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SUSTAINABLE ENERGY TRANSITION CHALLENGES IN SELECTED ASEAN COUNTRIES: A 4A FRAMEWORK AND DATA ENVELOPMENT ANALYSIS PERSPECTIVE

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ABSTRACT

Energy security—considering depleting fossil fuel sources, growing energy demand, the availability and affordability of renewables, and the environmental effects of energy production and consumption is a significant issue for all governments. The research examines the 2010–2021 ASEAN energy transition hurdles. The 4A framework statistically monitored availability, acceptability, affordability, and application, while the DEA approach assessed renewable energy sustainability. Oil, gas, and coal reserve-production ratios, energy intensity, CO2 emissions, renewable energy, fossil fuel subsidies, and GDP per capita are indicators. The 4A paradigm depicts countries regressing on availability and affordability while maintaining application and acceptability. The DEA technique suggests using renewable energy to enhance productivity and reduce CO2 emissions in developed nations. The suggested DEA technique uses renewable energy consumption, total energy consumption, labor, natural resource rent, and installed renewable capacity as inputs and GDP and CO2 emissions as outputs to prioritize economic or environmental criteria in sustainable development evaluations. All nations except Vietnam have comparable

2010 GDP and CO2 emissions. CO2 consumption increased Vietnam's GDP and decreased in the Philippines in 2015. The input suggests that policymakers prioritize energy policy assessment and development utilizing the 4A framework and DEA methodology. Policymakers should also examine inventive ways to promote renewable energy and deliver cheap, low-carbon power. ASEAN should also address pricing, energy imports, and energy use's environmental and climate change implications to hasten the low-carbon energy transition. The research emphasizes economic development but may miss renewable energy's political and economic effects. Future studies should examine ASEAN renewable energy hurdles and their economic, social, and employment effects.

Keywords: *Energy Transition, 4A framework, DEA, ASEAN, Sustainability*

INTRODUCTION

The sustainable growth of ASEAN is faced with a considerable set of difficulties, all tied to increasing demand for power, a fast-growing population, increased transportation demand, depleting fossil fuels, and substantial electricity consumption. As energy demand grows, scarcity may lead to resource conflicts, creating the spectre of national security concerns since depleting oil and gas sources can no longer fulfil expanding demand in the future. Therefore, the countries are not exempted from the effects of the rising number of energy security risks, the slow pace of transition, the lack of policy implementation, and the forecasting of renewable capacity. As a result, ASEAN has conducted a thorough empirical investigation regarding energy security and the switch to renewable energy sources. Due to their recognition of the importance of renewable energy in achieving their various energy and developmental goals, the ASEAN member countries have each created a distinct renewable energy policy framework or integrated renewable energy concerns into their overall respective energy and development policy frameworks. Singapore ranked first in Southeast Asia and 21st in the world on the Energy Transition Index 2021, published by the World Economic Forum. The index supports the design of energy transition roadmaps and provides a numeric value indicating how well a country is advancing in its transition to renewable energy. Its rating system is based on three criteria: 1) energy access and security, 2) environmental sustainability, and 3) economic development and growth. Thailand and Vietnam are at positions 55 and 65, respectively, with Malaysia at 39 and Indonesia at 71. Several ASEAN nations are in the top 100, including Brunei, the Philippines, Indonesia, and Cambodia.

This study has analyzed the obstacles to transitioning to a sustainable energy source in selected ASEAN nations between 2010 and 2021. The 4A framework was used to statistically measure progress in various categories, including availability, acceptability, affordability, and applicability, as well as the DEA approach to evaluate countries' efficacy in utilizing renewable energy for national sustainability. The DEA variables are more specific to efficiency measurement, whereas the 4A framework variables reflect broader aspects of energy security. Indicators included the reserve-production ratio of oil, gas, and coal, energy intensity, per capita CO2 emissions, per capita renewable energy consumption, fossil fuel subsidies, and per capita GDP. The second aim of this study is to quantify renewable energy transitions for sustainable energy security.

There are four contributions to this research. First, normalization is employed in the context of the 4A energy security framework to bring diverse indicators or aspects of energy security to a similar scale. It guarantees that each component is given equal weight and that no one factor dominates the evaluation. In terms of energy availability, accessibility, acceptability, and cost, these ratings may be used to identify best practices, measure performance, and highlight areas for improvement. Second, we demonstrate the applicability of the proposed DEA method for prioritizing economic or environmental criteria in sustainable development assessments. Third, we find that if economic criteria are prioritized, the disparity between countries in terms of sustainable development rapidly narrows after the early 2000s.

Fourth, regardless of which criterion is prioritized, the disparity between the sustainability levels of countries in various regions has decreased over time, indicating convergence in sustainable development across the globe. No matter whether economic prosperity or environmental protection is prioritized, renewable energy always has a positive and highly significant impact on sustainability. As a result of the pervasiveness of climate change's effects, it has been emphasized for a long time that addressing climate change's challenges requires international cooperation.

The Paris Agreement which was signed by 195 countries serves as a road map for future actions, is the result of recent global efforts to mobilize and coordinate collective actions against climate change.

LITERATURE REVIEW

The concept of energy security can aid nations in achieving economic stability and has therefore risen to the top of the energy literature's discussion agenda (Amin et al., 2021d). Ang et al. (2015) note that the recent literature on energy security has also gained momentum due to its critical importance to various stakeholders, diverse energy markets, and transitional energy problems. Existing literature argues that the traditional definition of energy security is possibly limited and should be expanded for a better understanding of its implications (Vivoda, 2010; Von Hippel et al., 2011; Martisauskas et al., 2018; Taghizadeh-Hesary et al., 2019; Sarangi et al., 2019). In addition to the fundamental criteria, Von Hippel et al. (2011) emphasize several new factors, including the environment, technology, and sociocultural factors. In contrast, Vivoda (2010) analyzed the energy security level while discussing the significance of human security, geopolitical incidents, and well-structured policies. Obstacles still exist regarding the structure of energy use, with a high reliance on fossil fuels and low proportions of geothermal, hydro, solar, and wind energy (Yang et al., 2019). Jamil et al. (2020) conducted an empirical experiment to determine the factors influencing Green Building prices in Klang Valley, Selangor. The results showed that tenure-related factors significantly contribute to the GB price. The Multiple Regression Analysis (MRA) model was tested on a real dataset. Senderov & Vorobev (2018) demonstrated that the area has a balanced natural gas supply and demand given that Brunei and Myanmar produce roughly 26 million tons of natural gas in total.

The paper's primary goal was to quantify energy security and evaluate energy sustainability. This study used the DEA methodology by choosing a small number of input and output factors to represent the transitional situation towards sustainable energy use in the chosen ASEAN nation. This methodology was used to determine which ASEAN nations were experiencing higher or more ideal economic development. Is it due to the use of fossil fuels, which causes CO2 emissions, or the shift to renewable energy, which causes CO2 emission reductions? Chachuli et al. (2021) used the Malmquist index (MI) and DEA to assess Malaysia's renewable energy transition. The study analysis considers three inputs: employment, electricity production, and renewable energy licensed capacity, as well as two outputs: GDP and renewable energy production. Roslee et al. (2022) discussed Malaysian green building issues and solutions. The study used a quantitative questionnaire. Selangor and KL G5–G7 contractors were studied. They found that Malaysia's green building development was impeded by a lack of public understanding of its benefits, financial aid or government incentives for green building efforts, and green building expertise.

Zhou et al.'s (2018) research used DEA to analyze the energy efficiency of several Chinese regions. GDP was the output, with labor, capital, and energy consumption being the inputs. The research revealed information on the relative effectiveness of energy use and its bearing on economic output. Sueyoshi et al. (2021) used DEA and panel data analysis to examine country-level sustainability and the impact of renewable energy from 1990 to 2014. Economic criteria outperformed environmental criteria until the early 2000s. The gap closed shortly after the period. If environmental factors are prioritized, developed and emerging countries will perform similarly over time. In this study, we quantify sustainability by capturing economic and environmental elements using the non-parametric technique of Data Envelopment Analysis (DEA). Since human society may prioritize either economic or environmental aims in setting sustainability goals, this study addresses how to prioritize criteria in sustainability evaluation, in contrast to the majority of other studies of country-level sustainability.

CONCEPTUAL FRAMEWORK

It is also important to note that energy security is a highly context-dependent concept, which characterizes it as a challenging endeavor. Until now, diverse methods have been utilized to quantify energy security, at least in terms of comparative measurement. The 4As framework proposed by Yao and Chang (2014) has proven to be a reliable method because it permits the incorporation of indicators based on the economic context and reduces the likelihood of complications that may arise when examining comprehensive energy security. The framework is comprised of four dimensions: (i) Availability,

(ii) Applicability, (iii) Acceptability, and (iv) Affordability (Sovacool et al. 2011). Most country-level sustainability assessments are methodology-based and rely on establishing and quantifying key performance measures and indicators, particularly various types of sustainability indices. Even though such indices could reveal significant implications, there are two main issues with index-based analysis. One point is that most sustainability indices base their calculations on the ratio of a single output, like carbon emissions, to a single input, like GDP, leaving out other elements that play a role in determining sustainability. The second issue is that some indices combine more than two components using the weighted average technique; however, the weights given to the factors are typically arbitrary and open to criticism. We require a rigorous, comprehensive, and reliable approach to get past the problem with index-based research and properly evaluate sustainability. In this study, we quantify sustainability by capturing economic and environmental elements using the non-parametric technique of data envelopment analysis (DEA).

The study focuses on the ASEAN countries with the highest nominal GDP, which are Indonesia, Malaysia, the Philippines, Singapore, Thailand, and Vietnam. These six ASEAN countries are attractive investment locations because of their enormous natural and human resources and vast marketplaces for goods and services. According to Statista, Singapore received the most foreign direct investment (FDI) in 2020, with a total of almost 91 billion USD. Indonesia, Vietnam, the Philippines, and Malaysia came in second with 18.3, 15.8, 6.59, and 3.55 billion USD, respectively. Only Thailand shows negative FDI inflows, suggesting that outflows are increasing. According to the World Economic Outlook 2021, Indonesia, Thailand, Malaysia, Singapore, Vietnam, and the Philippines have higher nominal GDP than the rest of ASEAN, which affected the study's selection. According to the ASEAN Secretariat Report in 2021, Singapore exported 27.6% of ASEAN exports in 2020, followed by Vietnam (20.7%), Malaysia (17.1%), and Thailand (14.4%). In 2020, Singapore bought 26.7% of ASEAN imports, followed by Vietnam (21.2%), Malaysia (15.4%), and Thailand (13.7%).

LITERATURE REVIEW GAP

ASEAN heavily relies on fossil fuels for energy in the transportation and electrical sectors, which presents difficulties in the Applicability and Acceptability dimensions. Each ASEAN member nation has a unique energy security environment, affecting the various energy security situations across the region.

Renewable energy and energy-efficient technology development are critical to meeting ASEAN's goals for energy security and sustainable energy policy.

Regional cooperation is necessary to ensure energy security and effectiveness, including sharing cross-border energy resources, financial resources, and knowledge (Tongsopit et al., 2016; Kanchana & Unesaki, 2015; Fan & Bhattacharyay, 2015).

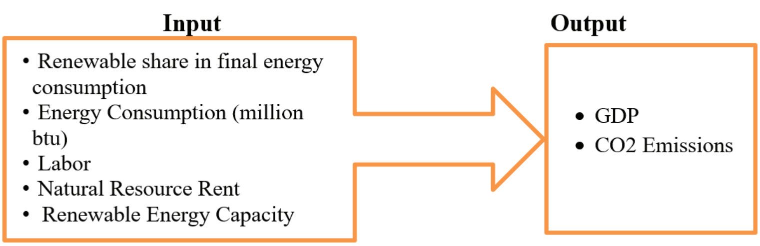

Figure 1. Framework of Assessment Procedure of DEA

Source: Author

Table 1. Dimensions of 4As Framework and Its Indicators

Availability	**Short Form**	**Impact on Energy Security**
Net Energy Import (petajoul)	NEIM	Negative
Renewable Energy Consumption Per Capita (Kwh)	REC	Positive
Reserve/Production of Oil	R/P O	Positive
Reserve/Production of Gas	R/P G	Positive
Reserve/Production of Coal	R/P C	Positive
Applicability		
Energy Intensity level of primary energy (MJ/$2011 PPP GDP)	ENIP	Negative

RE Installed Capacity million kwt	REICAP	Positive
Electricity Transmission and Distribution Loss ()	ETDL	Negative
Fossil Fuel Power Generation (% of total electricity)	FFE	Positive
Acceptability		
CO2 Emission Per capita (Metric ton)	CO2PC	Negative
Share of World CO2 Emissions	WCO2	Negative
Share of RE in final energy consumption	REENC	Positive
Affordability		
Energy use per capita (kwh)	ENU	Positive
GDP per capita, ppp (constant 2017)	GDP	Positive
Fossil Fuel Subsidy (USD)	FFS	Negative
Global Oil price (Per barrel/USD)	OP	Negative

Source: Author's accumulation

METHODOLOGY

Historically, four A has emerged due to calculating the traditional fossil fuel-based environmental and socio-economic evaluation of energy security. According to Bohi and Toman (2012), energy security must consider three essential ideas of today's global energy supply chain: pricing, sustainability, and environmental stewardship. For the current national energy security challenges, energy reserves and stockpiles, fuel mixes and diversification, price stability and affordability, justice and equity, and environmental quality are significant influences (Sovacool & Mukherjee, 2011). They deal with both classic energy security issues like the security of supply, as well as newer considerations such as environmental, financial, social, and technological problems (international dimension) (von Hippel et al., 2011). While the DEA (Data Envelopment Analysis) model is a mathematical technique used to evaluate the relative efficiency of decision-making units (DMUs), such as companies, organizations, or institutions. The purpose of using the DEA model in energy efficiency measurement is to identify the most efficient energy-producing or consuming units and to determine ways to improve the efficiency of less efficient units. By analyzing these units' input and output data, the DEA model can identify the best practices of efficient units and highlight areas where improvements can be made in less efficient units.

We normalize the data to compare and quantify the level of energy security for the ASEAN economies because the indicators from each dimension are in various units. In this regard, we use the min-max normalization method, which involves a linear transformation of the original data series into an ordinal (scoring) data series. Previously, Yao and Chang (2014), Tongsopit et al. (2016), and Malik et al. (2020) used the method.

Because the data from each dimension is in a different unit, we normalize the data to compare and measure the energy security level for the economy as a whole. In this case, we use the min-max method of normalization, which is a linear transformation of the original data set to an ordinal (score) data set, as shown in the equation. As a result, the indicator values were translated into values ranging from 0 to 10. To attain a normalized scale of 0–10, we must scale up the right-hand portion of the equation by 10.

$$1 + \left(\frac{X - Min\ A}{Max\ A - Min\ A}\right) x\ 10 \qquad (1)$$

Where;
X'= Normalized value based on 0-10 scale
Min A=Minimum value of data range A
Max A= Maximum value of data range A

In some cases, though, the scale has no bearing on the sign. The higher the value in this inverse correlation, the less secure the energy supply is. For example, a higher percentage of energy imports have smaller scale values indicates worse energy security. In this instance, the equation is:

$$1 + \left(\frac{X - Max\ A}{Min\ A - Max\ A}\right) x\ 10 \qquad (2)$$

This data transformation enables us to monitor the performance of each indicator. While the scale measures relative performance, it does not examine absolute performance. If the data points from which the indicators are constructed are not significantly different, even a small change will be interpreted as significant. As a result, these indications should be interpreted in terms of their raw values.

The DEA model can also help policymakers and regulators design and implement energy efficiency policies that encourage companies and organizations to improve their energy efficiency performance. By providing a benchmark for efficiency, the DEA model can help policymakers set performance targets, allocate resources efficiently, and monitor progress towards achieving energy efficiency goals. The following equation represents the fundamental DEA model for determining the efficiency of DMUj's:

$$\max \theta_j = \frac{\sum_{m-1}^{M} y_m^j \, u_m^j}{\sum_{n-1}^{n} x_n^j \, v_n^j} \tag{3}$$

Where, DMUj outputs M are y_1^j.........y_m^j multiplied by their individual weights, u_1^j.........u_m^j and divided by the N inputs, x_1^j...... x_n^j multiplied by their individual weights, v_1^j...... v_n^j. The objective is to maximize the efficiency score θ_j, subject to the stipulation that the weights on each DMUk, where k=1,....,K, no efficiency score exceeds one.

$$\frac{\sum_{m-1}^{M} y_m^j \, u_m^j}{\sum_{n-1}^{n} x_n^j \, v_n^j} \leq 1 \tag{4}$$

Additionally, all inputs, outputs, and weights must be positive. Typically, to enable linear optimization, either the sum of outputs or the sum of inputs is constrained to equal a specific value. Overall, the use of the DEA model in energy efficiency measurement can help identify opportunities for energy savings, reduce greenhouse gas emissions, and improve energy security, all while promoting sustainable economic growth.

Data for this study was gathered from 2010 to 2021, and sources are mostly Global Economy.com, WDI-2021, Our World in Data, IEA, and EIA. This paper primarily uses normalization to check the energy security of the selected ASEAN countries. Moreover, it uses data envelopment analysis (DEA) to check the energy efficiency of the same countries. Considering the 4As framework as the theoretical background, this study uses several indicators that are of different units. Henceforth, normalization has been used to transform the original data into a scored data series. We have used the min-max method for data transformation. A similar method was also employed by Amin et al. (2022) and Tongsopit et al. (2016), who also used the 4As framework. After the transformation of the original series, the data are scored between 0 and 10, where, generally, a higher scale number indicates higher energy security, and a lower scale number indicates lower energy security. However, this circumstance is subject to change depending on the indicator that will be explicitly explained in the discussion of the paper. The relative energy security is explained by the average values of dimensions and sample years.

DEA is a well-known method of performance measurement in the field of energy efficiency (Mardani et. al. 2017). This paper has an estimated relative efficiency. DEA uses linear relations between input and output. This paper uses DEA to determine how the selected countries are performing in terms of energy efficiency.

ANALYSIS AND FINDINGS

We shall present the results and discuss the key findings in this section. The results of the normalization of selected countries are presented below. After discussing the normalization method, we shall corroborate the result with DEA.

Average Value of 4A Framework

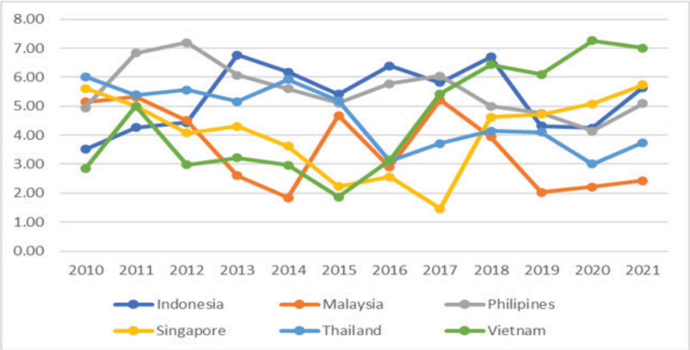

Figure 2. Trend in Availability

Source: Authors Calculation

Indonesia consistently ranks high in availability scores, with the highest score of 8.83 in 2019. Malaysia, the Philippines, Singapore, Thailand, and Vietnam also have fluctuating scores throughout the years. Singapore consistently ranks lowest in availability scores, while Thailand has had the highest score in some years (Yao and Chang, 2014; Tongsopit et al., 2016).

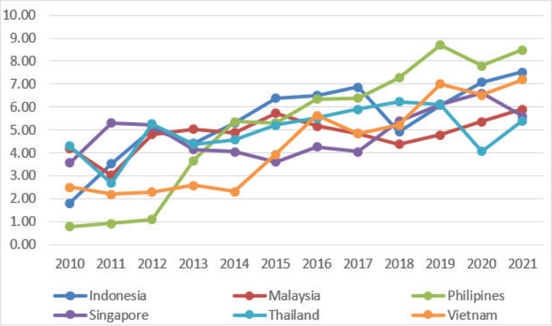

Figure 3. Trend in Applicability

Source: Authors Calculation

The applicability dimension refers to the extent to which a technology or innovation can be adopted and applied in a specific context. The values in the figure range from 0.77 to 8.70, with higher values indicating greater applicability. Overall, the dataset suggests that the applicability of technology and innovation has generally increased over time in these countries, with some fluctuations from year-to-year (Sovacool et al., 2011).

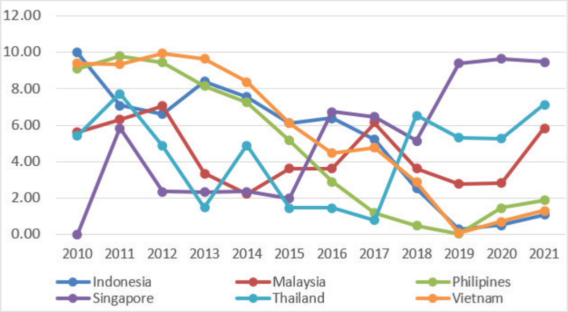

Figure 4. Trend in Acceptability

Source: Authors Calculation

Some countries have high acceptability scores, such as the Philippines and Vietnam in 2012 and 2019, respectively, while others have consistently low scores, such as Singapore. The data also shows some fluctuations in acceptability scores over time, which may be due to changes in energy policies, environmental awareness, and other factors that affect public perception (Amin et al., 2022; Tongsopit et al., 2016).

Figure 5 shows that in the early years of the dataset, Indonesia, Malaysia, and the Philippines had relatively low levels of affordability, while Singapore, Thailand, and Vietnam had relatively high levels. Most countries in the dataset experienced an increase in affordability over time, with the exception of Singapore and Thailand, which saw a modest decrease. Apart from Singapore and Thailand, the majority of countries in the dataset had relatively high levels of affordability in 2019 and 2020 (Li and Chang, 2019).

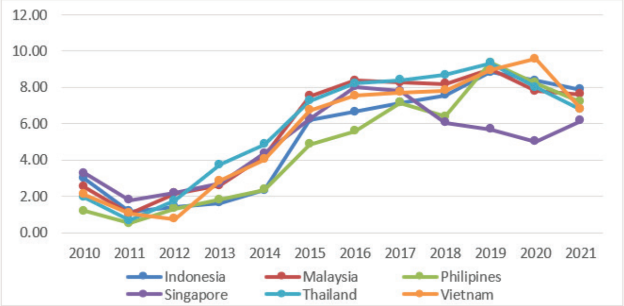

Figure 5. Trend in Affordability Dimension

Source: Authors Calculation

Considering the four dimensions of the 4As framework, the Philippines scores highest in the affordability dimension, which is 5.55, and Malaysia scores lowest, which is 3.53. In the applicability dimension, Indonesia is ahead of any other selected country, and it scores 5.45. On the contrary, Vietnam scores the least compared to other countries, at 4.35. Considering the average score, Vietnam stands at the top in the acceptability dimension with a score of 5.59, whereas Thailand scores the least with a score of 4.36. Lastly, Thailand scores the highest (5.81) in the affordability dimension, whereas the Philippines scores the least (4.67).

Data Envelopment Analysis (DEA)

Table 2. Data Envelopment Analysis

GDP as Output				CO2 as Output		
Period	DMU	Score	Rank	DMU	Score	Rank
2010	Indonesia	0.98	3	Indonesia	0.96	6
	Malaysia	0.97	4	Malaysia	0.98	5
	Philippines	1	1	Philippines	1	1
	Singapore	0.99	2	Singapore	1	1
	Thailand	0.97	4	Thailand	1	1
	Vietnam	0.71	6	Vietnam	1	1
2015	Indonesia	0.99	4	Indonesia	1	1
	Malaysia	0.96	5	Malaysia	0.95	5
	Philippines	1	1	Philippines	0.97	4
	Singapore	1	1	Singapore	1	1
	Thailand	1	1	Thailand	0.85	6
	Vietnam	0.82	6	Vietnam	1	1
2021	Indonesia	0.97	4	Indonesia	0.76	6
	Malaysia	1	1	Malaysia	1	1
	Philippines	0.92	5	Philippines	0.92	3
	Singapore	1	1	Singapore	0.81	4
	Thailand	1	1	Thailand	0.77	5
	Vietnam	0.82	6	Vietnam	1	1

Source: Authors Calculation

The scores in Table 2 represent the efficiency of each country in converting inputs into GDP and CO2 output separately to assess the contribution of energy efficiency, economic growth, and renewable energy to achieving greenhouse gas emission reduction and sustainable development goals. A score of 1 indicates that the country is fully efficient, while a score less than 1 means that the country is less efficient. The ranks show how each country compares to the others in terms of efficiency. GDP as Output: Countries with higher scores and ranks are considered more efficient in converting inputs into GDP. For CO2 as Output: Countries with higher scores and ranks are considered more efficient in minimizing CO2 emissions while maintaining GDP.

The use of renewable energy by countries to increase economic output in the nation is indicated if the above situation is the opposite, with optimal economic development but lower CO2 emissions. The objective of this study was to determine how nations may use the same input factors to assess economic output efficiently while emitting less CO2.

The efficiency of Indonesia's conversion of inputs into GDP grew somewhat between 2010 and 2015 (0.98 to 0.99) but marginally declined in 2021 to 0.97. Its position fell from third to fourth as well. Indonesia was less effective in reducing CO2 emissions over time, going from 0.96 in 2010 to 0.76 in 2021. Malaysia was the most efficient nation in terms of GDP as output in 2021 after significantly decreasing from 2010 to 2015 (0.97) and reaching the highest efficiency (1) in that year. Malaysia increased its CO2 efficiency from 0.98 in 2010 to 1 in 2021, keeping its top-ranking position.

The Philippines had the highest initial efficiency in 2010 (GDP score of 1), but by 2021, it had fallen to 0.92. The nation's effectiveness in reducing CO2 dropped from 1 in 2010 to 0.92 in 2021, moving it from first to third place. The GDP efficiency of Singapore increased from 0.99 in 2010 to 1 in 2015 and remained at that level in 2021. However, it became less effective in reducing CO2 from 1 in 2010 to 0.81 in 2021. Thailand's productivity efficiency increased from 0.97 in 2010 to a perfect score of 1 in 2021 GDP, while it decreased from 1 to 0.77 in CO2 reduction from 2010 to 2021. In terms of GDP, Vietnam's efficiency increased from 0.71 in 2010 to 0.82 in 2021, but it constantly maintained a perfect score of 1 for reducing CO2 emissions across all years.

The above depicts a scenario in which the Philippines and Vietnam are transitioning from the use of non-renewable energy to renewable energy. The other countries are still emitting CO2 while increasing their GDP and are yet to transition from non-renewable energy to renewable energy. Therefore, despite being a unified block, ASEAN countries have different scenarios in terms of energy efficiency and energy security. This relationship between CO2 usage and GDP is supported in the literature, i.e. (Lei et al., 2017; Inglesi-Lotz and Dogan, 2018; Le and Park, 2021; Liddle and Sadorsky, 2017; Wang et al., 2022). The DEA results suggest that, in terms of GDP production efficiency, the Philippines began 2010 as the most efficient nation, but their efficiency declined by 2021. Malaysia and

Thailand, on the other hand, obtained the highest efficacy in 2021. Vietnam, despite its improvements, remained the least efficient nation throughout the years. Vietnam has consistently maintained the maximum efficiency in CO2 reduction. While the majority of nations began with high CO2 minimization efficiencies in 2010, there was a general decline in efficiency by 2021, with Indonesia experiencing the greatest decrease in efficiency. These findings can be used to identify best practices and policies that can help improve the efficiency of economic production while reducing CO2 emissions in these countries.

Since we have applied the conventional DEA, we need to look at the reliability of the DEA scores. As a result, this study made use of the bias-corrected DEA robustness efficiency analysis that Simar Wilson proposed in 2000. Traditional DEA is sometimes susceptible to changes and outliers. The Simar and Wilson method corrects for potential biases and provides confidence intervals for efficiency scores, thereby increasing the validity of the findings (Simar & Wilson, 2000). Analyzing both output- and input-oriented efficiency, the study utilized a bootstrap-based estimation procedure to determine the production efficiency determinants. In this model, bias correction in DEA produces more precise and robust estimates of efficiency by adjusting for potential statistical biases.

Table 3. Bias Corrected DEA Robust Efficiency Score

GDP as Output				CO2 as Output		
Period	DMU	Score	Rank	DMU	Score	Rank
2010	Indonesia	0.83	5	Indonesia	0.95	2
	Malaysia	0.84	2	Malaysia	0.93	5
	Philippines	0.84	2	Philippines	0.95	2
	Singapore	0.84	2	Singapore	0.96	1
	Thailand	0.86	1	Thailand	0.88	6
	Vietnam	0.65	6	Vietnam	0.95	2
2015	Indonesia	0.81	3	Indonesia	0.92	4
	Malaysia	0.82	2	Malaysia	0.97	5
	Philippines	0.80	5	Philippines	0.99	1
	Singapore	0.81	3	Singapore	0.99	1
	Thailand	0.85	1	Thailand	0.85	6
	Vietnam	0.58	6	Vietnam	0.99	1

2021	Indonesia	0.81	3	Indonesia	0.81	4
	Malaysia	0.85	1	Malaysia	0.97	2
	Philippines	0.81	3	Philippines	0.96	3
	Singapore	0.82	2	Singapore	0.81	4
	Thailand	0.80	5	Thailand	0.80	6
	Vietnam	0.60	6	Vietnam	0.99	1

Source: Author

The table provides a more refined analysis than standard DEA scores. The table shows that from 2010 to 2021, Indonesia's GDP production efficiency decreased marginally, whereas its CO2 management efficiency declined significantly. Malaysia improved its GDP production and CO2 management efficiency, achieving the highest ranking for GDP efficiency in 2021. In 2021, the Philippines' GDP efficiency decreased, while its CO2 management remained highly efficient despite a slight drop in rank. By 2021, Singapore's GDP efficiency remained stable, while its CO2 management efficiency significantly declined, causing it to lose the top spot. Before 2015, Thailand had the highest GDP efficiency ranking, but by 2021, its ranking had dropped substantially. The country was consistently ranked last for CO2 effectiveness. In terms of GDP efficiency, Vietnam consistently rated last, but by 2015, it had attained and maintained the top position for CO2 efficiency.

CONCLUSION AND RECOMMENDATIONS

Energy security is crucial for global sustainability and climate safety. The 4A framework evaluates a country's energy supply security based on affordability, applicability, acceptability, and availability. ASEAN countries need to increase the use of renewable energy sources to improve energy security. The study suggests that implementing innovative policy alternatives can stimulate the use of renewable energy and provide inexpensive and low-carbon electricity (Hamed & Bressler, 2019). Policymakers can use the findings to identify areas of improvement in their respective countries' energy security. The paper highlights the importance of reducing reliance on fossil fuels and increasing the proportion of renewable energy in total energy consumption to achieve cleaner and more sustainable energy sources. The volatility of global crude prices could impact the country's energy affordability, which policymakers need to consider while making energy policies. The paper emphasizes the need to reduce fossil fuel subsidies to improve the affordability aspect of energy security. The paper provides a framework for evaluating energy security that policymakers and researchers in other regions can use to assess their energy security.

The DEA (Data Envelopment Analysis) method is used to calculate the efficiency scores of each country based on two outputs: GDP and CO2 emissions. The DEA scores range from 0 to 1, with 1 indicating the highest efficiency and 0 indicating the lowest efficiency. A Data Envelopment Analysis (DEA) efficiency score of 0.71 means that the decision-making unit (DMU) under analysis is operating at 71% efficiency relative to the best performing or most efficient DMU(s) in the sample. The DEA method computes efficiency scores by comparing each DMU to a "best practice" frontier made up of the most efficient units or a combination of them. The DEA model identifies these efficient units within the sample data.

In other words, a 29% inefficiency can be eliminated without requiring additional resources. This 29% can be viewed as a measure of potential improvement for the unit. The closer the score is to 1 (or 100%), the more efficient the unit is considered. However, by 2015 and 2021, all countries had improved their efficiency, with most countries achieving a score of 1. The rankings of countries in terms of GDP and CO2 emissions output have changed over time, indicating the need for continuous monitoring and evaluation of policies and practices.

The study provides insights into how countries can use the same input factors to assess economic output efficiently while emitting CO2 inefficiently (high emissions). The findings can be used to identify best practices and policies that can help improve economic production efficiency while reducing CO2 emissions in these countries. The rankings of countries in terms of GDP and CO2 emissions output have changed over time, indicating the need for continuous monitoring and evaluation of policies and practices. The study highlights the importance of using renewable energy sources to increase economic output while reducing CO2 emissions. The results of this study can be used by policymakers to design and implement effective strategies to promote sustainable economic growth while reducing the negative impact on the environment.

Indonesia: Increase investment in renewable energy infrastructure, such as wind and solar power, and implement policies to encourage the use of electric vehicles. Malaysia: Increase the use of biomass and biogas for electricity generation and promote the adoption of energy-efficient technologies in buildings and industries. The Philippines: Increase investment in geothermal and hydropower projects and implement policies to promote the use of electric vehicles and energy-efficient appliances. Thailand: Increase investment in solar and wind power and promote using electric vehicles and energy-efficient technologies in buildings and industries. Vietnam: Increase investment in solar and wind power and promote the use of energy-efficient technologies in buildings and industries. It is important to note that these are just some possible policy suggestions, and policymakers and energy stakeholders in each country should consider their specific energy needs, resources, and constraints when developing policies and strategies to increase the share of renewable energy in their electricity generation mix.

To our knowledge, no other study has combined the 4A framework and DEA to evaluate the energy security and efficiency of the selected ASEAN countries. This quantitative study offers a rigorous yet practical tool for energy regulatory improvements, demonstrating that high energy efficiency and renewable energy may improve ASEAN's energy security in all four dimensions. New issues, such as environmental and energy security, have emerged as the security concept has changed. ASEAN's unsustainable use of fossil fuels puts the area in jeopardy. To transition to a sustainable energy source, the government should enhance the number of renewable energies in the primary and power generation mix to achieve a proportional improvement in the degree of energy security. Although the shares are increasing, they are still insignificant as compared to conventional fossil sources. From the standpoint of accessibility, the utilization of renewable energy sources and the adoption of domestic policies that support resources like solar, wind, biomass, and small-scale hydropower could reduce supply limitations. The selected ASEAN countries can supply more inexpensive and low-carbon electricity by implementing innovative policy alternatives that stimulate the use of renewable energy. The study emphasizes economic growth but may overlook renewable energy's political and economic impacts. The study does not provide a detailed analysis of the environmental impacts of energy production and consumption in the selected ASEAN nations. Future research should analyze ASEAN countries' renewable energy barriers and their economic, social, and employment implications.

LIMITATION OF THE STUDY

The present analysis does not consider the numerous types of renewable energy (such as biomass, solar, wind, etc.) or sector-specific consumption, both of which may reduce the impact of renewable energy. In addition, technological progress has not been accounted for in this study, despite its influence on GDP and labor. Due to the paucity of natural resources in Singapore and the Philippines, only net energy import and renewable energy per capita have been considered in the availability dimension.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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