Estimation of Energy Transition Index based on Official Statistics and Satellite Imagery Data (Case Study: Regencies/Cities in Indonesia)

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Abstract. Energy has a crucial role in sustaining human life, its implementation should be optimized based on the principles of sustainable development through a shift from non-renewable to renewable sources. To monitor this shift, the World Economic Forum (WEF) developed the Energy Transition Index (ETI), which measures national-level transitions using conventional statistical data. However, the ETI is limited to the country level, while more detailed assessments are needed at smaller administrative scales such as regencies and cities to capture regional specificities. This study addresses the gap by constructing an energy transition index at the regency/city level in Indonesia for 2024. The analysis integrates official statistics with satellite imagery data to overcome limitations in subnational data availability. Methodologically, Exploratory Factor Analysis and uncertainty analysis were applied. Among five scenario of uncertaincy analysis tested, scenario 1 featuring min-max normalization, unequal weighting across indicators and factors, and linear aggregation produced the most reliable results. The findings reveal that the index is composed of four main factors. Overall, Indonesia's energy transition index values show a relatively even distribution, yet disparities remain evident across islands and between regencies/cities. Higher scores are concentrated in the western regions, while lower scores dominate the eastern parts of the country.

Keywords: Energy Transition Index, Factor Analysis, Official Statistics, Satellite Imagery, Uncertainty Analysis.

1. Introduction

The energy sector is a fundamental pillar in supporting economic activities and social life of a country [1]. In 2024, the Ministry of Energy and Mineral Resources through the Handbook of Energy and Economic Statistics of Indonesia states that Indonesia's total primary energy consumption is 4.53 BOE per capita with a growth percentage of 3.45% from the previous year. In this energy consumption, 84% of Indonesia's energy mix structure is still dominated by non-renewable resources, especially fossil energy [2]. This condition shows that primary energy continues to serve as the fundamental basis for fulfilling national energy demands. This finding is consistent with the notion that primary energy consumption, defined as energy derived directly from natural resources such as petroleum, natural gas, coal, hydropower, geothermal, and solar energy prior to any conversion process, constitutes a key indicator reflecting the overall well-being of society [3].

In the World Energy Outlook report by the International Energy Agency in 2021 [1], energy sources are classified into two main types, namely non-renewable resources and renewable resources. In connection with the dominance of non-renewable resources in the structure of Indonesia's energy mix, which mainly comes from petroleum and coal, it is necessary to realize that limited fossil energy reserves are depleting along with increasing energy demand. On the other hand, the burning of fossil energy is a major contributor to greenhouse gas (GHG) emissions, which contributes significantly to global climate change and environmental degradation [4]. These negative impacts not only burden the environment, but also have implications for public health and long-term economic stability [5]. Therefore, this dependence not only creates an imbalance in the national energy structure, but also has the potential to threaten long-term energy security and environmental sustainability [3].

Realizing this urgency, the development of new and renewable energy emerged as one of the solutions that can ensure the availability of sustainable, safe, and environmentally friendly energy [6]. Renewable energy is an energy source whose formation does not come from organic bodies, does not pollute or add pollutants to the atmosphere, and will not run out if managed properly. These energy sources are very diverse, including hydro (water), geothermal (geothermal), wind, solar, biomass, biofuels, and ocean waves [7]. In contrast to fossil energy, renewable energy is essentially derived from nature and can be used freely as well as constantly renewed, offering a fundamental solution to the dominance of fossil energy that not only creates structural imbalances, but also negative impacts on the environment [8]. Therefore, the Pertamina Energy Institute in the Pertamina Energy Outlook also supports that the transition to renewable energy such as hydropower, wind, solar, and biomass can be a strategic step to ensure long-term energy security that is environmentally friendly and sustainable [9].

Indonesia's commitment to the energy transition is reflected in various existing national policies. Explicitly, this transition is an integral part of the Sustainable Development Goals (SDGs), specifically point 7 on clean and affordable energy which aims to ensure access to affordable, reliable, sustainable and modern energy for all [10]. This commitment is also realized through policies to accelerate the development of renewable energy plants, one of which is regulated in Presidential Regulation No. 112 of 2022 concerning the Acceleration of Renewable Energy Development. This policy is the legal basis and strategy for Indonesia to realize the energy transition process from non-renewable to renewable.

In order to comprehensively monitor and facilitate the global energy transition, the World Economic Forum (WEF) has developed the Energy Transition Index (ETI) since 2018 [11]. In the latest edition of the ETI 2025, the WEF works with 118 countries to measure the Energy Transition Index. A country's readiness to carry out the energy transition is determined based on the extent to which the supporting environment in the country is created. The Energy Transition Index is compiled based on scores from 43 indicators which are divided into 2 main dimensions, namely system performance and transition readiness. The score is measured in each country using the minimum-maximum method for normalizing indicator scores on a scale of 0 to 100. According to the WEF, the higher the score obtained by a country, the better the progress of the energy transition in that country will be [12].

The value of Indonesia's Energy Transition Index is ranked third in ASEAN. From the index score of 56.7, it was obtained that 69.9 points described the system performance dimension and 36.9 points described the transition readiness dimension. In general, this value indicates that Indonesia is almost good in the performance of its energy system, which includes aspects of energy security, equitable access to energy, and environmental sustainability. However, Indonesia's energy transition readiness still shows significant gaps that need to be improved, especially in aspects related to regulation, investment, innovation, and infrastructure readiness for renewable energy adoption. This suggests that even though renewable energy capacity and infrastructure are beginning to develop, strengthening supporting aspects such as a conducive policy framework, attractive investment incentives, and building local innovation capacity is still needed for the energy transition to run effectively and fairly [13].

However, the energy transition index released by the WEF to date is only available at the national level, without more detailed measurements at the provincial and regency/city levels in each country [12]. Until now, there is still no measurement of the official energy transition index by the government at the regional level. In fact, Indonesia as an archipelagic country with very diverse geographical, demographic, and economic characteristics in each region, needs a more granular understanding of the conditions of the energy transition at the local level. The variability of renewable energy source potential, differences in urbanization levels, as well as regional fiscal capacity and uneven environmental awareness indicate spatial challenges in the implementation of the energy transition in Indonesia [14]. The preparation of indexes at the regional level is potentially important to be explored because it can capture conditions or problems that occur in more detail at the local level. Thus, local governments can accurately identify the specific needs and challenges of each region to support the improvement of the national index. Without detailed data and mapping at the regency/city level, energy transition efforts risk becoming uneven and causing inequality between regions, which can ultimately hinder the achievement of national and global energy targets. Therefore, the preparation of the energy transition index at the regency/city level is very relevant and urgent so that the energy transition process in all dist regencies/cities in Indonesia can be carried out together without inequality, and it can be seen how it compares objectively.

In addition, the energy transition index by the WEF tends to require official statistics data that is only available at the national level and is not yet available at the narrower level of scope (regency/city). To overcome these data limitations, data integration official statistics and satellite imagery can be a more efficient and adaptive alternative approach in compiling energy transition indices at the local level, especially regencies/cities. This approach allows for the adjustment of WEF indicators so that they can be applied at the regency/city level in a more contextual and up-to-date manner. Data from satellite image extraction has great potential to capture relevant information from geographic areas that may not be covered by the data official statistics Conventional [15].

Based on this background, this study aims to calculate the Energy Transition Index at the regency/city level in Indonesia by utilizing a combination of data official statistics and satellite imagery. The factor analysis method will be used to objectively produce the weight of the indicator, ensuring the validity and reliability of the resulting index [16].

2. Research Method

2.1. Scope of research

The scope of the area in this study is national with units of analysis at the regency/city level in Indonesia. Administratively, Indonesia consists of 514 regencies/cities spread across 38 provinces. The selection of the regency/city level as the unit of analysis aims to provide a more detailed and context-specific understanding of energy system performance and energy transition readiness across regions. While provincial-level analysis could offer a broader perspective and facilitate comparisons in terms of data availability and policy relevance, the regency/city level was chosen to capture local variations that are often masked at higher administrative scales. This level of granularity enables a more accurate identification of region-specific variables and supports the formulation of targeted policies that better reflect local conditions. This study uses data in 2024, the selection of this year is based on the availability of the latest data from two sources, namely official statistics and satellite imagery.

2.2. Stages of research

This study follows the systematic guidelines of the Handbook on Constructing Composite Indicators [17], which has been contextually adapted to calculate the Energy Transition Index at the regency/city level in Indonesia. Each stage is implemented by adjusting the objectives, scope, and availability of data within the scope of regencies/cities in Indonesia in 2024.

2.2.1 Preparation of theoretical frameworks

The first step in this study is to build a conceptual framework that explains the logical structure of the energy transition index. This framework is based on references from the ETI developed by the WEF which divides the indicators into two main aspects, namely system performance and transition readiness. The development of this framework aims to ensure that the indicators used have a logical and theoretical relevance to the energy transition and can be quantitatively measured at the regency/city level.

2.2.2 Indicator identification

Proxy indicators were developed at the regency/city level in Indonesia to accommodate variations in data availability across regions. Since not all indicators required for calculating the Energy Transition Index (ETI) based on the World Economic Forum framework were accessible at this spatial scale, several proxies were introduced to represent similar conceptual dimensions. The selection of these proxies was guided by their relevance to the original ETI constructs and the consistency of their measurement logic. The final set of indicators employed in this research is presented in table 1.

Table 1. Data and data sources in research.[a]

Indicator	Information	Direction	Data Source	Year
Proportion of the population with access to electricity	Ratio of households with access to electricity to total households	(+)	Susenas	2024
Proportion of families with clean fuel for cooking	Ratio of families using clean fuel for cooking	(+)	Podes	2024
Average household electricity expenditure (rupiah)	Average household expenditure on electricity per year	(-)	Susenas	2024
Average household gas expenditure (rupiah)	Average household expenditure on LPG, municipal gas, and biogas per year	(-)	Susenas	2024
Energy consumption per regency/ city	Total household energy converted to MJ divided by population	(-)	Susenas	2024
CO Concentration	The CO concentration value of Sentinel-5P	(-)	Sentinel -5P	2024
CH_4 Concentration	The CH_4 concentration value of Sentinel-5P	(-)	Sentinel -5P	2024

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Proportion of the use of village solar lights as clean energy consumption	The proportion of villages that use clean energy sources in energy consumption	(+)	Podes	2024
The proportion of village deliberation activities as policy stability	The proportion of villages with village deliberations and the existence of energy activity programs	(+)	Podes	2024
Proportion of KPP-E village credit access	Proportion of villages with access to Food and Energy Security Credit (KKP-E)	(+)	Podes	2024
Proportion of energy infrastructure activity programs to attract energy-related investment	The proportion of villages with NRE facilities such as solar PV, biogas, and microhydro	(+)	Podes	2024
Proportion of digital infrastructure readiness	Proportion of villages with computer, language, and electronics training facilities	(+)	Podes	2024
The proportion of jobs of most villagers in the low-carbon industrial sector	The proportion of villages with green economic activities according to the classification of certain sectors	(+)	Podes	2024
Human Development Index	BPS's official HDI which measures the dimensions of education, health, and living standards	(+)	BPS	2024

[a]World Economic Forum

2.2.3 Data preprocessing

Data preprocessing is carried out so that the data is ready for further analysis. For data taken from official statistics, preprocessing is carried out by processing raw data from Susenas and Podes as well as checking the missing value of the two data so that the data is ready for analysis. In the Podes data, processing is carried out by aggregating calculations, while in Susenas data, processing is carried out by aggregating the calculations needed and estimating population parameters. Data derived from Sentinel-5P satellite imagery will be taken in the period from January 1, 2024 to December 31, 2024. Furthermore, preprocessing of data is carried out which includes median reducing and clipping. Median reducing is done to take one image representation in each region that represents the collection of images from each pixel. The image is cut or clipped according to the boundaries of the research area to then extract features. The image data is integrated by utilizing zonal statistics. From the results of the median reduction, an average calculation was made at the regency/city level using zonal statistics. The data is then integrated with the official statistics data used.

2.2.4 Missing value imputation

Imputation on blank data is done by calculating the median of the same province so that the imputation results are more representative at the local level. There are only two indicators that have missing values, namely CH_4 concentration and average household gas expenditure and the amount of missing value is still below 5% so that the imputation with the median is carried out.

2.2.5 Data normalisation

After all variables are integrated, the indicator alignment is carried out in the form of indicator direction and indicator units as listed in table II. This alignment is carried out so that all indicators have the same direction as the formed index, where the greater the value of the indicator, the greater the value of the indicator, will increase or support the value of the index and vice versa. Variables that have a negative direction to the index are reversed by multiplying -1. Furthermore, to align the indicator units, data normalization or standardization is carried out using the Min-Max and Z-Score methods so that multivariate analysis of the data can be carried out. In the preparation of the OECD composite index, normalization of data is usually carried out before weighting, but because this study uses exploratory factor analysis, normalization is used before the data is analyzed so that all units are equal.

2.2.6 Exploratory factor analysis

Factor analysis is a widely used method to interpret multidimensional data by extracting latent factors from multivariate data and reducing the dimensions of the data [18]. This study uses the Exploratory Factor Analysis (EFA) because there is no standard theory regarding the number of factors and variables used. The stages in the factor analysis carried out are as follows.

a) Checking the Correlation and Sufficiency of Samples

   Before conducting a factor analysis, a data feasibility test is first carried out to ensure that the data is eligible for further analysis. This stage includes checking the correlation between variables and the adequacy of the number of samples. Correlation checking aims to assess the extent to which the variables in the research are interrelated and can be grouped into certain factors. Meanwhile, sample sufficiency tests are required to ensure that the amount of data used is sufficient to produce a valid analysis. Correlation tests were carried out using a correlation matrix and Bartlett's Test of Sphericity, while sample sufficiency tests were carried out using Kaiser-Meyer-Olkin (KMO) and Measure of Sampling Adequacy (MSA). To be able to proceed to the factor analysis stage, the results of the Bartlett test are needed which show that there is an adequate correlation between variables and the value of KMO and MSA, which is at least 0.6 for KMO and at least 0.5 for MSA [19].

b) Factor Extraction

   Factor extraction aims to identify and group a number of variables that have a relationship into one or several factors. This study uses the estimation method Principal Component Analysis (PCA). The first factor explains the largest variance, followed by the second factor, and so on. Only factors with an Eigenvalue ≥ 1 are considered significant and is retained for further interpretation. Value Eigenvalue shows the magnitude of the variance explained by each factor. If the value is less than 1, then the factor is considered insufficient to explain the variance and should be eliminated [20].

c) Rotation Factor

   Factor rotation is carried out to maximize loading variables on one particular factor and minimizes loading on other factors, making it easier to identify and name factors. The rotation method used in this study is Varimax rotation, which falls under the category of orthogonal rotation. This method maintains independence between factors and results in more interpretable rotation results [20].

d) Interpretation of Factor Results
The interpretation of the results of the factors is carried out based on the value factor loading, i.e. the correlation between variables and factors. Variables with higher loading of a single factor is interpreted as a group that represents a particular concept. Therefore, each factor is named according to the general characteristics of its constituent variables. This process is subjective, but it still needs to be logical and consistent with the theory used in the research [21].

2.2.7 Index weighting and aggregation

In this study, the unequal weighting method was employed, following the approach adopted in the formulation of the Indeks Pembangunan Desa by BPS and Bappenas. The weighting process was determined based on the loading factor values and the proportion of variance explained by each factor. This method was chosen to account for the varying contributions of each indicator to the overall Energy Transition Index, ensuring that indicators with stronger empirical associations exert greater influence on the composite score. Compared with the equal weighting approach, unequal weighting is considered more representative of the multidimensional structure of the energy transition, although potential bias arising from data-driven weights was also assessed to ensure robustness.

2.2.8 Evaluation of index results

In the process of compiling composite indexes, there is an element of uncertainty that can affect the final result and interpretation of the composite index. Uncertainty can come from various sources such as indicator selection, normalization methods, weighting, and aggregates used. Therefore, uncertainty analysis is an important step to evaluate the extent to which the index results are robust to changes in assumptions or parameters used [16]. In addition, it will also be carried out later face validity by comparing the results of the national index with the results of the index by the WEF.

In this study, uncertainty analysis was conducted by comparing Spearman correlations and the average changes in observation rankings across several scenarios. These scenarios combined different normalization, weighting, and aggregation methods to assess the robustness of the Energy Transition Index results. The selected combinations were chosen to represent a balance between methodological diversity and practical applicability, allowing the analysis to capture how variations in index construction techniques may influence the overall ranking outcomes.

1. Scenario 1: Min-max standardization, unequal weighting indicators, unequal weighting factors and linear aggregation.
2. Scenario 2: Standardization of z-score, unequal weighting indicator, unequal weighting factor and linear aggregation.
3. Scenario 3: Min-max standardization, unequal weighting indicators, equal weighting factors and linear aggregation.
4. Scenario 4: Min-max standardization, equal weighting indicators, equal weighting factors and linear aggregation.
5. Scenario 5: Min-max standardization, unequal weighting indicators, unequal weighting factors and geometric aggregation.

3. Result and Discussion

3.1 Indicator overview

There are as many as 14 indicators that build up the energy transition index which are grouped into 4 main dimensions based on references from the WEF ETI framework, namely fair, sustainable, regulatory and investment frameworks, and supporting factors before being grouped based on the results of factor analysis. The four dimensions are formed from two main aspects, namely system performance and transition readiness.

An overview of the variability and distribution of data on the indicators that build up the energy transition index in all regencies/cities in Indonesia can be seen in table 2. Overall, the characteristics of the indicators show a fairly high level of heterogeneity between regencies/cities. This level of heterogeneity is reflected not only in the magnitude of the standard deviation values in some indicators, but also in the distribution of data that shows asymmetrical patterns (skewed distribution), both in positive and negative directions. The extreme skewness value as in the indicator of the proportion of population electricity access (-5.218) or village credit access (13.075) indicates a significant disparity between regions, both in the form of adequate access and uneven concentration of development.

This indicates that achievements in terms of energy system performance and energy transition readiness have not been proportionately distributed. For example, the indicator of the proportion of the population with access to electricity which has an average value of 0.969 reflects that most areas have achieved almost full electrification, although there are some disadvantaged areas that are outliers. On the other hand, the proportion indicator of energy infrastructure activity programs only has an average value of 0.098, which shows that there is still a low initiative or infrastructure capacity to support clean energy investment at the local level. This imbalance is also seen in the digital infrastructure readiness indicator (average 0.119), which is one of the important supports in supporting technology-based energy transformation.

Table 2. Summary statistics of the indicators.

Variable	Average	Standard Deviation	Minimum	Median	Maximum	Skewness
Proportion of the population with access to electricity	0.969	0.109	0.142	0.998	1	-5.218
Proportion of families with clean fuel for cooking	0.752	0.366	0	0.942	1	-1.383
Average household electricity expenditure (thousand rupiah)	1686.145	103.302	103.348	1393.760	6604.684	1.878
Average household gas expenditure (thousand rupiah)	1022.696	755.068	300	722.792	5503.793	2.505
Energy consumption per regency/city	22811.967	7586.562	506.551	22.188	46.567	0.057
CO Concentration	0.028	3.02×10^{-3}	0.017	0.029	0.038	0.214
CH_4 Concentration	1868.620	22.217	1796.169	1870.933	1948.428	-0.549
Proportion of the use of village solar lights as clean energy consumption	0.384	0.233	0	0.339	0.971	0.571
The proportion of village deliberation activities as policy stability	0.955	0.102	0.122	0.986	1	-4.927

The proportion of village credit access includes KPP-E	0.022	0.503	0	0.011	1	13.075
Proportion of energy infrastructure activity programs to attract energy-related investment	0.098	0.094	0	0.078	0.993	3.969
Proportion of digital infrastructure readiness	0.119	0.118	0	0.083	0.630	1.807
The proportion of jobs of most villagers in the low-carbon industrial sector	0.737	0.305	0	0.884	1	-1.316
Human Development Index	71.919	6.288	36.3	71.685	88.770	-0.767

3.2 Determination of the factors that build up the energy transition index

By using a correlation matrix, relationships between variables can be identified more simply. Based on figure 1, it is known that each pair of variables has a different linear relationship. It can be concluded that there is a significant interdependence between indicators, showing the existence of several types of relationship patterns.

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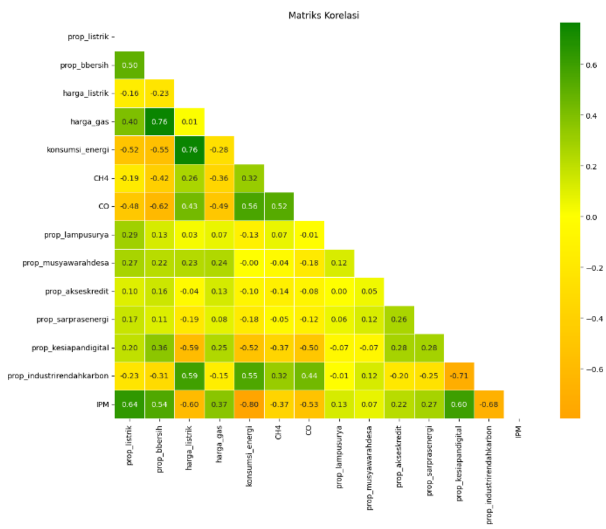

Figure 1. Indicator correlation matrix.

However, this correlation matrix only provides a preliminary picture of the research indicators. So to strengthen the information from the correlation matrix, the Bartlett test, the KMO test and the MSA test were carried out as several steps in factor analysis. The results of the Bartlett test showed that a statistical value of 3,972.641 was obtained, which means that at a significance level of 5%, it was concluded that there was enough evidence to reject so that there was a correlation between the variables used in the study. Furthermore, in the results of the KMO test, an overall KMO value of 0.80004 was obtained, which indicates that the data is adequate and feasible to continue in the processing stage of factor analysis because the correlation between the indicators that build up the energy transition index can be concluded strongly. Furthermore, the variable selection stage is carried out using the MSA test, variables with an MSA value of < 0.5 will be eliminated. However, after testing was carried out, it was found that until this stage no variables would be eliminated.

After it is proven that all indicators can proceed to the next stage of factor analysis, the analysis of the indicators is carried out. In the process of factor analysis, it was found that there was one variable, namely the proportion of village deliberation activities as policy stability which had a fairly low communality value, which was 0.487. The variable is not feasible if assessed from its communality value because it < 0.5. After the factor analysis, the variable exhibited a relatively low loading value (<0.5) and showed limited interpretability in relation to the extracted factors. Although the variable representing village deliberation may hold conceptual relevance as a proxy for policy stability, it was excluded to maintain statistical validity and ensure that each retained variable contributed meaningfully to the factor structure. The exclusion was therefore based on methodological considerations rather than theoretical disregard.

Therefore, the number of initial variables used to compile the index is as many as 14, then reduced to 13 variables that will be extracted into factors. The process of extracting factors is carried out using the PCA method. The first four factors have an eigenvalue of more than 1 so that the number of factors of 4 is chosen which maintains the variation of data with a cumulative value of variance of 72.503%. Furthermore, factor rotation is carried out using the varimax method so that the loading of the new factors that are formed will be maximized and the interpretation of factors will be easier to do based on values loading of indicators. Values loading This will be the basis of the scales for each dimension formed based on the new factor. Indicators which are grouped into new factors must meet the criteria, namely the value of loading of variables greater than 0.5 [18]. If there is a variable that meets the criteria on more than 1 factor, the variable with a value will be selected the largest loadings of these two factors.

Table 3. Factors that build up the energy transition index.

Factor	Variable	Loadings Factor	% of Var	BSI	BFU
Socio-Economic	Average household electricity expenditure	0.910	28.111	0.089	0.388
	Household energy consumption per regency/city	0.800		0.078	
	Proportion of digital infrastructure readiness	0.730		0.071	
	The proportion of jobs of most villagers in the low-carbon industrial sector	0.790		0.077	
	Human Development Index	0.740		0.072	
Energy Consumption and	Proportion of households with access to clean fuel for cooking	0.840	22.366	0.086	0.308

Environmental Impact	Average household gas consumption	0.880		0.090	
	CH_4	0.620		0.063	
	CO	0.680		0.069	
Access to Clean and Renewable Energy	Proportion of households with access to electricity	0.650	11.285	0.070	0.156
	Proportion of the use of village solar lights as clean energy consumption	0.800		0.086	
Investment and Finance	The proportion of village credit access includes KPP-E	0.820	10.742	0.079	0.148
	Proportion of energy infrastructure activity programs to attract energy-related investment	0.710		0.069	
Total			72.503	1.000	1.000

Based on table 3, there are four factors with each of the constituent indicators, where BSI is the Standard Indicator Weight and BFU is the General Factor Weight. Factor 1 (Socio-Economic) represents the social and economic capacity of a region. If the value in this factor is large enough, then the indicator tends to describe the characteristics of areas that have socio-economic capacity and energy system infrastructure that are relatively more advanced than other regions.

Factor 2 (Energy Consumption and Environmental Impact) specifically interprets the process of adopting clean fuels within the household scope and the environmental impact created so far. The relationship between indicators in this factor shows a relationship between clean energy access and local environmental conditions as measured through air pollutant concentrations.

Factor 3 (Access to Clean and Renewable Energy) is formed from two indicators that describe the form of accessibility to cleaner and more sustainable energy sources, namely the proportion of households with access to electricity and the proportion of the use of solar lights in villages as part of energy consumption at the local level. This factor captures electrification efforts at the regional level as well as renewable energy development initiatives by local governments.

Factor 4 (Investment and Finance) groups two indicators related to institutions and funding in supporting the development of the energy sector, namely the proportion of villages with access to KPP-E credit and the proportion of energy infrastructure activity programs where these two things are quite sustainable, an activity definitely requires investment, so that with the increase in investment value, the activities carried out will also increase.

Furthermore, to calculate the energy transition index, a factor score is calculated by multiplying the standardized weight by the normalized indicator value for each factor first, then linear aggregation is carried out. The weighted value shows the relative contribution of each indicator. All scores are summed up to form the following formula for calculating the energy transition index.

$$Indeks\ Transisi\ Energi = \qquad (1)$$

$$0.070x_1 + 0.086x_2 + 0.089x_3 + 0.090x_4 + 0.078x_5$$
$$+ 0.069x_6 + 0.063x_7 + 0.086x_8 + 0.079x_9$$
$$0.069x_{10} + 0.071x_{11} + 0.077x_{12} + 0.072x_{13}$$

with a caption:

x_1 = Proportion of the population with access to electricity
x_2 = Proportion of families with clean fuel for cooking
x_3 = Average household electricity expenditure (rupiah)
x_4 = Average household gas expenditure (rupiah)
x_5 = Energy consumption per regency/city
x_6 = CO concentration
x_7 = CH_4 concentration
x_8 = Proportion of the use of village solar lights as clean energy consumption
x_9 = The proportion of village credit access includes KPP-E
x_{10} = Proportion of energy infrastructure activity programs to attract energy-related investment
x_{11} = Proportion of digital infrastructure readiness
x_{12} = The proportion of jobs of most villagers in the low-carbon industrial sector
x_{13} = Human Development Index

Figure 2. Index mapping.

After the energy transition index is calculated based on the formula that has been formed, the index is classified with five categories, namely very low, low, medium, high, and very high using the natural break jenks categorization method so that mapping in all regencies/cities in Indonesia is obtained in figure 2 and the classification of the regency/city energy transition index in table 4.

Table 4. Classification of energy transition index results.

Classification	Index Value Range	Number of Regencies/Cities	Percentage (%)
Very Low	index < 0.458	46	8.949
Low	0.458 ≤ index < 0.508	84	16.342
Medium	0.508 ≤ index < 0.553	129	25.097
High	0.553 ≤ index < 0.590	161	31.323
Very High	> index 0.590	94	18.288

The Energy Transition Index (ETI) distribution map visually represents significant spatial disparities in energy system performance and energy transition readiness throughout Indonesia. In general, a clear

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geographical pattern was identified, where index values tended to be highly concentrated in the western part of Indonesia, especially the island of Java, and gradually declined towards the eastern region. This gap indicates that the spatial variation in the energy transition index is likely associated with differences in economic development levels and infrastructure availability across regions.

Based on the mapping, it can be detailed that the island of Java is dominated by the value of the energy transition index with high and very high categories. This is certainly inseparable from the concentration of energy infrastructure, the economy, as well as the readiness of technology and digitalization more evenly in this region. Provinces such as West Java, Central Java, and East Java show superior energy transition index values. However, areas on the southern coast and the western or eastern tip of Java showed slightly lower performance. This can show that there are still limitations in infrastructure and regional fiscal capacity, so that even on the same island, there are still inequalities in the transition index, which reflect the progress of energy system performance and energy transition readiness in these various regions.

The islands of Sumatra and Kalimantan also showed quite good achievements with the dominance of the medium to high index category, especially in provinces such as Riau, South Sumatra, and East Kalimantan. This can be driven by the availability of energy resources and relatively good basic infrastructure. However, inequality between regency is still visible, especially in coastal or inland areas, which show a low or even very low index category. This phenomenon indicates that the existence of energy resources alone is not enough without inclusive energy governance and equitable access to technology that supports the transition to a sustainable energy system.

On the other hand, Sulawesi Island shows significant diversity between regencies/cities, with the dominance of the medium index category, as well as a number of areas in South and Southeast Sulawesi that are included in the high index category. This shows positive dynamics in some regions, but also indicates that there are still challenges in realizing a comprehensive energy transition on the island, especially in the central and northern regions.

Meanwhile, the eastern region of Indonesia, especially the Maluku, Papua, and most of East Nusa Tenggara, is dominated by the low to very low index category. This achievement indicates serious challenges in terms of energy access, basic infrastructure, and digital readiness, which are important prerequisites for the energy transition. These regions still face limitations in terms of adequate energy system performance to drive readiness for a cleaner and more sustainable energy transition. Thus, this can be a reference for the government to strengthen the urgency of affirmative policies for eastern and disadvantaged regions in supporting the development of a fair, resilient, and sustainable national energy system and in accordance with all applicable regulations, both nationally and globally.

3.3 Evaluation of index results

In this study, uncertainty analysis was carried out by changing the input factors in the form of the type of normalization, the type of weighting, and the type of aggregation in each scenario to be used. Measurement of uncertainty using correlation rank-spearman and the average change in ranking between the scenarios compiled. Scenarios that have a large correlation value on each other pair as well as a low average ranking change are the most stable and robust [22].

Table 5. Mean Spearman correlation and change in rank between scenarios.

Variable	Spearman Correlation Average	Average Ranking Change
Scenario 1	0.885	42.576
Scenario 2	0.861	51.938
Scenario 3	0.859	50.232
Scenario 4	0.881	43.233
Scenario 5	0.636	101.029

Based on table 5, it can be seen that scenario 1 has a strong average correlation with other scenarios. Furthermore, the consistency of the index can be seen from the change in the average rating between scenarios with a value range between 42.576 to 101.029 where scenario 1 has the lowest average change in rating compared to the other 5 scenarios. Therefore, Scenario 1 is identified as the most robust and consistent among the tested scenarios. This configuration applies min–max normalization and unequal weighting for both indicators and factors, which allows each variable's contribution to be proportionally represented according to its empirical significance while preserving the original data distribution. This approach enhances comparability across regions and ensures that differences in indicator scales do not distort the composite index. The selection of this scenario is consistent with previous studies on composite index construction [17], which emphasize the importance of normalization and weighting strategies that maintain interpretability and data integrity.

The validation of the energy transition index compiled in this study was carried out by comparing the results of the aggregation of regency/city scores nationally with the ETI scores released by the WEF. This step is carried out as a form of face validity or plausibility check, which aims to assess the fairness of the results of the index calculation through comparison with widely recognized global data sources. This approach is commonly used in the preparation of composite indices, as it is not always possible to perform conventional validation tests such as reliability or predictive validation [23]. Therefore, the conformity of the national index value of the research results with the WEF ETI index can be seen as an indication that the construction of the developed index is on the methodologically correct track.

The calculation results show that the national score of the Indonesian Energy Transition Index obtained from the aggregation of all regencies/cities is 54.3 (on a scale of 0 – 100), while the score of the WEF version of the ETI Indonesia in 2024 is recorded at 56.7 [12]. This difference of 2.4 points can be considered relatively small and within the reasonable range, given the difference in methodology used. The index developed in this study is calculated using a bottom-up approach, which is to measure from the smallest unit (regency/city) and then aggregate it to the national level. In contrast, the WEF ETI index is top-down, using national macro data and indicators sourced from international institutions. This difference in measurement scale is what causes the variation in values, although in general the pattern of results remains consistent. The value of the WEF Indonesia index is still within the range of the energy transition index calculated in this study.

4. Conclusion

Based on the results and discussion in the previous section, several things can be concluded as follows.

1. Descriptive statistical analysis of the initial 14 indicators revealed significant spatial heterogeneity in almost all observation areas. This is confirmed by the high variability of the data, which is indicated by the large standard deviation, as well as the distribution of the data that is mostly very asymmetrical (having extreme skewness values). This pattern indicates a spatial disparity, where the performance of basic energy systems (such as access to electricity) has reached good levels, but readiness for the transition to sustainable energy (measured by access to clean fuels and energy infrastructure) is still at a formative and highly concentrated stage.

2. The preparation of the Energy Transition Index is carried out through an exploratory factor analysis approach after its validity is confirmed through Bartlett, MSA, and KMO tests. Through this process, the initial 14 indicators were reduced to 13 after one variable, namely the proportion of village deliberations as policy stability, was eliminated due to the low value of communality and loading factor. Furthermore, the remaining 13 indicators were successfully extracted into four main factors that cumulatively were able to explain 72.503% of the total variation in the data. The four factors are (1) Socio-Economic, (2) Energy Consumption and Environmental Impact, (3) Access to Clean and Renewable Energy, and (4) Investment and Finance. The energy transition index is then constructed with unequal weighting of standardized indicator scores based on the weights generated by PCA and linear aggregation. After the energy transition index was formed, it was found that there was an imbalance in the classification of the index in all regencies/cities with the average high classified index value in the western region of Indonesia and the average low classified index value in the eastern region of Indonesia.
3. Uncertainty analysis was conducted to test the robustness of the index methodology by comparing the results of five different methodological scenarios. Based on the evaluation using the rank-Spearman correlation coefficient and the average change in rank, it was found that scenario 1 showed the highest level of stability compared to the other 4 scenarios. This is evidenced by the highest average value of Spearman correlation (0.885) and the lowest average value of rank change (42.576) compared to other scenarios. From the results of face validity, the fairness of the comparison of the value between the index in this study and the index in the reference for its preparation was obtained, namely the WEF ETI. This confirms that the conceptual and methodological framework chosen to build this index is the most consistent.

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