IJEEP
INTERNATIONAL JOURNAL OF ENERGY ECONOMICS AND POLICY
EJ EconJournals
ISSN: 2146-4553

International Journal of Energy Economics and Policy

ISSN: 2146-4553

available at http: www.econjournals.com

International Journal of Energy Economics and Policy, 2026, 16(2), 547-557.

EconJournals

Evaluation of Green Efficiency of the Industrial Sector and Its Influencing Factors in West Sumatra

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Received: 12 October 2025 **Accepted:** 21 January 2026 **DOI:** https://doi.org/10.32479/ijeep.22678

ABSTRACT

One effort to achieve sustainable economic development is to conduct a green efficiency evaluation analysis. This study aims to evaluate green performance in the two-digit industrial sector in West Sumatra, as well as the factors that influence it. The purpose of this study is to evaluate green efficiency for 11 industries in West Sumatra and to analyze the impact of the energy structure, indirect taxes and COVID-19 on green efficiency in the industrial sector of West Sumatra. The methods used are SBM DEA and logistic panel regression. This policy simulation study will align with government policy to ensure that all research results comply with it. The results of the study indicate that in 2021 the efficient sectors were the food sector; the printing and reproduction of recorded media; chemicals and chemical materials; rubber and rubber materials; non-machinery metal goods and equipment; and the furniture sector. Meanwhile, the inefficient sectors were the beverage sector, the textile sector, apparel, paper and paper materials, and non-metallic minerals. When viewed from the influencing factors, indirect taxes had a significant positive impact on green efficiency in West Sumatra. Meanwhile, the energy structure and COVID-19 were not significant.

Keywords: Green Efficiency, Carbon Emissions, Industry, Tax, West Sumatera
JEL Classifications: E60, Q43, Q50

1. INTRODUCTION

Economic growth is one indicator of prosperity (Mankiw, 2021). However, increasing economic growth leads to increased pollution from waste generated from economic activities (Perman, 2011). From November 30 to December 11, 2015, the 21st meeting of the United Nations Framework Convention on Climate Change in Paris, France, revealed an agreement to reduce carbon emissions (UNFCCC, 2016). The Paris Agreement further defined the global concept of climate governance as low-carbon green development. The path to low-carbon green development is one option for future human development and a core concept of global climate governance (Shuai and Fan, 2020). Therefore, green economic development has become a strategic goal for countries worldwide to ensure sustainable development.

One effort to achieve sustainable economic development is green efficiency analysis (Song and Wang, 2014). Green efficiency is generally defined as the ratio of the economic value of goods and services that meet human needs to the environmental burden (Schmidheiny, 1992; Henriques and Catarino, 2017). However, Kortelainen (2008) defines green efficiency as the ratio of added value to environmentally harmful inputs. In addition, green efficiency is generally defined as the ratio of the minimum feasible environmental damage at the observed input level (Reinhard et al., 2000). Green efficiency evaluation is proposed by experts with several quantitative models to solve complex environmental problems (Jebaraj and Iniyan, 2006; Zhou et al., 2006). Green/environmental efficiency evaluation can provide quantitative information to public policy designers and makers for performance evaluation, policy analysis, and public communication (Wang and Nguyen, 2021).

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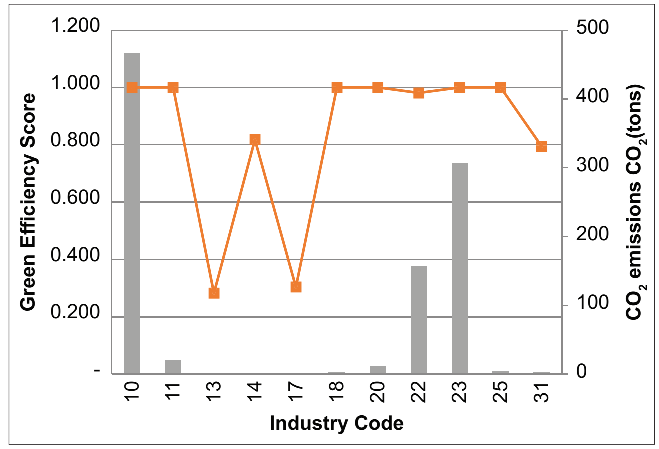
Several methods for evaluating environmental efficiency have been proposed in recent decades. The Environmental Performance Index (EPI) plays an important role in evaluating environmental efficiency, which is simpler and more comprehensive, depending on the actual conditions of efficiency evaluation (Díaz-Balteiro and Romero, 2004; Färe and Grosskopf, 2004; Zhang et al., 2008). Another method of evaluating environmental efficiency is Life Cycle Analysis (LCA), which analyzes the environmental impacts of raw material use and energy consumption during a given production life cycle (Miettinen and Hämäläinen, 1997; Finnveden and Ekvall, 1998; Ayalon et al., 2000; Färe and Grosskopf, 2004). Another evaluation method is Stochastic Frontier Analysis (SFA), a parametric approach that considers environmental degradation as an independent variable or input with a desired output (Aigner et al., 1977; Reinhard et al., 2000).

Recently, Data Envelopment Analysis (DEA) has gained popularity in green/environmental efficiency analysis. DEA, according to Charnes et al. (1978), is an effective nonparametric approach for evaluating relative efficiency with multiple inputs and multiple outputs. Ramanathan (2005) used a DEA model to analyze energy consumption and CO_2 emissions in 17 North African and Middle Eastern countries. Zhou et al. (2006) applied DEA to estimate CO_2 emissions from 30 Organization for Economic Co-operation and Development (OECD) countries. They analyzed the environmental efficiency of regional industrial systems using a DEA model, considering various undesirable outputs. Zhou et al. (2008) discuss the performance of various environmental DEA technologies under the assumption of variable returns to scale (VRS) and non-increasing returns to scale (NIRS). Bian and Yang (2010) adopted the Shannon-DEA procedure to analyze the resource and environmental efficiency of 30 provinces in China. Song and Wang (2014) analyzed the environmental efficiency of various regions in China using the ratio-DEA decomposition algorithm and concluded that environmental regulations and technological progress affect environmental efficiency differently. Wang and Nguyen (2021) analyzed green efficiency in the Chinese manufacturing sector using SBM-DEA. Jamil (2023) analyzed green evaluation and its impact in East Java, and Kumar and Madheswaran (2010) the cement industry in India.

However, many previous studies focused on calculating environmental efficiency scores without analyzing the influencing factors. This makes it difficult to find ways to improve environmental efficiency. Wang's research on 29 manufacturing companies revealed that greater openness in a country will increase its green efficiency (Bian and Yang, 2010; Wang and Nguyen, 2021). Industry scale (Bian and Yang, 2010; Henriques and Catarino, 2017; Wang and Nguyen, 2021) revealed that the larger the industrial scale, the higher the level of green efficiency. Another variable suspected of influencing green efficiency is energy structure. The higher the energy structure, as seen from coal, the lower the level of efficiency of an industry (Wang and Nguyen, 2021; Jamil, 2023).

The manufacturing industry plays a crucial role in the economy. This is evident in the manufacturing industry's largest contribution to Indonesia's Gross Domestic Product (GDP). Figure 1 shows the contribution of business sectors to GDP, where, at 19.24% in 2021,

Figure 1: Green efficiency scores for 11 industries in West Sumatra from 2017



Source: Data processed by the Author (2024)

the manufacturing industry sector had the largest contribution to total GDP, followed by agriculture, forestry, and fisheries at 13.28%, and wholesale and retail trade and car and motorcycle repair at 12.96%. However, despite its positive impact on the economy, industrial activity can certainly cause environmental problems.

West Sumatra is one of the provinces in Indonesia whose proportion of added value of the manufacturing industry sector to GDP is 9.03% (BPS West Sumatra, 2023). When viewed from the distribution of GRDP (Gross Regional Domestic Product), agriculture, forestry, and fisheries business fields continue to dominate the economic structure of West Sumatra with a share of GRDP of 21.69%, followed by wholesale and retail trade business fields and car and motorcycle repair with a contribution of 15.84%, transportation and warehousing of 10.29%, and construction of 10.18%. Next is the manufacturing industry sector with a contribution to the GRDP of West Sumatra Province of 8.79%. It can be seen that the manufacturing industry business field is among the top five contributing to the GRDP of West Sumatra. However, in producing manufacturing industry output based on data from BPS West Sumatra, it shows that there are a number of fuels used in production. In 2022, the three largest fuels were coal (148,226,056 tons), diesel (17,744,976 L), and biodiesel (2,929,416 L). Therefore, the use of these fuels will inevitably have an indirect impact, resulting in undesirable outputs, such as carbon emissions (pollution).

Based on this background, it is known that the industrial sector contributes a fifth to West Sumatra's economic growth. However, this sector also negatively impacts the environment through its emissions. Therefore, to maintain the industrial sector's productivity trend while reducing its negative impacts on the environment, environmental efficiency, or green efficiency, is necessary. The green efficiency evaluation analysis was conducted using a new method, Data Envelopment Analysis (DEA), with an extension to the SBM (Source Energy Standards) due to indications of undesirable outputs in addition to the desired output of increased GRDP (economic growth). Previous research has little discussion of the undesirable output of carbon emissions. Furthermore, this study will identify factors influencing green efficiency, which has made it difficult to find ways to improve environmental efficiency. This study will examine the impact of green efficiency on 11 industries in West Sumatra. How does the energy structure impact green efficiency in the industrial sector of West Sumatra? How does indirect tax impact green efficiency in the industrial sector of West Sumatra? How does COVID-19 impact green efficiency in the industrial sector of West Sumatra?

2. LITERATURE REVIEW

2.1. Green Efficiency

One way to balance economic, environmental, and social growth is by evaluating land use. Generally, the definitions of eco-efficiency, green efficiency, and environmental efficiency are similar, meaning achieving optimal benefits from the economic and ecological sectors with fewer resources (Sorvari et al., 2009). Therefore, the term "green efficiency" will be used in this study. Green efficiency is an important analytical tool for calculating the relationship between human development activities and environmental impacts (Wang et al., 2011; Xiang et al., 2021). Green efficiency refers to reducing ecological impacts and resource intensity across all industrial activities, or at least maintaining consistency within the Earth's carrying capacity to provide goods and services at competitive prices (Zhang et al., 2018). Industrial land use should maximize the combined benefits felt by the economic sector, society, and the ecological system (Wey and Hsu, 2014). Therefore, it is very important to evaluate land use efficiency to achieve sustainable economic development (Chen et al., 2021; Hsu et al., 2022).

2.2.1. Green efficiency evaluation analysis

Zhou et al. (2006) analyzed the DEA of SBM in 30 OECD countries from 1998 to 2002. The inputs used were total primary energy supply and population, the desired output was GDP (billion 1995 US$ in purchasing power parities), and the undesired output was CO_2 emissions (million tons). The results showed that no country achieved an efficiency of 1, except Luxembourg. Many countries remain inefficient due to the inputs used, even considering environmental regulations. However, when considering economic and environmental performance, some countries have values approaching 1.

Zhou et al. (2008) examined 26 OECD countries from 1995 to 1997, with inputs of labor and primary energy consumption, desired output of GDP, and undesired output of CO_2, SO_2, NO_2, and NO_2. The results showed that the traditional DEA method yielded different results when incorporating CO_2 emissions. Including carbon emissions as an undesirable output indicates that countries are becoming increasingly inefficient, meaning that green efficiency is not achieved, and increasing economic growth is accompanied by increasing carbon emissions. Similarly, Bian analyzed green efficiency using DEA in 30 provinces in China. The results show differences between provinces in the resulting green efficiency levels.

Wang et al. (2017) analyzed green efficiency in 29 manufacturing sectors in China, using inputs of capital, labor, energy consumption, and technology; output as manufacturing sector GDP; and undesirable output as the amount of greenhouse gas emissions produced. The results show that industries classified as heavily polluting primarily consist of pollution-intensive industries and traditional heavy chemical industries such as the Ferrous Metals Industry and Processing; the Non-Ferrous Metals Industry and Processing and Paper Products; and the Chemical Raw Materials and Chemical Products Industry. The efficiency scores of highly polluting industries are quite low, and there is little difference between the scores with and without considering undesirable outputs. Furthermore, the environmental efficiency scores are slightly higher than those without considering environmental factors, as environmental factors lower the efficiency scores as undesirable outputs. These results indicate that heavily polluting industries are inherently inefficient. The input and output efficiency of highly polluting industries needs to be improved because coordination between the economy and the environment remains poor and environmental risks remain high.

Li (2010) used SBE DEA in 95 countries from 1996 to 2007, using inputs of gross fixed capital, labor force, and energy use, with GDP as the input, and CO_2 emissions as the unused output. They found international differences in environmental efficiency and technological gaps across different groups of countries.

2.2. Green Efficiency Determinants

Li (2010) analyzed the effect of GDP per capita, GDP share value in the industrial sector, coal energy consumption, Foreign Direct Investment (FDI) ratio, and openness index (export to import ratio) on green efficiency. The results showed that GDP per capita, GDP share value in the industrial sector, and Foreign Direct Investment (FDI) ratio significantly positively increased green efficiency, and the openness index (export-to-import ratio) and coal energy consumption significantly negatively decreased green efficiency opportunities. Wang and Nguyen (2021) analyzed the effect of the economic openness index, industrial scale, energy structure, technology, and profitability index on green efficiency in China's manufacturing sector using a tobit model. The results showed that the economic openness index, industrial scale, and energy structure significantly increased the green efficiency of the manufacturing sector. Jamil (2023) analyzed the effect of energy structure, R&D, and industrial concentration on green efficiency in the East Java manufacturing sector. The results showed that energy structure and industrial concentration did not significantly affect green efficiency, and R&D expenditure significantly negatively increased efficiency. Pan (2011) analyzed the influence of market structure, GDP per capita, coal consumption, and R&D expenditure on 28 provinces in China. The results showed that market structure, GDP per capita, and R&D expenditure had a significant positive effect on energy efficiency, but coal consumption was not significant. The results differed based on regions in China, where the central region showed a significant negative effect on R&D expenditure on energy efficiency, while the western and eastern regions showed a significant positive effect. Market structure and GDP per capita in the eastern region were significant, but the central and western regions were not significant on efficiency.

Indirect taxes, such as energy taxes, transport taxes, and Value Added Tax (VAT) policies, are seen as fiscal instruments that can influence green efficiency through pricing mechanisms and economic incentives. By increasing the relative costs of energy consumption and activities that negatively impact the environment, indirect taxes encourage producers to improve energy efficiency and adopt more environmentally friendly technologies. The environmental fiscal policy literature emphasizes that the effectiveness of indirect taxes depends not only on the tariff size but also on policy design and the repurposing of tax revenues to support green investment and sustainable technology transitions (Eurostat, 2013; Hidayah and Faresa, 2025).

Empirical evidence shows mixed results but tends to be positive in the medium and long term. A study by Bampatsou et al. (2024) found that energy and transport taxes have a significant impact on industrial eco-efficiency, although the impact is strongly influenced by how these tax revenues are allocated and combined with supporting policies. Meanwhile, research on VAT incentives shows that promotional indirect tax policies can lower the cost barriers to green technology investment and improve the environmental efficiency of the industrial sector, particularly for companies sensitive to changes in capital costs (Hidayah and Faresa, 2025). Overall, the literature concludes that indirect taxes have the potential to increase green efficiency if properly designed and integrated with complementary policies that encourage innovation and energy efficiency (Bampatsou et al., 2024).

Recent literature shows that the COVID-19 pandemic has had a significant impact on green efficiency, both at the firm level, in the financial sector, and across countries. A study by He et al. (2024) found that economic uncertainty during the pandemic led to a decline in short-term green investment, which ultimately reduced the efficiency of green resource use at the firm level. A similar impact was also seen in sustainable finance instruments, where Tsipas et al. (2024) reported that the efficiency of the green bond market and the renewable energy sector weakened during the pandemic period, reflecting increased market volatility and risk. From a macro and energy perspective, Yao et al. (2024) through a systematic review and bibliometric analysis showed that the pandemic slowed global energy efficiency progress, particularly in the transportation and building sectors, although the impact was heterogeneous across regions. Meanwhile, a DEA-based cross-country analysis by Sağlam et al. (2025) revealed that green efficiency and productivity declined during the initial phase of the pandemic, but began to recover in the post-pandemic period depending on the strength of each country's green recovery policies. In the context of developing countries, Reschiwati et al. (2025) showed that the pandemic drove changes in green accounting practices at the corporate level, which had direct implications for environmental efficiency and financial performance. Overall, the literature concludes that COVID-19 caused temporary disruptions to green efficiency, but also opened up opportunities to accelerate the green transition through targeted recovery policies.

2.3. Hypothesis

1. Energy structure has a significant negative impact on green efficiency in the industrial sector in West Sumatra.
   This study includes an energy structure variable, which is the percentage of expenditure on petroleum and diesel fuel to total expenditure on fuels incurred by industry.
2. Indirect tax expenditure has a significant positive impact on green efficiency in the industrial sector in West Sumatra.
3. COVID-19 has a significant positive impact on green efficiency in the industrial sector in West Sumatra.

3. RESEARCH METHODS

3.1. Research Design

This research uses an economic approach focused on the impact of policies on economic variables. The research method is descriptive and quantitative.

3.2. Population and Sample

The data used are secondary data, obtained from relevant agencies supporting the research. The data used are: Capital: fixed assets of industrial machinery; Material: domestic raw materials; Labor: number of workers; Energy Consumption: fuel purchase costs; Production Value: output of each industry; fuel used; production value of each industrial sector; energy structure; fuel expenditures; R&D expenditures; and industrial sector output.

3.3. Data Collection Techniques

Data collection techniques were taken from data sources from the West Sumatra Statistics Agency (BPS) and the West Sumatra Regional Development Planning Agency (Bappeda).

3.4. Research Variables and Variable Measurement

This study consists of three stages of analysis: first, due to limited data on industrial pollution, this study attempts to measure the amount of CO_2 emissions from fuel use in each subsector studied. Then, a Slack-Based Measurement-Data Envelopment Analysis (SBM-DEA) is conducted to measure the green efficiency value of each manufacturing subsector. Finally, a Tobit regression is conducted to identify variables that significantly influence the green efficiency value.

3.4.1. CO_2 emission analysis

The fuel-to-total CO_2 emission conversion coefficient is based on a publication published by the U.S. Energy Information Administration (EIA) (2024), as follows.

Fuel Type	Volume or mass to produce 1 ton of CO_2
Gasoline	8,78 gallons=33,25*10-3 liter
Diesel	10,19 gallons=38,56*10-3 liter
Natural Gas	54,87 thousand cubic feet=1,55*10-3 m3
Coal	1.827,04 short ton=1.657,12*10-3 ton

The green efficiency formula is as follows:

$$E_{hi} = \frac{1}{c_h} \times P_{hi}$$

$$E_j = \sum E_{hi}$$

Where E is the total CO_2 emissions produced, c is the CO_2 emission coefficient based on fuel type, and P is the amount of fuel used. Meanwhile, h is the fuel type indicator, i is the company indicator, and j is the manufacturing subsector indicator.

3.4.2. Slack-based measurement-data envelopment analysis (SBM-DEA)

To measure green efficiency, a non-parametric statistical method, Data Envelopment Analysis (DEA), is used. This method can demonstrate the relative ability of a Decision-Making Unit (DMU) in utilizing a combination of outputs and inputs compared to other units. This results in an efficiency score ranging from 0 to 1. The closer the DMU's efficiency score is to 1, the more efficient the DMU. Conversely, the further the DMU's efficiency score is from 1, the more efficient the DMU.

Objective function is:

$$\min \rho = \frac{1-\frac{1}{m}\sum_{i=1}^{m}\frac{S_i^-}{x_{io}}}{1-\frac{1}{s}\sum_{r=1}^{s}\frac{S_r^-}{y_{ro}}}$$

Constraint is:

$$\sum_{j=1}^{n}\lambda_j\, x_{rj}+S_i^- = x_{io}\ ;i=1,\ldots,m$$

$$\sum_{j=1}^{n}\lambda_j\, y_{rj}+S_i^+ = x_{io}\ ;r=1,\ldots,s$$

$$\lambda_j \geq 0, S_i^- \geq 0, S_r^+ \geq 0$$

Where:
ρ = efficiency score
x_{io} = amount of input used by DMU
y_{ro} = amount of output produced by DMU
S_i^- = input slack (input excess)
S_r^+ = output slack (output shortfall)
λ_j = intensity variable (weight) of peer DMUs

A DMU is considered efficient if:

ρ =1 and $S_i^- = 0, S_r^+ = 0$,

Input variable	Desired output variable	Unwanted variable output
Capital: fixed assets of industrial machinery Material: costs of domestic raw materials Labor: expenses for productive labor and other expenses Energy consumption: costs for purchasing fuel	Production Value: output of each industry	Emissions generated: the amount of emissions generated from the use of fuel obtained from the conversion of CO2 is analyzed.

3.4.3. Logistic analysis

Logistic regression analysis is used in this study to analyze the impact of variable x on variable y, which is binary, with a lower limit of 0 and an upper limit of 1. The research equation for panel data from 2017 to 2021 is

$$EH_{it} = \beta_0 + \beta_1 X1_{it} + \beta_2 X2_{it} + \beta_3 XD1_{it} + \varepsilon_i$$

Where:
EH_{it} = Green Efficiency
$X1_{it}$ = Energy structure
$X2_{it}$ = Indirect Taxes
$D1_{it}$ = Covid-19
β_0: Constant
β_1, β_2, β_3 = Coefficient
ε: error term
i = industry
t= time

4. RESULTS AND DISCUSSION

In this section, the author will explain the research findings regarding the efficiency of the industrial sector in West Sumatra. The explanation is as follows.

4.1. Carbon Emission Measurement Results

The results of carbon emission are as follows.

Table 1 shows that CO_2 emissions produced by 11 industrial sectors in West Sumatra Province are the highest at 570,625 tons of CO_2 and the lowest at 0.01 tons of CO_2. The difference in CO_2 emissions is very large, namely 142,033 tons of CO_2 with an average CO_2 production of 73,246 tons of CO_2.

Furthermore, if we look at the structure of the use of raw materials that produce CO_2 in Table 2, namely from gasoline energy in 1 manufacturing industry sector from 2017 to 2021 in total, it can be seen that the movement of CO_2 emissions produced by each sector experiences fluctuating movements. If we look at the total from 2017 to 2021, it can be seen that the sector that produces the highest CO_2 is the food sector, with a total of 420,567 tons of CO_2. Next, the rubber and plastic materials sector is 28,433 tons of CO_2, and non-metallic mining goods are 25,374 tons of CO_2; the least is the paper and paper materials industry sector, at 0.522 tons of CO2. However, if we look at the movement each year, the first sector that produces the largest CO_2 due to gasoline use is still the food sector, but the second order is the beverage sector, and the third is the printing and reproduction of recorded media. Although the rubber and rubber-based materials sector is quite large in total, CO_2 emissions have decreased significantly since 2018, amounting to 0.389 tons, and will be below 1 ton by the end of 2023. Similarly, the non-metallic mining sector has experienced a significant decrease in CO_2 emissions. This means that the rubber and rubber-based materials industry, as well as the non-metallic mining sector, can significantly reduce CO_2 in gasoline consumption.

Furthermore, Table 3 examining the structure of CO_2 producing raw material usage, specifically solar energy, across 11 industrial

Table 1: Descriptive statistics of CO_2 emissions produced by industry (gasoline, diesel, coal and natural gas) in West Sumatra Province

Variable	Obs	Mean	Standard Deviation	Min	Max
$EmisiCO_{2\_}$	55	73.24638	142.0338	0.01	570.625

Source: Data processed by the author (2024)

sectors from 2017 to 2021, the overall CO_2 emissions fluctuated. Overall, the food sector generated 1,189,132 tons of CO_2 from 2017 to 2021. The non-metallic mining sector produced 1,549,099 tons of CO_2, followed by the rubber and plastic materials sector with 242,269 tons of CO_2, and the paper and paper materials sector with the lowest CO_2 emissions, at 0.522 tons.

However, examining the annual CO_2 emissions from solar energy use in the industrial sector in West Sumatra, almost all sectors showed a year-over-year decrease, particularly during the COVID-19 pandemic in 2020-2021. An interesting development occurred in the non-metallic mineral sector, where there was an increase in activity in 2020-2021, resulting in significant CO_2 emissions, amounting to 320,805 tons of CO_2. In 2021, the non-metallic mineral sector was the largest contributor to CO_2 production, followed by food (96,375 tons of CO_2), chemicals and chemical materials (2,439 tons of CO_2), rubber and rubber-based products, and plastics (18,741 tons of CO_2). Furthermore, the industrial sector in West Sumatra produced <1 ton of CO_2 from diesel fuel in 2021, with the lowest CO_2 emissions coming from the apparel sector, at 0.076 tons of CO_2.

Furthermore, Table 4 shows the structure of the use of raw materials that produce CO_2, namely from natural gas energy in 11 industrial sectors from 2017 to 2021. It can be seen that the movement of CO_2 emissions produced by each tends to be zero, meaning that many industrial sectors no longer use natural gas as a raw material for production, such as in 2021 in all sectors except the food sector, rubber and plastic goods, and non-metallic minerals. Sectors that have never used natural gas are seen in the paper and paper goods sector, resulting in 0 emissions from year to year. The sectors that produced the most emissions in 2021 were the Rubber and Non-Metallic Minerals sector, amounting to 0.267 tons of CO_2; food, at 0.085 tons of CO_2; and Non-Metallic Minerals, at 0.031 tons of CO_2.

Table 5 shows CO_2 emissions from coal use in the industrial sector in West Sumatra. It shows that quite a number of industrial sectors no longer use coal as a raw material. From 2017 to 2021, the paper and paper goods, non-machinery and equipment metal products, and furniture industries produced no CO_2 emissions from coal. Furthermore, from 2018 to 2021, the beverage, rubber, rubber goods, and plastic products sectors produced no CO_2 emissions. From 2019 to 2021, the food and textile sectors produced no CO_2 emissions. Meanwhile, the non-metallic minerals and chemicals and chemical materials sectors continued to produce CO_2 emissions in 2021.

As can be seen from the use of raw materials such as gasoline, diesel, natural gas, and coal, the non-metallic minerals sector consistently produced CO_2 emissions for every type of raw material, even ranking second on average among other sectors after the food sector. In total, gasoline use is the largest source of carbon emissions compared to diesel, natural gas, and coal.

Table 2: Descriptive statistics of CO_2 emissions in gasoline use (Ton CO_2) in the industrial sector of West Sumatra, 2017-2021

Industrial sector code	Industrial sector	CO_2 emissions in gasoline use (Ton CO_2)					Total
		2017	2018	2019	2020	2021	
10	Food	71,243	77,720	183,129	80,291	8,183	420,567
11	Beverages	3,511	5,282	4,379	4,258	4,684	22,115
13	Textiles	0,195	0,190	0,223	0,772	0,457	1,837
14	Apparel	0,141	0,201	0,152	0,146	0,144	0,783
17	Paper and Paper Products	0,000	0,000	0,174	0,174	0,174	0,522
18	Printing and Reproduction of Recorded Media	2,037	2,591	2,542	5,343	2,520	15,034
20	Chemicals and Chemical-Based Materials	1,277	0,519	0,470	0,470	0,303	3,040
22	Rubber and Rubber and Plastic Products	23,289	0,389	2,314	1,805	0,636	28,433
23	Non-Metallic Minerals	10,192	7,451	7,251	0,420	0,420	25,734
25	Metal Products, Other Than Machinery and Equipment	0,088	0,501	0,342	0,226	0,165	1,323
31	Furniture	1,853	1,817	2,138	0,055	0,551	6,414

Source: Data processed by the author (2024)

Table 3:Descriptive statistics of CO_2 emissions in diesel use (Ton CO_2) in the industrial sector of West Sumatra 2017-2021

Industrial sector code	Industrial sector	CO_2 emissions in diesel use (Ton CO_2)					Total
		2017	2018	2019	2020	2021	
10	Food	383,884	334,482	249,125	125,266	96,375	1189,132
11	Beverages	5,214	6,735	11,895	23,134	0,161	47,139
13	Textiles	0,180	24,450	0,170	0,547	0,872	26,220
14	Apparel	0,378	0,062	0,084	0,052	0,076	0,652
17	Paper and Paper Products	0,000	0,073	0,000	0,225	0,225	0,523
18	Printing and Reproduction of Recorded Media	0,292	0,325	0,297	0,272	0,272	1,458
20	Chemicals and Chemical-Based Materials	5,057	3,055	22,649	26,027	21,439	78,227
22	Rubber and Rubber and Plastic Products	48,205	35,221	106,229	33,874	18,741	242,269
23	Non-Metallic Minerals	294,411	334,134	312,676	287,073	320,805	1549,099
25	Metal Products, Other Than Machinery and Equipment	4,376	0,213	0,432	0,264	0,086	5,370
31	Furniture	0,742	0,477	0,035	0,090	0,039	1,383

Source: Data processed by the author (2024)

4.2. Green Efficiency Measurement Results

Based on green efficiency measurements using the SBM-DEA model as described by Tone (2003), the green efficiency results for 11 industrial sectors in West Sumatra from 2017 to 2021 were obtained.

In Table 6 Showing the Green Efficiency Score in 11 Industries in West Sumatra from 2017 to 2021, it can be seen that the green efficiency score is from 0to 1, 0 is very inefficient, and 1 is efficient. The non-metallic mining sector and the land sector from 2017 to 2021 always show a value of 1, meaning that both sectors are efficient. In general, the industrial sectors of West Sumatra have shown efforts to maintain environmental stability, which is indicated by the efficiency value in 11 sectors that have approached 1. The sector that is still far from efficient is the Paper and paper goods sector, which is marked from year to year with a very small value of, even below 0.2 points. Furthermore, the Textile sector and the non-machinery and equipment metal goods sector also show inconsistent efforts in maintaining environmental health.

Table 6 shows that in 2017, the inefficient sectors were the textile sector with a score of 0.282, the apparel sector with a score of 0.818, the paper and paper products sector with a score of 0.304, and the rubber and rubber and plastic products sector with a score of 0.980. The remaining sectors were efficient, with scores equal to 1. In 2018, the textile sector, the apparel sector, and the paper and paper products sector had become efficient, while the rubber

Table 4: Descriptive statistics of CO_2 emissions in natural gas use (Ton CO_2) in the industrial sector in West Sumatra 2017-2021

Industrial sector code	Industrial sector	CO_2 emissions in natural gas use (Ton CO_2)					Total
		2017	2018	2019	2020	2021	
10	Food	11,390	8,566	137,945	0,083	0,085	31,614
11	Beverages	11,730	0,085	0,290	0,000	0,000	2,421
13	Textiles	0,324	1,494	0,000	0,000	0,000	0,363
14	Apparel	0,025	0,010	0,000	0,000	0,000	0,007
17	Paper and Paper Products	0,000	0,000	0,000	0,000	0,000	0,000
18	Printing and Reproduction of Recorded Media	0,000	0,014	0,000	0,000	0,000	0,003
20	Chemicals and Chemical-Based Materials	5,374	0,503	0,101	0,426	0,000	1,281
22	Rubber and Rubber and Plastic Products	85,189	0,000	0,048	0,162	0,267	17,133
23	Non-Metallic Minerals	1,432	0,000	0,075	0,044	0,031	0,317
25	Metal Products, Other Than Machinery and Equipment	0,000	0,000	0,051	0,000	0,000	0,010
31	Furniture	0,000	0,149	0,000	0,000	0,000	0,030

Source: Data processed by the author (2024)

Table 5: Descriptive statistics of CO_2 emissions in coal use (Ton CO_2) in the industrial sector in West Sumatra 2017-2021

Industrial sector code	Industrial sector	CO_2 emissions in coal use (Ton CO_2)					Total
		2017	2018	2019	2020	2021	
10	Food	0,516	0,758	0,425	0,000	0,000	0,340
11	Beverages	0,009	0,000	0,000	0,000	-	0,002
13	Textiles	0,108	0,494	0,205	0,000	0,000	0,161
14	Apparel	0,002	0,000	0,001	-	-	0,001
17	Paper and Paper Products	-	-	-	-	-	-
18	Printing and Reproduction of Recorded Media	0,002	-	0,002	-	-	0,001
20	Chemicals and Chemical-Based Materials	0,078	0,001	0,004	0,000	0,005	0,018
22	Rubber and Rubber and Plastic Products	0,002	0,000	0,000	0,000	0,000	0,000
23	Non-Metallic Minerals	0,869	0,967	0,942	0,553	89,426	18,552
25	Metal Products, Other Than Machinery and Equipment	-	-	-	-	-	-
31	Furniture	-	0,000	-	-	-	0,000

Source: Data processed by the author (2024)

Table 6: Green efficiency score in the industrial sector in West Sumatra 2017-2021

Industrial sector code	Industrial sector	Green efficiency value				
		2017	2018	2019	2020	2021
10	Food	1	1	1	0.983863	1
11	Beverages	1	0.657454	1	1	1
13	Textiles	0.282581	1	0.214646	1	0.880905
14	Apparel	0.818188	1	1	1	1
17	Paper and Paper Products	0.304127	1	0.153301	0.155503	0.141792
18	Printing and Reproduction of Recorded Media	1	0.783036	0.166298	1	1
20	Chemicals and Chemical-Based Materials	1	1	1	1	1
22	Rubber and Rubber and Plastic Products	0.980975	0.868082	1	0.845686	1
23	Non-Metallic Minerals	1	1	1	1	1
25	Metal Products, Other Than Machinery and Equipment	1	0.525591	1	0.801616	1
31	Furniture	0.794501	1	1	1	1

Source: Data processed by the author (2024)

and paper materials sector remained inefficient, with a score of 0.868. Furthermore, changes occurred in 2018. The beverage sector, the printing and reproduction of recorded media, and the non-machinery metal goods sector showed a shift from efficiency to inefficiency, indicated by scores below 1.

Then, in 2019, the printing and reproduction of recorded media sector continued to show inefficiency, while the textile and paper and paper materials sector returned to inefficiency. Meanwhile, the other sectors were efficient. In 2020, the textile and printing and reproduction sectors demonstrated efficiency, but the paper and paper-based materials sector remained inefficient. In fact, initially efficient sectors became inefficient in 2020, including the food sector, rubber and rubber-based materials, and non-machinery and equipment metal goods. This could be due to the effects of the COVID-19 pandemic. Furthermore, in 2021, all sectors demonstrated efficiency, except for the textiles, paper, and paper-based materials sector, which had a value below 1.

Based on this description, it can be concluded that the chemicals, chemical materials, and non-metallic minerals sectors consistently achieved green efficiency from 2017 to 2021, indicated by a constant value of 1. Furthermore, the apparel and textiles sector consistently shifted from inefficiency in 2017 to efficiency from 2018 to 2021. Other sectors showed inconsistent efforts to achieve green efficiency from 2017 to 2021, indicated by fluctuating efficiency values each year.

Results of the relationship between CO_2 emissions and green efficiency in the industrial sector in West Sumatra from 2017 to 2021.

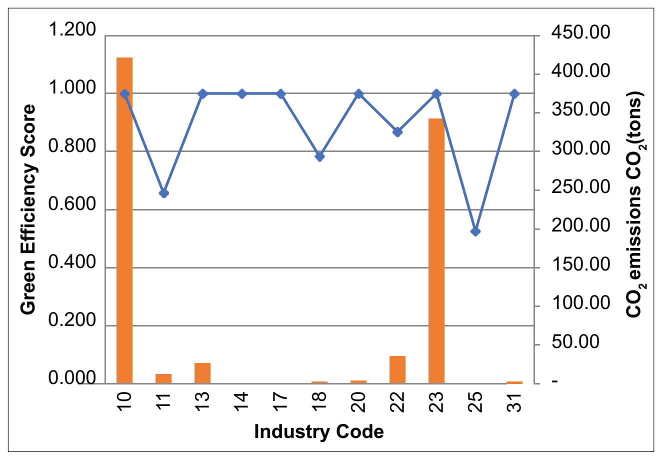
In the SBM-DEA analysis, three slacks are identified: excess input usage, scarcity in the production of desired outputs, and excess production of undesirable outputs. These three slacks can affect the green efficiency value, making it difficult to interpret directly. Therefore, Figures 1 untul Figure 5 are needed to explain the value of green efficiency.

Based on Figure 1, it can be seen that during 2017 in the industrial sector in West Sumatra Province there was an interesting indication: where the average value of the green efficiency score is low, the sector has high CO_2 emissions. It is interesting to find that the rubber and rubber materials sector (industry code 23) shows high carbon emissions and has not achieved efficiency. Sectors with industry codes 12, 14, 17, and 31 show that although they do not produce many carbon emissions, namely less than 1 ton, this sector shows an inefficient green efficiency score, which is marked by a green efficiency figure of less than 1. Sector codes no. 18 and 25 show efficiency in the emissions produced. An interesting thing happened in the food sector, which had the highest CO_2 emissions but actually showed an efficient value, as well as the non-metallic mining sector, which showed an efficient score but high CO_2 emissions. The high CO_2 in the food sector and the rubber and non-rubber sector with the achievement of efficiency shows that this sector is able to achieve green efficiency from unwanted output in the form of carbon emissions.

Based on Figure 2, it can be seen that during 2018 in the industrial sector in West Sumatra Province there were interesting indications. An interesting thing was found: the rubber and rubber materials sector (industry code 22) showed high carbon emissions and did not achieve efficiency. Sectors with industry codes 11, 18, and 25 showed that although they did not produce many carbon emissions, namely less than 1 ton, this sector showed an inefficient green efficiency score marked by a green efficiency figure of less than 1. Sector codes no. 13, 14, 17, 20, and 31 showed efficiency in the emissions produced. An interesting thing happened in the food sector with the highest CO_2 emissions, even showing an efficient value, as well as the non-metallic mining sector showing an efficient score but high CO_2 emissions. The high CO_2 in the food sector and the rubber and non-rubber sectors with the achievement of efficiency indicates that this sector is able to achieve green efficiency from unwanted output in the form of carbon emissions.

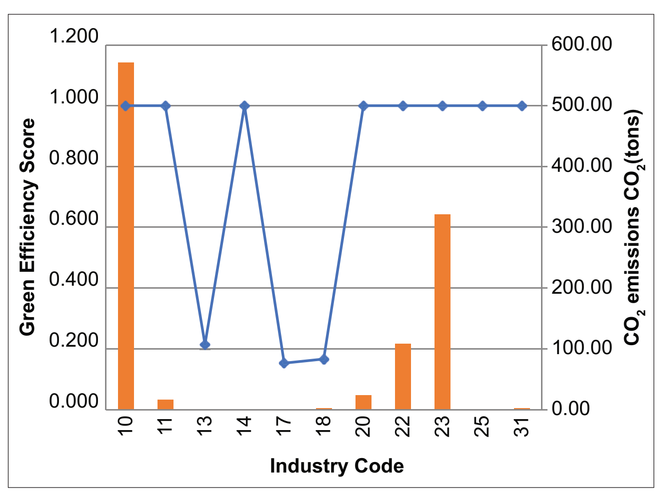
Based on Figure 3, it can be seen that the industrial code sector 22, which has carbon emissions exceeding 5 tons of CO_2, has shown efficiency. The sector with industrial code 18 is still the same as in 2018, where even though it does not produce many carbon emissions, namely <1 ton, this sector shows an inefficient green efficiency score, which is indicated by a green efficiency figure

Figure 2: Green efficiency scores for 11 industries in West Sumatra from 2018



Source: Data processed by the Author (2024)

Figure 3: Green efficiency scores for 11 industries in West Sumatra from 2019

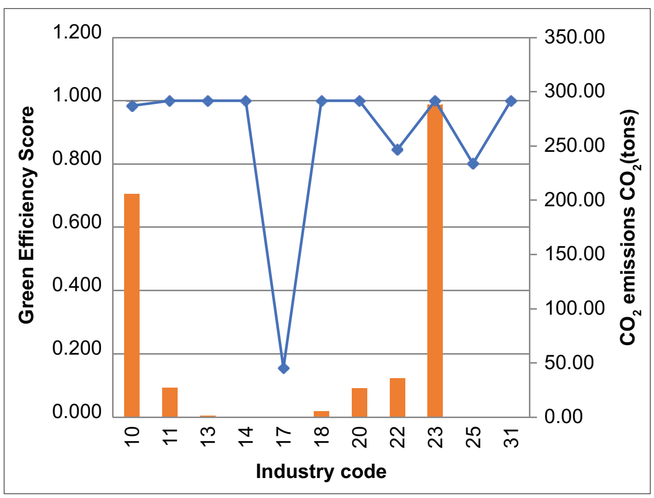


Source: Data processed by the Author (2024)

of <1. Sector codes no. 13, 14, 20, and 31 show efficiency in the emissions produced, while sector 17 has changed to inefficient. An interesting thing still occurs in the food sector, which has the highest CO_2 emissions but actually shows an efficient value, as well as the non-metallic mining sector; sectors no. 22 and 20 show efficient scores but high CO_2 emissions. The high CO_2 in the food sector and the rubber and non-rubber sectors with the achievement of efficiency shows that these sectors are able to achieve green efficiency from unwanted output in the form of carbon emissions.

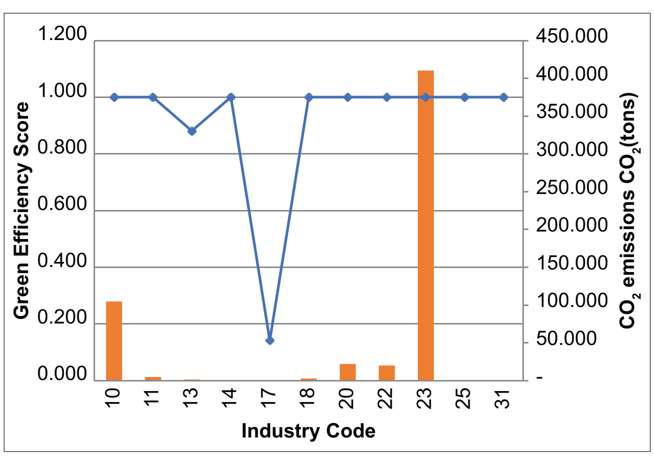
Based on Figure 4, it can be seen that during 2020 in the industrial sector in West Sumatra Province, the industry code 22 sector, whose carbon emissions exceed 5 tons of CO_2, again showed inefficiency. Sectors with industry codes 25 and 17 are still the same as in 2020, where, although they show that they do not produce much carbon emissions, namely less than 1 ton, this sector shows an inefficient green efficiency score, which is indicated by a green efficiency figure of <1. Other sectors except the food sector show efficiency in the emissions produced. The food sector has the highest CO_2 emissions; in 2020, showing an inefficient value,

Figure 4: Green efficiency scores for 11 industries in West Sumatra from 2020



Source: Data processed by the Author (2024)

Figure 5: green efficiency scores for 11 industries in West Sumatra from 2021



Source: Data processed by the Author (2024)

this sector is unable to achieve green efficiency from unwanted output in the form of carbon emissions.

Based on Figure 5, it can be seen that during 2021 in the industrial sector in West Sumatra Province, the industry code 22 sector with carbon emissions exceeding 5 tons of CO_2 again showed inefficiency. Sectors with industry codes 25 and 17 remained the same as in 2020, where, although it shows not producing much carbon emissions, namely <1 ton, this sector shows an inefficient green efficiency score marked by a green efficiency figure of <1. Other sectors show efficiency in the emissions produced. The food sector carbon emissions were already low, below 100 tons of CO_2 in 2021, showing an efficient return value; this sector was able to achieve green efficiency from unwanted output in the form of carbon emissions.

4.3. Estimation Results of Factors Influencing Green Efficiency

Based on the formulation of the problem and research methods, the results of the logistic analysis research using the Tobit panel model, logit panel model and probit panel are found to test the robustness of the resulting estimates.

Table 7 shows the results, where the initial data set (55) was reduced to 52 due to three zero values, which were automatically filtered by the statistical tool (5 years across 11 industrial sectors). Table 7 shows that the Tobit panel regression, logit panel regression, and probit panel regressions show identical results, both in terms of significance level and direction of the relationship between variables influencing green efficiency. Therefore, the results of the three regression methods can be explained.The energy structure variable does not significantly influence green efficiency in the industrial sector, as indicated by

Table 7: Green Efficiency Scores in the Industrial Sector in West Sumatra 2017-2021

Independent variable	Dependent variable: Green efficiency		
	panel logit	panel probit	panel tobit
Structure of energy (gasoline)	-0.0177 (0.0173)	-0.0106 (0.0102)	-0.00324 (0.00337)
Ln Indirect tax	0.242* (0.131)	0.146* (0.0758)	0.0461** (0.0230)
covid	0.0260 (0.795)	-0.00375 (0.471)	0.00880 (0.159)
_cons	-2.282 (1.593)	-1.361 (0.942)	0.0840 (0.299)
lnsig2u			
_cons	-12.56 (57.20)	-12.98 (55.45)	
sigma_u			
_cons			1.80e-19 (0.182)
sigma_e			
_cons			0.452**** (0.0443)
N	52	52	52

Standard errors in parentheses. * P<0.1, ** P<0.05, *** P<0.01, **** P<0.001

a P-value greater than the 10% alpha significance level (95% CI). This finding does not support the initial hypothesis in the study but aligns with the results of research conducted by Wang et al. (2017). This can be attributed to the relatively low composition of coal consumption compared to total fuel consumption. Although the insignificant results indicate a negative relationship between energy structure and green efficiency, this is in line with research by Pan et al. (2013), which explains that coal consumption can reduce environmental efficiency. This is because coal use can produce high levels of emissions. Therefore, this study includes an energy structure variable, which is the percentage of expenditure on coal to expenditure on all fuels issued by the industry.

Indirect taxes significantly increase green efficiency in the industrial sector in West Sumatra. The coefficient value shows a positive sign, indicating that as indirect taxes increase, green efficiency is achieved. This is consistent with the findings of the study. Indirect taxes, such as carbon taxes or excise taxes on fossil fuels, are important instruments in increasing green efficiency by encouraging changes in economic behavior. These taxes increase the price of goods or services that produce high carbon emissions, thus providing incentives for producers and consumers to adopt environmentally friendly technologies. For example, the implementation of a carbon tax in Japan successfully reduced carbon emissions by 8.2% in the first six years of implementation (Ministry of Finance of the Republic of Indonesia, 2022). Countries such as Germany and the United Kingdom also utilize tax incentives to increase investment in green technologies, including renewable energy and electric vehicles, through value-added tax (VAT) reductions or other tax incentives (OECD, 2024). In Indonesia, a carbon tax was introduced as part of the roadmap to a green economy, starting in the coal-fired power generation sector through a cap-and-tax scheme. This policy is expected to gradually reduce carbon emissions while maintaining economic sustainability (Ministry of Finance, 2024). Despite challenges in implementation, such as its impact on certain business sectors, this approach has proven effective in other countries in promoting sustainable energy transitions through market mechanisms, such as carbon trading (Cao et al., 2024).

While COVID-19 has not significantly affected green efficiency, the COVID-19 pandemic has had a significant impact on green efficiency and investment dynamics globally. Various studies have shown mixed impacts, revealing both challenges and opportunities in promoting sustainability. Decline in Green Investment: In regions heavily impacted by COVID-19, corporate green investment often declines. A study of Chinese companies found that increased exposure to the pandemic correlated with a reduced willingness to fund green projects, likely due to limited financial resources and increased economic uncertainty. However, larger companies with greater financial stability tended to maintain their green investments (Kaakeh and Gokmenoglu, 2022). However, some have also noted an acceleration in green policy: On the other hand, the pandemic has prompted governments and organizations to review and strengthen sustainability-focused energy policies. With reduced industrial activity during lockdowns, there has been a temporary decline in carbon emissions, prompting discussions about long-term structural changes to promote renewable energy and green infrastructure. For example, policymakers have emphasized the need for a stronger green finance framework and incentives for environmentally friendly projects (Kaakeh and Gokmenoglu, 2022).Other research on the global response to COVID-19 highlights the potential for coordinated action to address environmental challenges. Lessons learned from pandemic management are being applied to climate action, emphasizing science-driven policies, public support, and ongoing monitoring of outcomes. However, political and economic factors continue to hamper a comprehensive green transition, with fossil fuel subsidies and inconsistent enforcement of green policies remaining key obstacles (Skovgaard and van Asselt, 2018). This underscores the pandemic's dual impact on green efficiency, reflecting a decline in direct investment and optimism for a long-term policy shift towards sustainability. While the impact in West Sumatra is not significant.

5. CONCLUSION

Thus, it can be seen that green efficiency fluctuates from year to year. The chemical and chemical-based materials and non-metallic mineral sectors consistently achieved green efficiency from 2017 to 2021, indicated by a constant value of 1. Furthermore, the apparel and textile sector consistently shifted from inefficiency in 2017 to efficiency from 2018 to 2021. Meanwhile, other sectors showed inconsistencies in their efforts to achieve green efficiency from 2017 to 2021, indicated by fluctuating efficiency values. Looking at the influencing factors, indirect taxes significantly and positively affected green efficiency, while energy structures, such as gasoline and COVID-19, had no significant impact.

6. ACKNOWLEDGEMENT

We would like to thank the Faculty of Economics and Business, Andalas University for supporting and facilitating this research on SCIENCE GROUP RESEARCH SCHEME 2024.

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