indonesia case. Sustain. 13(20). DOI: https://doi.org/10.3390/su132011415

[2] Wahyudi, H., Suripto, Palupi, W.A., 2023. Long-term implications of economic complexity and energy intensity on the environment in lower-middle-income countries in Asia. Int. J. Energy Econ. Policy. 13(1), 164–171. DOI: https://doi.org/10.32479/ijeep.13737

[3] Dat, N.D., Hoang, N., Huyen, M.T., et al., 2020. Energy consumption and economic growth in Indonesia. Int. J. Energy Econ. Policy. 10(5), 601–607. DOI: https://doi.org/10.32479/ijeep.10243

[4] Hanh, H.T., Huy, D.T.N., Dat, P.M., 2020. Utilization of energy sources, financial stability and prosperity in the economy of Indonesia. Int. J. Energy Econ. Policy. 10(5), 631–637. DOI: https://doi.org/10.32479/ijeep.10242

[5] Fallin, D., Lee, K., Poling, G.B., 2023. Clean energy and decarbonization in Southeast Asia: Overview, obstacles, and opportunities. Center for Strategic and International Studies. 1–15. Available from: https://csis-website-prod.s3.amazonaws.com/s3fs-public/2023-05/230501_Fallin_SEA_Decarbonization.pdf?VersionId=mZRX4SCptRpseo_OB5sds9ocp0uiS1VG

[6] Indonesia Petroleum Association, Wood Mackenzie, 2023. Achieving resilience in the energy transition to safeguard Indonesia's economic growth & sustainable development.

[7] Kyriakopoulos, G.L., Sebos, I., 2023. Enhancing climate neutrality and resilience through coordinated climate action: Review of the synergies between mitigation and adaptation actions. Climate. 11(5). DOI: https://doi.org/10.3390/cli11050105

[8] Kyriakopoulos, G.L., Sebos, I., Triantafyllou, E., et al., 2023. Benefits and synergies in addressing climate change via the implementation of the common agricultural policy in Greece. Appl. Sci. 13(4). DOI: https://doi.org/10.3390/app13042216

[9] Kyriakopoulos, G.L., 2022. Energy communities overview: Managerial policies, economic aspects, technologies, and models. J. Risk Financ. Manag. 15(11). DOI: https://doi.org/10.3390/jrfm15110521

[10] Wahyudi, H., 2024. The relationship between the renewable energy and CO2 emissions to the Indonesian economy. Int. J. Energy Econ. Policy. 14(3), 349–357. DOI: https://doi.org/10.32479/ijeep.15903

[11] Raihan, A., Pavel, M.I., Muhtasim, D.A., et al., 2023. The role of renewable energy use, technological innovation, and forest cover toward green development: Evidence from Indonesia. Innov. Green Dev. 2(1), 100035. DOI: https://doi.org/10.1016/j.igd.2023.100035

[12] Mardiana, D.A., Kartoatmodjo, R.T., Kasmungin, S., 2018. Estimation of Indonesia's energy demand to 2030 and alternatives scenario to reduce oil dependence. Indones. J. Energy. 1(2), 113–126. DOI: https://doi.org/10.33116/ije.v1i2.24

[13] Paundra, F., Nurdin, A., 2022. Study of the potential and development of renewable energy power in Indonesia: A review. Steam Eng. 3(2), 62–72. DOI: https://doi.org/10.37304/jptm.v3i2.4024

[14] Zhu, J., Bailly, A., Zwiewka, M., et al., 2016. TWISTED DWARF1 mediates the action of auxin transport inhibitors on actin cytoskeleton dynamics. Plant Cell. 28(4), 930–948.

[15] Shahbaz, M., Tiwari, A.K., Nasir, M., 2013. The effects of financial development, economic growth, coal consumption and trade openness on CO2 emissions in South Africa. Energy Policy. 61, 1452–1459. DOI: https://doi.org/10.1016/j.enpol.2013.07.006

[16] Kasman, A., Duman, Y.S., 2015. CO2 emissions, economic growth, energy consumption, trade and urbanization in new EU member and candidate countries: A panel data analysis. Econ. Model. 44, 97–103. DOI: https://doi.org/10.1016/j.econmod.2014.10.022

[17] Mazur, D.M., Polyakova, O.V., Artaev, V.B., et al., 2017. Novel pollutants in the Moscow atmosphere in winter period: Gas chromatography-high resolution time-of-flight mass spectrometry study. Environ. Pollut. 222, 242–250. DOI: https://doi.org/10.1016/j.envpol.2016.12.049

[18] Handayani, I.G.A.K.R., As'Adi, E., Hamzah, G., et al., 2017. Relationship between energy consumption in international market and Indonesia prices regulation. Int. J. Energy Econ. Policy. 7(5), 9–15.

[19] Chen, Y., Zhu, M., Zhou, Q., et al., 2021. Research on spatiotemporal differentiation and influence mechanism of urban resilience in China based on MGWR model. Int. J. Environ. Res. Public Health. 18(3), 1–27. DOI: https://doi.org/10.3390/ijerph18031056

[20] Anselin, L., 1995. Local indicators of spatial association—LISA. Geogr. Anal. 27(2), 93–115. DOI: https://doi.org/10.1111/j.1538-4632.1995.tb00338.x

[21] Feng, R., Liu, S., Wang, F., et al., 2024. Quantifying the environmental synergistic effect of cooling-air purification-carbon sequestration from urban forest in China. J. Clean. Prod. 448, 141514. DOI: https://doi.org/10.1016/j.jclepro.2024.141514

[22] Cui, Y., Zhong, C., Cao, J., et al., 2024. Spatial effect of carbon neutrality target on high-quality economic development—Channel analysis based on total factor productivity. PLoS One. 19(1), 1–27. DOI: https://doi.org/10.1371/journal.pone.0295426

[23] Yang, Y., Tang, D., Zhang, P., 2020. Double effects of environmental regulation on carbon emissions in China: Empirical research based on spatial econometric model. Discret. Dyn. Nat. Soc. 2020. DOI: https://doi.org/10.1155/2020/1284946.

[24] Li, L., Chi, T., Wang, S., 2016. Is energy utilization among Chinese provinces sustainable? Technol. Forecast. Soc. Change. 112, 198–206. DOI: https://doi.org/10.1016/j.techfore.2016.07.003

[25] Xu, X., Song, Y., 2023. Is there a conflict between automation and environment? Implications of artificial intelligence for carbon emissions in China. Sustain. 15(16). DOI: https://doi.org/10.3390/su151612437

[26] Lan, K., Kelley, S.S., Nepal, P., et al., 2019. Dynamic life cycle carbon and energy analysis for cross-laminated timber in the Southeastern United States. Environ. Res. Lett. 15(12). DOI: https://doi.org/10.1088/1748-9326/abc5e6

[27] Wei, H., Zheng, C., 2024. Spatial network structure and influencing factors of carbon emission intensity in Guangdong-Hong Kong-Macao Greater Bay Area. Front. Environ. Sci. 12, 1–21. DOI: https://doi.org/10.3389/fenvs.2024.1380831

[28] Huang, N., Liu, C., Liu, Y., et al., 2024. Spatial effects of economic modernization on carbon balance in China. Land. 13(5), 1–19. DOI: https://doi.org/10.3390/land13050595

[29] Wang, X., Zhang, R., Jiang, T., 2024. Energy justice and decarbonization: A critical assessment for just energy transition in China. Environ. Impact Assess. Rev. 105, 107420. DOI: https://doi.org/10.1016/j.eiar.2024.107420