Decision Science Letters 14 (2025) ***–***

Contents lists available at GrowingScience

Decision Science Letters

homepage: www.GrowingScience.com/dsl

Multi-criteria analysis of renewable energy alternatives in southwest Sumba using TOPSIS method with 5C framework

Hamzah[a*], Retno Martanti Endah Lestari[a], Hendro Sasongko[a], Heirunissa[b] and Daud Obed Bekak[c]

[a]*Faculty of Economics and Business, Pakuan University, Bogor, Indonesia*
[b]*Faculty of Economics and Business, STIE GICI, Bogor, Indonesia*
[c]*Politeknik Negeri Kupang, Indonesia*

C H R O N I C L E

Article history:
Received: October 14, 2024
Received in revised format: November 27, 2024
Accepted: February 21 2025
Available online: February 21, 2025

Keywords:
Energy Security
Renewable Energy
Solar Energy
Sustainable Development
TOPSIS

A B S T R A C T

Renewable energy development is important for improving energy security and economic growth in Indonesia. This study identifies the best renewable energy potential in Southwest Sumba, East Nusa Tenggara Province, using the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method based on 5C criteria: Consolidated, Controllable, Continue, Clean, and Cheap. The research uses a multi-criteria decision-making approach, using primary data from expert interviews and secondary data from literature reviews. The TOPSIS analysis shows that solar energy has the highest preference value, followed by bioenergy and hydropower. Technical assessments show important implementation requirements for each renewable energy option. The study recommends prioritizing solar energy development, supporting bioenergy projects, improving micro-hydro facilities, and creating clear renewable energy policies. Success depends on cooperation between stakeholders and aligning renewable energy development with regional sustainability and community needs. These efforts can help Southwest Sumba develop its renewable energy sector and contribute to national energy security goals.

1. Introduction

Energy is a vital element in human life, playing a crucial role in various activities such as lighting, transport, industry and households. The availability of sufficient and sustainable energy is a strategic priority for every country as it directly contributes to economic growth and people's welfare. The Central Bureau of Statistics (2024) states that there is a positive correlation between a country's Gross Domestic Product (GDP) growth and energy availability per capita. Globally, attention to renewable energy is increasing in line with growing energy needs and pressing environmental issues. According to Databoks (2023), China leads with the world's largest renewable energy capacity in 2022, followed by the United States, Brazil and India. This reflects the global trend towards cleaner and more sustainable energy use. Indonesia, as an archipelago with a tropical climate, has enormous renewable energy potential. According to the Secretary General of the National Energy Council (2023), Indonesia's total renewable energy potential reaches 3,643 GW, but only about 0.3% or 11.6 GW of the total potential is utilised. This potential includes solar, wind, hydro, bioenergy, geothermal and ocean energy as shown in Table 1. Despite this, there are still significant gaps in renewable energy utilisation in Indonesia, especially in the central and eastern regions. Sumba Island, particularly Southwest Sumba Regency in East Nusa Tenggara (NTT) Province, is an example of an area with limited access to electrical energy. According to NTT Central Bureau of Statistics (2022), the electrification ratio in Southwest Sumba only reaches 43.89%, far below the national average. This condition has an impact on the limited economic and social activities of the local community. Efforts to increase the

* Corresponding author.
E-mail address hamzah.fe@unpak.ac.id (Hamzah)

ISSN 1929-5812 (Online) - ISSN 1929-5804 (Print)

doi: 10.5267/j.dsl.2025.2.002

electrification ratio are a serious challenge that requires strategic and sustainable solutions. Renewable energy development in Southwest Sumba has great potential to improve energy security and encourage green economic development. The green economy concept offers a development approach that integrates economic growth with environmental sustainability. Studies by Tiawon and Miar (2023) show that renewable energy production and energy efficiency in Indonesia contribute positively to sustainable economic growth and carbon emission reduction, making renewable energy an important element in achieving sustainable economic development. Another study by Surya et al. (2021) also confirmed that renewable energy utilization in the Mamminasata Metropolitan area contributes to improved economic productivity and environmental quality, demonstrating the importance of renewable energy management strategies for sustainable urban development.

Table 1
Indonesian's Renewable Energy Potential

Renewable Energy Commodities	Total Potential (GW)	Installed Capacity (GW)	Utilisation Percentage (%)
Solar	3.294.0	0.2	0.01
Wind	154.9	0.2	0.1
Hydro	95.0	6.6	7.0
Bioenergy	56.9	2.3	4.0
Geothermal	23.9	2.3	9.6
Ocean	17.9	-	-
Total	3.643.0	11.6	0.3

Source: OEI 2023

In addition, renewable energy development efforts in Indonesia include addressing technological and governance challenges to reduce barriers to low carbon development (Sambodo et al., 2022). Renewable energy utilisation is also identified as an important element in supporting economic sustainability in the ASEAN region, including Indonesia, which helps to reduce the ecological footprint and improve long-term environmental well-being (Zeraibi et al., 2021). However, renewable energy development in Indonesia faces several key challenges, including limited infrastructure, technology affordability, lack of socialisation, and suboptimal institutional models. Recent studies identify specific barriers to renewable energy implementation. Sambodo et al. (2022) highlighted the lack of infrastructure support, such as smart power grids and technical capacity in renewable energy project management, as well as limited capital and investment for the development of related technologies. Institutional and political factors also play a significant role in hindering the implementation of renewable energy projects. Guild (2020) observed that available incentives are often not aligned with local needs and are less effective in supporting long-term development. This points to the need for policy evaluation and adjustment that is more responsive to the local context. To address these challenges, Sulaeman et al. (2021) proposed a more comprehensive and systematic approach in determining renewable energy sources. This approach should consider local characteristics, taking into account technical, economic, social and institutional aspects holistically. The implementation of such a strategy could improve the effectiveness and sustainability of renewable energy projects in Indonesia. This research aims to identify the best renewable energy potential in Southwest Sumba using the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method based on 5C criteria: Consolidated, Controllable, Continue, Clean, and Cheap. This approach allows an objective evaluation of various alternative renewable energy sources, so as to identify the most suitable option according to local needs and conditions. The results of this research are expected to provide strategic recommendations for local governments and other stakeholders in formulating effective and efficient renewable energy development policies and strategies in Southwest Sumba. In addition, this research also contributes to efforts to increase the electrification ratio, energy security, and support sustainable green economic development in the region.

2. Literature review

2.1 Renewable energy

Renewable energy encompasses several types of energy sources that each have unique characteristics and potential in the global effort to reduce dependence on fossil fuels and mitigate climate change. Solar energy is one of the most abundant and clean renewable energy sources. It utilises photovoltaic (PV) panels or concentrated solar power (CSP) systems to convert sunlight into electricity (Pérez-Cutiño et al., 2022). The main advantages of solar energy include its low environmental impact, its decentralised nature, and its ability to generate electricity in remote areas (Terrén-Serrano & Martínez-Ramón, 2021). However, solar energy also faces challenges such as intermittency, the need for energy storage, and extensive land requirements for utility-scale projects (Abid et al., 2023). Wind energy has been rapidly growing as a renewable energy source. It uses wind turbines to capture kinetic energy from moving air and convert it into electricity (Sarkar & Fitzgerald, 2022). Wind energy offers the advantages of low greenhouse gas emissions, relatively small land requirements, and the potential for offshore wind farm development (Shouman, 2020). However, wind energy also faces challenges such as intermittency, noise pollution, and potential impacts on wildlife, especially birds and bats (Kumar, 2020). Biofuels are renewable fuels produced from biomass, such as plants, algae, or organic waste. The two most common types of biofuels are bioethanol and biodiesel, which are produced from sugar and starch crops and vegetable oils and animal fats (Teh et al., 2021; Singh & Satapathy, 2018). Biofuels have the potential to reduce greenhouse gas emissions in the transport sector (Medina & Magalhães Jr, 2021). However, the sustainability of biofuels is still debated as their production can compete with food production, cause deforestation, and have other environmental impacts.

Bioenergy or biomass energy is a form of renewable energy derived from organic materials such as plants, agricultural waste, and municipal solid waste (Nath, 2024). Biomass can be burned directly to produce heat or converted into biofuels such as biogas or syngas for electricity generation or transport fuels (Huerta-Reynoso et al., 2019). The sustainability of bioenergy depends on factors such as land use, feedstock production, and efficiency of conversion technologies (Kluts et al., 2017). Proper management of biomass resources and development of advanced conversion technologies are essential to maximize the benefits of bioenergy while minimizing its environmental impacts (Garba, 2021). Hydropower is an established form of renewable energy that utilizes the energy of falling or flowing water to generate electricity. It is the world's largest renewable electricity source, accounting for approximately 16% of global electricity production in 2020 (Schroeder et al., 2023). Hydropower plants vary from large-scale dams to small river installations, offering the advantages of reliability, flexibility and low operational costs (Siciliano, 2023). However, hydropower projects can also have significant environmental and social impacts, such as changes to river ecosystems, community displacement, and in some cases, greenhouse gas emissions from reservoirs (Xu et al., 2023). Each of these renewable energy types has an important role to play in the transition to a more sustainable energy system. While each faces specific challenges, the development and integration of these different renewable energy sources can significantly reduce dependence on fossil fuels and contribute to climate change mitigation. Continued research, technological innovation and supportive policies are essential to overcome the existing challenges and maximize the potential of renewable energy in the future.

2.2 Renewable Energy Criteria

Renewable energy development requires a comprehensive and systematic approach to ensure its sustainability and effectiveness. In this context, the 5C criteria (Consolidated, Controllable, Continue, Clean, Cheap) emerge as a holistic evaluation framework to assess and select the most suitable renewable energy sources. Each criterion in the 5Cs framework plays an important role in ensuring seamless integration, operational efficiency, and long-term sustainability of renewable energy sources. The 'Consolidated' criterion emphasizes the importance of effective integration between renewable energy sources and existing electricity infrastructure to maintain grid stability, especially given the intermittent nature of sources such as wind and solar. Worighi et al. (2019) revealed that smart grid technology requires proper coordination between renewable energy generation, energy storage systems (ESS), and the electricity grid to handle fluctuations in energy from renewable sources. Yelmanchli (2018) added that the integration of information and communication technology (ICT) in smart grids can improve grid efficiency and stability, especially in managing renewable energy variability. The 'Controllable' criterion refers to the flexibility of the energy source to be regulated according to demand. Energy storage technologies, as discussed by Tephiruk et al. (2022), and hybrid energy management strategies can help improve the stability and efficiency of renewable energy use. By combining batteries and supercapacitors, these storage systems enable rapid response to load changes, as well as keeping the energy supply stable amid fluctuations in generated energy (Tephiruk et al., 2022). Meanwhile, the 'Continue' criterion emphasizes the importance of long-term reliability. The study by Guezgouz et al. (2019) shows that hybrid storage technologies, such as pumped hydro and batteries, can improve long-term reliability and reduce system costs, making them an important solution in ensuring the continuity of renewable energy supply in the future. The 'Clean' aspect of renewable energy is crucial in global efforts to reduce greenhouse gas emissions and combat climate change. The use of renewable energy, such as solar and wind energy, is proven to be significant in reducing carbon emissions when compared to the use of fossil fuels. Research by Mittal et al. (2016) shows that increasing the penetration of renewable energy in the primary energy mix of countries such as China and India can effectively lower greenhouse gas emissions and reduce climate change mitigation costs. Furthermore, the 'Cheap' criterion ensures that renewable energy can be widely and rapidly adopted. Technologies such as smart networks have proven effective in lowering operational costs and improving energy efficiency. According to research by Worighi et al. (2019), smart networks enable more efficient energy management through the integration of renewable energy sources, which results in reduced costs and improved grid stability. By considering these five criteria together, developers and policy makers can make more informed and effective decisions in selecting and implementing renewable energy sources. The 5Cs approach ensures that renewable energy solutions are not only environmentally friendly but also reliable, efficient and economically sustainable in the long run.

3. Materials and method

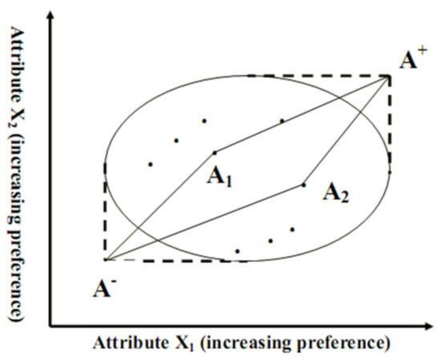
This research was conducted in Southwest Sumba from May to August 2024. The research design used a multi-criteria decision making (MCDM) approach with the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) analysis tool.

3.1 Data collection

The data used consisted of primary and secondary data. Primary data was obtained through in-depth interviews and focus group discussions (FGDs) with experts or key persons related to renewable energy and regional development. Interviews were conducted by purposive sampling using closed and open-ended questionnaires. The number of experts/practitioners interviewed was 9 people, including representatives of the Energy and Mineral Resources Agency (1 person), academics in renewable energy (2 people), renewable energy practitioners (2 people), community leaders (1 person), representatives of environmental NGOs (1 person), local government representatives (1 person), and energy policy experts (1 person). Secondary data was collected through literature studies, government reports, and data from relevant institutions. The research was also supported by various literatures to obtain theoretical basis on renewable energy and multi-criteria decision making.

3.2 Technique for Order Preference by Similaryty to Ideal Solution (TOPSIS)

The TOPSIS method was first developed by Hwang and Yoon (1981). Its basic concept is that the chosen alternative should have the shortest distance from the ideal solution and the farthest from the negative-ideal solution (Fig. 1).



(Source: Georgiadis et al., 2013; Balioti et al., 2018)

Fig. 1. Basic concept of TOPSIS method (A+: Ideal point, A- : Negative- Ideal Point).

The TOPSIS method is used to evaluate and rank renewable energy alternatives. The steps in the TOPSIS method are as follows:

Construct a normalized decision matrix:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \quad i = 1,2,\dots,n \quad j = 1,2,\dots.,n$$

Construct the weighted normalized decision matrix:

$$v_{ij} = w_j \times r_{ij}$$

Determine the positive ideal solution (A*) and negative ideal solution (A-):

A* = {(max v_{ij} | j ∈ J), (min v_{ij} | j ∈ J') | i = 1, 2, ..., m} A- = {(min v_{ij} | j ∈ J),

(max v_{ij} | j ∈ J') | i = 1, 2, ..., m}

Fig. 1 illustrates the concept of ideal solutions in multi-criteria decision making, where A+ represents the positive ideal solution comprising the best performance values, while A- represents the negative ideal solution comprising the worst performance values. Between these points, alternatives (such as A_1 and A_2) can be evaluated based on their relative positions in the criteria space.

Calculate the separation measures for each alternative:

$$D^* = \sqrt{\left(\sum_{j=1}^{n} (v_{ij} - v_i^*)\right)^2} \;, i = 1,2,\dots..m, j = 1,2,\dots,n$$

$$D^- = \sqrt{\left(\sum_{j=1}^{n} (v_{ij} - v_i^-)\right)^2} \;, i = 1,2,\dots..m, j = 1,2,\dots,n$$

Calculate the relative closeness to the ideal solution Ci

$$C_i = D_i\text{-} / (D_i^* + D_i\text{-})$$

The data used in the TOPSIS method is obtained from interviews with experts using a questionnaire. The questionnaire is designed to assess the weight of criteria (w_j) and alternative values on each criterion (x_{ij}). The results of the TOPSIS calculation will show the priority of alternative renewable energy solutions in Southwest Sumba based on the preference value (C_i) obtained. To validate the results, a forum group discussion (FGD) was conducted as a form of face validity with experts, practitioners, and relevant stakeholders.

4. Results

4.1 Selection Criteria Best Renewable Energy Potential in Southwest Sumba

The development of renewable energy requires a comprehensive and systematic approach to ensure its sustainability and effectiveness. In this context, the 5C criteria (Consolidated, Controllable, Continue, Clean, Cheap) emerge as a holistic evaluation framework for assessing and selecting appropriate renewable energy sources. Each criterion within the 5C framework plays a crucial role in ensuring seamless integration, operational efficiency, and long-term sustainability.

Consolidated

The Consolidated criterion emphasizes integrating renewable energy technologies with existing power grids for a more stable and resilient system. Integration of renewable sources (solar, wind, hydropower) with energy storage solutions enables better energy flow management to address generation variability. Hybrid systems combining solar and wind energy provide more reliable output than single sources, improving system stability and efficiency (Hassan et al., 2023). Smart grid technologies with real-time monitoring and automated control systems facilitate efficient energy distribution and adaptation to generation and demand fluctuations across local and national grids (Khalid, 2024). This consolidation optimizes energy usage and enhances overall network resilience, making it more adaptive and cost-efficient while promoting stability, sustainability, and operational efficiency.

Controllable

The controllable criteria in renewable energy systems focus on managing operational parameters for efficient and sustainable performance. Energy optimization maximizes renewable outputs by adjusting operations to accommodate resource fluctuations. In distributed systems, performance evaluation combines energy production and cost metrics, with cost-effectiveness control being crucial for balancing capital and operational expenses (Osman et al., 2024). Environmental impact assessment integrates sustainability metrics and efficiency optimization, with systems evaluated on production capacity and conversion efficiency (Majhi & Mohanty, 2024). In hybrid configurations, power flow management employs controllable criteria for demand response while maintaining stability. Advanced algorithms enable optimal monitoring to ensure efficient utilization while minimizing inefficiencies (Khadem, 2019). These controllable criteria facilitate parameter optimization to enhance performance, optimize costs, and reduce environmental impacts.

Continue

The continuity criterion in renewable energy systems focuses on maintaining reliable and uninterrupted energy supply. Hybrid systems with energy storage help maintain operational continuity by storing energy during peak generation for use during low output periods (Ling & Mulani, 2024). Hydropower, wind, and geothermal show better continuous service capability than solar due to more stable generation profiles (Cuviello, 2024). Advanced decision support frameworks help identify technologies that optimize efficiency and environmental performance while maintaining consistent supply (Mathu, 2023). This criterion ensures stable energy provision critical for grid reliability and sustained demand satisfaction.

Clean

The "clean" criterion evaluates renewable energy systems based on sustainability metrics and environmental impacts, incorporating pollution indices, resource efficiency, and ecological footprint assessment. Using Multi-Criteria Decision-Making (MCDM) methodologies, Dincer and Acar (2015) found nuclear energy systems optimal in technical and economic criteria, while geothermal systems performed best when considering comprehensive pollution parameters. Ghenai et al. (2020) identified wind energy and solid oxide fuel cells as top performers in sustainability metrics. Regional analysis in Jiangsu, China by Zhang et al. (2015) ranked solar PV as optimal, followed by wind, biomass, and nuclear technologies. Troldborg et al. (2014) emphasized the importance of incorporating uncertainty analysis in clean energy assessment. The criterion requires multi-dimensional evaluation using MCDM and Life Cycle Analysis for evidence-based implementation decisions.

Cheap

The "cheap" criterion focuses on cost-effectiveness and economic viability of renewable energy systems. Dranka et al. (2020) showed that energy efficiency measures in Brazil reduced system costs by 7.7% while cutting CO2 emissions by 4.3%. Shrimali et al. (2016) found that long-term, reduced-cost debt policies were more cost-effective than accelerated depreciation for solar and wind energy implementation in India. Cantore et al. (2016) demonstrated positive correlation between renewable energy adoption and employment creation in African contexts, with improved cost-effectiveness at larger implementation scales. By considering these five criteria together, developers and policymakers can make more informed and effective decisions in selecting and implementing renewable energy sources. The 5C approach ensures that renewable energy solutions are not only environmentally friendly but also reliable, efficient, and economically sustainable in the long term.

4.2 Analysis of the Best Renewable Energy Potential Selection in Southwest Sumba

Southwest Sumba has a fairly high potential for renewable energy, consisting of solar, wind, microhydro and biomass energy. However, the utilisation of renewable energy potential to strengthen energy security in this region is still low. The low utilisation of renewable energy is due to several things, including the low affordability of the community, because most people in Southwest Sumba are middle to lower class people. Access to renewable energy technology is also still difficult for some people in Southwest Sumba, due to the lack of socialisation and promotion of renewable energy utilisation. Supporting infrastructure such as energy distribution facilities and electricity networks are one of the factors for the low utilisation of renewable energy in Southwest Sumba, and the non-optimal institutional model makes it difficult to develop renewable energy. The results of determining weights on aspects of renewable energy development based on regional potential and indicator weights with the Eckenrode method are used as criteria and weights to assess each renewable energy potential in Southwest Sumba. The calculation of the weight of each renewable energy development criterion/indicator based on the Eckenrode method commonly used in MCDM is the most important part of the TOPSIS process. The aspects assessed in this study are the potential of renewable energy resources based on Clean (efficiency of energy utilization, environmental friendliness, positive impact, environmental carrying capacity, ideal energy mix), Consolidated (ease of access, availability of experts, quality of supply, local industry support, infrastructure), Continue (resource availability, weather resistance, operational continuity, policy support, investment support), Controllable (energy management, stable supply, storage ability, electricity needs compliance, environmental carrying capacity), and Cheap (development costs, operational costs, maintenance costs, future cost reduction, purchasing power).

Determine Positive Ideal Solution (A+) and Negative Ideal Solution (A)-

Based on the results of determining the weight of renewable energy development aspects with the Eckenrode method, the criteria used must fulfil positive and negative criteria according to the absolute requirements of the TOPSIS method. The highest weights are Clean (0.320), Controllable (0.280), Continue (0.190), Consolidated (0.150), and Cheap (0.060). There are 5 criteria and 25 sub-criteria used in the assessment, with a total weight of 1.000 (Table 1).

Table 1
Weighting Aspects of Selecting The Best Renewable Energy

Aspects	Indicators	Sub-Criteria Weight	Weight
Clean	Efficiency of energy utilisation by the community	0.058	0.320
	Environmentally friendly because it does not produce pollution. especially CO2	0.006	
	Energy utilisation that has a positive impact on society and the environment	0.064	
	Environmental carrying capacity/land use	0.099	
	Achieving the ideal energy mix by reducing the negative impact of waste on the en-	0.093	
Consolidated	Ease of community access to sustainable energy	0.039	0.150
	Availability of sustainable energy experts and technicians	0.017	
	Improved quality of sustainable energy supply	0.027	
	Support local industries in securing sustainable energy	0.035	
	Infrastructure supporting accessibility in obtaining sustainable energy	0.033	
Continue	Long-term resource availability	0.040	0.190
	Resistance to weather changes	0.030	
	Ability to continue operating without interruption	0.059	
	Government policy support for sustainable energy provision	0.025	
	Business capital investment support in energy supply	0.036	
Controllable	Ease of managing the amount of sustainable energy produced	0.039	0.280
	Stable. sustainable energy supply has a positive impact on society and the environ-	0.067	
	Ability to store energy for the long term	0.092	
	Compliance with people's daily electricity needs	0.053	
	Environmental carrying capacity for green economy development	0.028	
Cheap	Early development costs of sustainable energy for green economy development	0.012	0.060
	Daily operational cost of sustainable energy for green economy development	0.012	
	Sustainable energy maintenance costs for green economy development	0.012	
	Potential future cost reductions	0.013	
	People's purchasing power in obtaining energy	0.011	

It is important to note that there is one criterion that could be considered negative, namely Cheap, as lower costs may indicate less advanced technology or lower quality. However, in the context of renewable energy development in lower-middle economic areas, affordability remains an important factor to consider in the TOPSIS analysis. The 25 subcriteria of the 5C framework are a novelty in determining priority new and renewable energy that can be developed in a certain area or zone or area based on the potential of its natural resources. These criteria are used by experts to determine the priority renewable energy that will be developed using the TOPSIS method.

Creating a Decision Matrix

The decision matrix was created based on the justification of 5 experts using the TOPSIS questionnaire instrument. The final value processed is the mode value and squared to produce a normalised squared matrix (Table 2 and Table 3).

Table 2
Decision Rij Matrix Selection Of The Best Renewable Energy

ASPECT	Matrix rij Types of natural resources produced						Weight
	Ocean	Bioenergy	Hydro	Geothermal	Wind	Solar	
Clean	1.338	2.391	2.158	1.140	1.899	2.709	0.320
Consolidated	1.394	2.568	2.201	1.247	1.833	2.568	0.150
Continue	1.202	2.318	2.080	1.753	1.920	2.636	0.190
Controllable	1.520	2.457	2.299	1.449	1.611	2.544	0.280
Cheap	2.068	1.622	1.958	2.201	2.044	1.970	0.060

Table 3
Matrix Vij Best Renewable Energy Selection Decision In Southwest Sumba

ASPECT	Matrix vij Types of natural resources produced					
	Ocean	Bioenergy	Hydro	Geothermal	Wind	Solar
Clean	0.099	0.152	0.133	0.074	0.125	0.170
Consolidated	0.041	0.077	0.066	0.038	0.055	0.077
Continue	0.046	0.087	0.079	0.066	0.075	0.100
Controllable	0.083	0.139	0.127	0.079	0.090	0.145
Cheap	0.025	0.019	0.024	0.026	0.025	0.024

Calculating the S+ and S- Values of Each Element

The next step is to determine the distance between the value of each alternative and the positive (S+) and negative (S-) ideal solution matrix.

Table 4
Calculation Of Positive Ideal Solution (A+) Selection Of The Best Renewable Energy In Southwest Sumba

ASPECT	Types of natural resources produced						Weight
	Ocean	Bioenergy	Hydro	Geothermal	Wind	Solar	
Clean	0.099	0.152	0.133	0.074	0.125	0.170	0.170
Consolidated	0.041	0.077	0.066	0.038	0.055	0.077	0.077
Continue	0.046	0.087	0.079	0.066	0.075	0.100	0.100
Controllable	0.083	0.139	0.127	0.079	0.090	0.145	0.150
Cheap	0.025	0.019	0.024	0.026	0.025	0.024	0.020

Solar energy shows the best performance in most of the positive criteria, with the highest values in Clean (0.170), Consolidated (0.077), Continue (0.100), and the second highest value in Controllable (0.145). Bioenergy also performed well, especially in the Consolidated and Controllable aspects, where it scored on par with solar energy. Hydro energy consistently ranked third in most aspects (Table 5). For the negative criterion Cheap, the positive ideal value (A+) is 0.020, which is the lowest value. Bioenergy has the lowest value of 0.019, indicating that it is the cheapest option. It is followed by solar and hydro energy with a value of 0.024, then wind with 0.025. Geothermal energy has the highest value (0.026) for the Cheap criterion, meaning it is the least desirable in terms of cost (Table 5).

Table 5
Calculation Of Negative Ideal Solution (A-) Selection Of The Best Renewable Energy In Southwest Sumba

ASPECT	Types of natural resources produced						Weight
	Ocean	Bioenergy	Hydro	Geothermal	Wind	Solar	
Clean	0.099	0.152	0.133	0.074	0.125	0.170	0.068
Consolidated	0.041	0.077	0.066	0.038	0.055	0.077	0.038
Continue	0.046	0.087	0.079	0.066	0.075	0.100	0.046
Controllable	0.083	0.139	0.127	0.079	0.090	0.145	0.075
Cheap	0.025	0.019	0.024	0.026	0.025	0.024	0.026

The calculation of the positive ideal solution matrix (S+) shows that solar energy has the lowest total value (0.00004), closest to the positive ideal solution, while geothermal energy has the highest total value (0.00433), furthest from the positive ideal solution. The order of preference based on proximity to the positive ideal solution is: Solar > Bioenergy > Hydro > Wind > Ocean > Geothermal (Table 6).

Table 6
Positive Ideal Solution Matrix (S+) Selection Of The Best Renewable Energy In Southwest Sumba

ASPECT	S+ Types of natural resources produced					
	Ocean	Bioenergy	Hydro	Geothermal	Wind	Solar
Clean	0.00144	0.00010	0.00039	0.00228	0.00062	0.00000
Consolidated	0.00029	0.00000	0.00003	0.00034	0.00011	0.00000
Continue	0.00062	0.00005	0.00011	0.00025	0.00015	0.00000
Controllable	0.00132	0.00007	0.00027	0.00142	0.00094	0.00003
Cheap	0.00005	0.00000	0.00001	0.00004	0.00003	0.00001
∑	0.00373	0.00022	0.00081	0.00433	0.00184	0.00004

The results of the calculation of the negative ideal solution matrix (S-) show that solar energy has the highest total value (0.00497), furthest from the negative ideal solution.

Table 7
Negative Ideal Solution Matrix (S-) Selection Of The Best Renewable Energy In Southwest Sumba

ASPECT	S- Types of natural resources produced					
	Ocean	Bioenergy	Hydro	Geothermal	Wind	Solar
Clean	0.00035	0.00174	0.00102	0.00003	0.00086	0.00258
Consolidated	0.00001	0.00034	0.00018	0.00000	0.00011	0.00034
Continue	0.00000	0.00035	0.00023	0.00009	0.00022	0.00062
Controllable	0.00003	0.00103	0.00061	0.00002	0.00009	0.00139
Cheap	0.00000	0.00004	0.00002	0.00000	0.00001	0.00004
∑	0.00039	0.00350	0.00206	0.00014	0.00128	0.00497

Determining the Preference Value for Each Alternative (C+)

The preference value for each alternative (C+) of renewable energy potential in Southwest Sumba is obtained from the result of dividing S- by the total S+ and S-. As a result, solar energy has the highest C+ value (0.99258), followed by bioenergy (0.94024), hydro (0.71925), wind (0.40902), marine (0.09551), and geothermal (0.03101) (Table 8). Based on the results of the analysis, the potential for solar energy in Southwest Sumba is very potential and large. The main reason is the geographical location of Southwest Sumba which is in the tropics with high sunlight intensity throughout the year. The summer season in Southwest Sumba tends to be longer than the rainy season, so the potential for solar energy utilization becomes more optimal. In addition, the development of solar panel technology that is increasingly efficient and affordable also supports the utilization of solar energy in the region (Fig. 2).

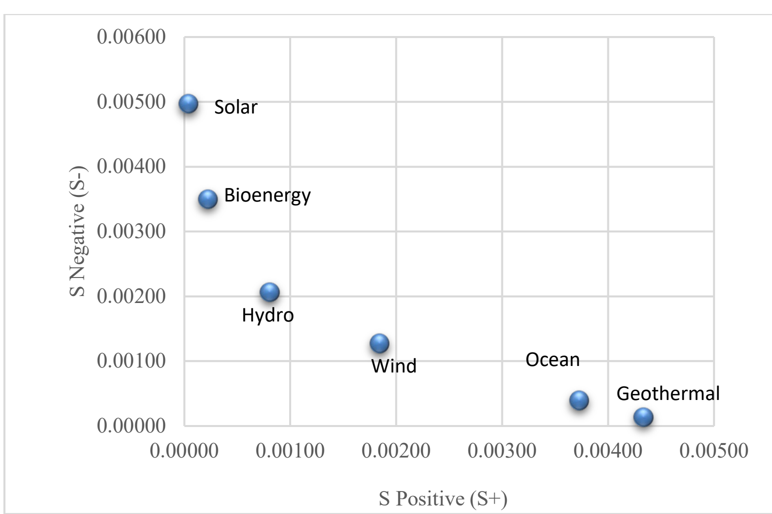


Fig. 2. TOPSIS Distance Analysis of Renewable Energy Alternatives in Southwest Sumb

Table 8
Ci+ Value (TOPSIS Final Result) of the best renewable energy selection in southwest Sumba

No.	Criteria Type of natural resources produced	S+	S-	Ci+
1	Ocean	0.00373	0.00039	0.09551
2	Bioenergy	0.00022	0.00350	0.94024
3	Hydro	0.00081	0.00206	0.71925
4	Geothermal	0.00433	0.00014	0.03101
5	Wind	0.00184	0.00128	0.40902
6	Solar	0.00004	0.00497	0.99258

Bioenergy occupies the second position in the analysis results, showing good potential. This is supported by the abundant availability of biomass raw materials in Southwest Sumba, especially from the livestock and agriculture sectors. Hydro energy is in the third position, showing quite good potential with the presence of several rivers and water sources that can be utilised for small-scale hydro power plants (micro hydro). Wind energy, ocean energy, and geothermal are at the bottom of the TOPSIS analysis. This could be due to several factors, such as more limited resource availability, wind speeds that are not as optimal as in other regions, development cost challenges and technological readiness of ocean energy, and geothermal potential that has not been optimally explored or requires greater investment. Fig. 2 presents a scatter plot visualization of the TOPSIS analysis results, where each point represents a renewable energy alternative plotted according to its S+ (positive ideal solution distance) and S- (negative ideal solution distance) values. The data shows that solar energy achieves the most optimal position with the lowest S+ value (0.00004) and highest S- value (0.00497), leading to the highest Ci+ score of 0.99258. Bioenergy follows as the second-best option with low S+ (0.00022) and high S- (0.00350) values, resulting in a Ci+ of 0.94024. Hydro energy maintains a moderate position (Ci+ = 0.71925), while wind (Ci+ = 0.40902), ocean (Ci+ = 0.09551), and geothermal energy (Ci+ = 0.03101) demonstrate progressively less optimal positions in the analysis. This visualization provides clear graphical support for the numerical TOPSIS results and the prioritization of renewable energy alternatives in Southwest Sumba.

5. Discussion

The comprehensive analysis of renewable energy potential in Southwest Sumba reveals a complex interplay between technological feasibility, environmental sustainability, and socio-economic considerations. Through systematic evaluation using the TOPSIS methodology with 5C criteria framework (Clean, Consolidated, Continue, Controllable, Cheap), three primary renewable energy options emerge as viable solutions: solar energy, bioenergy, and hydropower, achieving preference values of 0.99258, 0.94024, and 0.71925 respectively. The analysis demonstrates significant differentiation in performance across the established criteria. Solar energy exhibits superior performance in Clean (0.170) and Continue (0.100) criteria, reflecting optimal environmental sustainability and resource reliability. Bioenergy demonstrates strong performance in Controllable (0.139) and Clean (0.152) aspects, indicating robust operational management potential and environmental benefits. Hydropower, while showing balanced performance across criteria, particularly excels in Clean (0.133) considerations, though operational challenges affect its Consolidated (0.066) performance. Critical examination of implementation parameters reveals distinct technological and operational requirements for each energy source. Solar energy implementation necessitates precise structural specifications and environmental adaptations, bioenergy requires sophisticated process control and feedstock management systems, while hydropower demands enhanced operational protocols and maintenance frameworks. These technical considerations intersect with local infrastructure capabilities, resource availability, and management capacity. The following subsections examine each renewable energy option in detail, analyzing specific technical parameters, implementation considerations, and optimization requirements. This analysis provides a foundation for strategic energy development decisions in Southwest Sumba while considering local conditions and development objectives.

5.1 Solar energy

The dominance of solar energy in the TOPSIS analysis, achieving a preference value of 0.99258, reveals several critical implications for renewable energy development in Southwest Sumba. This section examines these findings within broader theoretical frameworks and practical considerations. Southwest Sumba's geographical characteristics present both opportunities and challenges for solar energy implementation. The region's tropical location ensures consistent solar radiation throughout the year, aligning with findings from similar geographical contexts (Pérez-Cutiño et al., 2022). However, this advantage must be balanced against local infrastructure limitations and community needs. The strong performance across Clean criteria (0.170) validates recent theoretical approaches emphasizing environmental sustainability in energy development. This aligns with Mittal et al. (2016) findings regarding the effectiveness of renewable energy in reducing greenhouse gas emissions. However, local implementation requires careful consideration of land-use patterns and community agricultural practices.

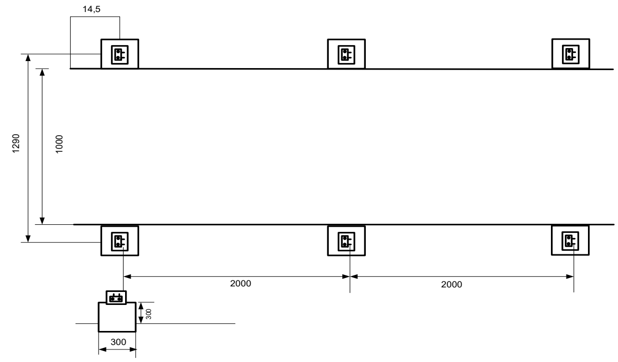


Fig. 3. Foundation Configuration has been directly implemented and field observation

The technology's high Controllable score (0.145) suggests promising integration potential with existing energy systems. This supports Worighi et al. (2019) research on smart grid technology implementation. However, Southwest Sumba's current grid infrastructure limitations necessitate strategic planning for system integration and storage solutions. Economic considerations, reflected in the Cheap criterion (0.024), reveal an interesting paradox. While solar technology demonstrates competitive long-term costs, initial capital requirements may challenge local economic conditions. This supports Guild (2020) observations regarding the misalignment between available incentives and local needs in renewable energy implementation. The Continue criterion performance (0.100) indicates robust long-term viability, yet raises questions about maintenance capacity and technical expertise availability. This connects to Sambodo et al. (2022) findings regarding infrastructure support and technical capacity challenges in renewable energy development. The technical analysis of solar module installation designs reveals critical engineering considerations for Southwest Sumba's renewable energy infrastructure development. The proposed installation specifications demonstrate a systematic approach to addressing regional implementation challenges while optimizing system performance. Fig. 3 illustrates the fundamental foundation layout for solar modules, depicting critical spacing parameters. The foundation configuration, utilizing 2000mm spacing intervals with 300mm × 300mm foundation blocks, presents a balanced solution between structural stability and material efficiency. This design parameter aligns with Khalid's (2024) findings regarding optimal foundation spacing for tropical regions, particularly considering Southwest Sumba's soil characteristics and seismic considerations. Figure 4 presents the detailed PV module arrangement specifications.

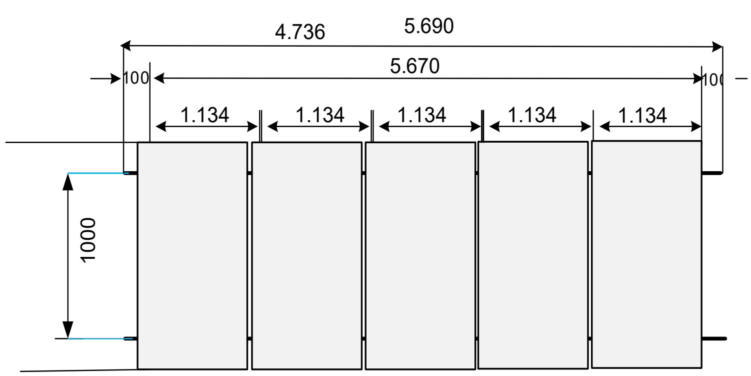


Fig. 4. PV Solar Module Support Structure has been directly implemented and field observation

Implementation analysis of the solar PV system design reveals critical technical considerations that must be addressed for optimal deployment in Southwest Sumba's environmental context. The foundation and structural systems demand particular attention to soil bearing capacity and seismic resistance, with specifications requiring minimum 0.3g horizontal acceleration tolerance. Given Southwest Sumba's coastal environment, corrosion mitigation measures become essential, particularly in foundation design where depths of 300-450mm must be optimized based on local soil conditions. The installation and operational protocols demonstrate careful consideration of regional environmental factors. Module mounting angles require optimization between 15-20 degrees to maximize solar insolation capture, while maintaining minimum inter-row spacing of 2000mm ensures adequate maintenance access and shadow mitigation. Thermal management considerations, including 100mm minimum edge clearance, address the challenges posed by Southwest Sumba's tropical climate. The structural design accommodates maximum wind speeds of 120 km/h, reflecting local meteorological conditions. Infrastructure integration specifications emphasize the importance of grid stability, requiring voltage fluctuation containment within ±5%. This technical parameter proves particularly critical given Southwest

Sumba's developing power infrastructure. Energy storage system integration and load management protocols must account for peak load handling capacity, ensuring system reliability despite variable generation patterns. These specifications align with Worighi et al. (2019) findings regarding smart grid implementation in developing regions. Structural design optimization incorporates material specifications that balance durability with cost-effectiveness. Concrete foundations utilize minimum C25/30 grade material with B500B steel reinforcement, while support structures employ galvanized steel with minimum 85μm coating or 6061-T6 grade aluminum alloy alternatives. These material choices reflect careful consideration of both structural requirements and environmental resilience. The implementation framework establishes specific mounting parameters, including torque requirements of 20-25 Nm and precise mounting bracket spacing of 1134mm (±2mm). Array configuration optimization limits string sizing to maximum 20 modules with voltage drop restricted to less than 1% per string, ensuring optimal system performance and maintenance efficiency. These technical specifications support Hassan et al. (2023) recommendations for photovoltaic array optimization in high-insolation environments.

Future development considerations emphasize system scalability and performance monitoring capabilities. The technical framework incorporates modular expansion capabilities and grid capacity enhancement protocols, supported by comprehensive real-time data acquisition systems. This forward-looking approach ensures that initial implementations can adapt to growing energy demands while maintaining operational efficiency. The integration of performance evaluation metrics and maintenance scheduling optimization provides a foundation for sustainable system operation in Southwest Sumba's specific environmental context.

5.2 Bioenergy

The TOPSIS analysis positions bioenergy as the second most viable renewable energy option for Southwest Sumba, with a preference value of 0.94024. This significant ranking warrants detailed examination within the context of regional agricultural characteristics and implementation feasibility. The integration potential of bioenergy in Southwest Sumba based on Onwosi et al. (2022) demonstrates strong alignment with existing agricultural practices and livestock management systems. Figure 6 illustrates the comprehensive bioenergy ecosystem, depicting the systematic flow from agricultural waste generation to electricity production and community benefits.

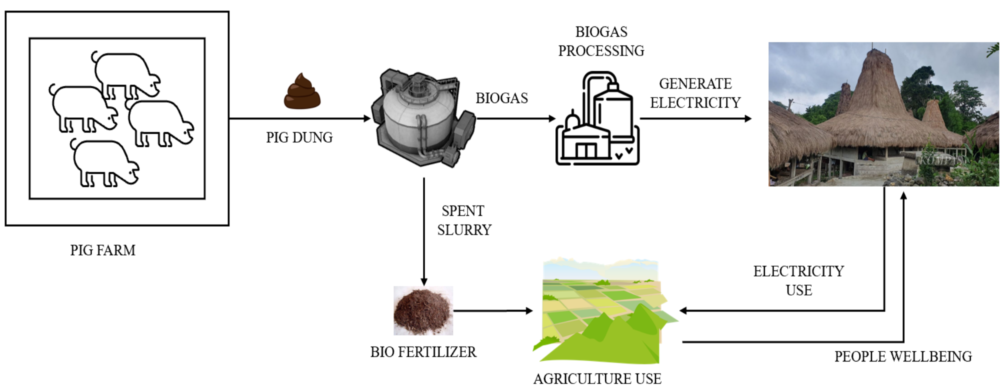


Fig. 5. Bioenergy System Integration Framework (Adopted form Onwosi et al. (2022))

The technical configuration of bioenergy systems in Southwest Sumba demonstrates significant integration potential through a multi-stage processing framework. Primary feedstock sourcing leverages the region's substantial livestock sector, particularly pig farming operations, which provides consistent organic waste generation capacity. The systematic analysis indicates feedstock availability of approximately 2.5-3.0 kg of waste per livestock unit daily, supporting steady biogas production potential.

The biogas generation process employs anaerobic digestion technology optimized for the region's tropical climate conditions. The digestion system maintains mesophilic temperature ranges (35-37°C), facilitating optimal bacterial activity and methane production. This temperature-controlled environment ensures conversion efficiency rates of 50-60% organic matter to biogas, with methane content typically ranging between 60-65%. The process demonstrates strong performance in the Controllable criterion (0.139) through consistent biogas production parameters and systematic operational control mechanisms. System integration encompasses dual-stream value creation through both energy generation and agricultural input production. The biogas stream undergoes purification processes to remove hydrogen sulfide and moisture content, ensuring compatibility with electricity generation equipment. Typical electrical conversion efficiency ranges from 35-40% using biogas-optimized generator sets. Simultaneously, the digested slurry undergoes stabilization processes, producing bio-fertilizer with nitrogen content of 1.5-2.0%, phosphorous at 1.0-1.2%, and potassium at 0.8-1.0%.

The circular economy approach validates the high Clean criterion score (0.152) through multiple environmental benefits. Primary advantages include reduction in methane emissions from conventional waste management practices, estimated at 4.5-5.0 tons CO2 equivalent per installation annually. Additionally, the bio-fertilizer production offsets chemical fertilizer usage, contributing to soil health improvement and reduced agricultural chemical runoff. Economic viability analysis, reflected in the Cheap criterion (0.019), indicates favorable cost-benefit ratios. Initial installation costs range between IDR 15-20 million per kilowatt capacity, with operational costs averaging IDR 1,500-2,000 per kilowatt-hour. These parameters align with Sulaeman et al. (2021) findings regarding cost-effective renewable energy solutions in agricultural communities. The dual-benefit outcome of power generation and fertilizer production enhances the economic sustainability of the system.

Implementation considerations encompass several critical domains requiring systematic attention. Feedstock supply chain management necessitates coordinated collection systems and storage facilities. Biogas plant operational protocols require standardized procedures for optimal performance maintenance. Grid integration specifications must address power quality requirements and load management protocols. Community engagement frameworks ensure equitable benefit distribution and sustained participation in the bioenergy ecosystem.

The bioenergy system demonstrates strong potential for supporting Southwest Sumba's renewable energy objectives while providing additional agricultural benefits. This integrated approach to energy and agricultural development aligns with regional sustainability goals and community economic development objectives. The implementation framework establishes a foundation for scalable renewable energy infrastructure that leverages existing agricultural resources while promoting environmental sustainability and economic development.

6. Conclusion

The TOPSIS analysis with 5C criteria reveals that solar energy is the most promising renewable energy option for Southwest Sumba, followed by bioenergy and hydropower. Solar energy excels in environmental sustainability and resource reliability, bioenergy demonstrates strong operational controllability and environmental benefits, while hydropower presents a balanced performance with strengths in environmental considerations.

Technical analysis highlights critical implementation parameters for each renewable energy alternative. Solar energy requires careful structural design, environmental adaptations, and grid integration. Bioenergy necessitates systematic feedstock management, process control, and value chain integration. Hydropower demands operational efficiency improvements, governance frameworks, and maintenance protocols. A multi-faceted renewable energy development approach is recommended, prioritizing solar energy deployment while fostering bioenergy ecosystem development and optimizing micro-hydro infrastructure.

The methodology and findings demonstrate broad applicability across Indonesia's diverse regions, offering a replicable framework for renewable energy assessment and implementation. The 5C criteria provide a comprehensive yet flexible evaluation approach that can be adapted to various geographical, socio-economic, and infrastructure conditions while supporting national renewable energy targets. This framework promotes inclusive economic growth by identifying renewable energy solutions that create local employment and business opportunities while balancing environmental sustainability with development priorities.

Establishing comprehensive renewable energy policies with incentives, regulations, and technical assistance creates an enabling environment for implementation across different regions. Through rigorous analysis and stakeholder engagement, regions throughout Indonesia can harness their renewable energy potential, optimize infrastructure, and foster inclusive development, contributing significantly to national energy security and sustainability objectives.

References

Abid, M. K., Kumar, M. V., Raj, V. A., & Dhas, M. (2023). Environmental impacts of solar photovoltaic systems in the context of globalisation. *Ecological Engineering and Environmental Technology*, *24*.

Balioti, V., Tzimopoulos, C., & Evangelides, C. (2018, July). Multi-criteria decision making using TOPSIS method under fuzzy environment. Application in spillway selection. In *Proceedings* (Vol. 2, No. 11, p. 637). MDPI.

Cantore, N., Nussbaumer, P., Wei, M., & Kammen, D. (2016). Promoting renewable energy and energy efficiency in Africa: A framework to evaluate employment generation and cost effectiveness. *Environmental Research Letters*, *12*.

Central Bureau of Statistics. (2024). Indonesia's Economy in the Fourth Quarter of 2023 Grew 5.04 per cent (y-on-y). https://www.bps.go.id/id/pressrelease/2024/02/05/2379/ekonomi-indonesia-triwulan-iv-2023-tumbuh-5-04-persen--y-on-y-.html

Cuviello, L. (2024). Modeling Renewable Energy Communities in Italy: Performance, economics and geographic optimization [Doctoral dissertation, Politecnico di Torino].

Databoks. (2023). Indonesia's Installed Capacity of Renewable Electricity Generation by Energy Source (2023). https://databoks.katadata.co.id/datapublish/2024/01/19/kapasitas-ebt-indonesia
Dincer, I., & Acar, C. (2015). A review on clean energy solutions for better sustainability. *International Journal of Energy Research*, *39*, 585-606.
Dranka, G. G., Ferreira, P., & Vaz, A. I. F. (2020). Cost-effectiveness of energy efficiency investments for high renewable electricity systems. *Energy*, *198*, 117198.
Garba, A. (2021). Biomass conversion technologies for bioenergy generation: An introduction. In *Biotechnological applications of biomass*. IntechOpen.
Georgiadis, D. R., Mazzuchi, T. A., & Sarkani, S. (2013). Using multi criteria decision making in analysis of alternatives for selection of enabling technology. *Systems Engineering*, *16*(3), 287-303.
Ghenai, C., Albawab, M., & Bettayeb, M. (2020). Sustainability indicators for renewable energy systems using multi-criteria decision-making model and extended SWARA/ARAS hybrid method. *Renewable Energy*, *146*, 580-597.
Guezgouz, M., Jurasz, J., Bekkouche, B., Ma, T., Javed, M. S., & Kies, A. (2019). Optimal hybrid pumped hydro-battery storage scheme for off-grid renewable energy systems. *Energy Conversion and Management*, *199,* 112046.
Guild, J. (2020). The political and institutional constraints on green finance in Indonesia. *Journal of Sustainable Finance & Investment*, *10*, 157-170.
Hassan, Q., Algburi, S., Sameen, A. Z., Salman, H. M., & Jaszczur, M. (2023). A review of hybrid renewable energy systems: Solar and wind-powered solutions: Challenges, opportunities, and policy implications. *Results in Engineering*, 101621.
Huerta-Reynoso, E. A., López-Aguilar, H. A., Gómez, J. A., Gómez-Méndez, M. G., & Pérez-Hernández, A. (2019). Biogas power energy production from a life cycle thinking. In *New Frontiers on Life Cycle Assessment-Theory and Application*. IntechOpen.
Hwang, C. L., & Yoon, K. (1981). *Multiple Attribute Decision Making: Methods and Applications*. Springer-Verlag. http://dx.doi.org/10.1007/978-3-642-48318-9
Khalid, M. (2024). Technology and Architecture of Smart Grids. In *Handbook of Energy and Environment in the 21st Century* (pp. 86-108). CRC Press.
Khadem, M. (2019). *Economic Valuation of Inter-Annual Reservoir Storage in Water Resources Systems: Theory, Development, and Applications* [Doctoral dissertation, The University of Manchester].
Kluts, I., Wicke, B., Leemans, R., & Faaij, A. (2017). Sustainability constraints in determining European bioenergy potential: A review of existing studies and steps forward. *Renewable and Sustainable Energy Reviews*, *69*, 719-734.
Kumar, M. (2020). Social, economic, and environmental impacts of renewable energy resources. In *Wind Solar Hybrid Renewable Energy System* (pp. 1). IntechOpen.
Ling, J. M., & Mulani, F. I. (2024). Planning and optimization of a residential microgrid utilizing renewable resources and integrated energy storage. *Journal of Energy Storage*, *97,* 112933.
Majhi, A. A. K., & Mohanty, S. (2024). A Comprehensive Review on Internet of Things Applications in Power Systems. *IEEE Internet of Things Journal*.
Mathu, L. (2023). *Determinants of Successful Delivery of Public-Private Partnership Renewable Energy Projects in Kenya* [Doctoral dissertation, Strathmore University].
Medina, J. D. C., & Magalhães Jr, A. I. (2021). Ethanol production, current facts, future scenarios, and techno-economic assessment of different biorefinery configurations. *Bioethanol Technologies*, *23*, 1-14.
Mittal, S., Dai, H., Fujimori, S., & Masui, T. (2016). Bridging greenhouse gas emissions and renewable energy deployment targets: comparative assessment of China and India. *Applied Energy*, *166*, 301-313.
Nath, S. (2024). Biotechnology and biofuels: paving the way towards a sustainable and equitable energy for the future. *Discover Energy*, 4, 8.
NTT Central Bureau of Statistics. (2022). Electric Power Capability. https://ntt.bps.go.id/id/statistics-table/2/NjM0IzI=/kemampuan-daya-listrik.html
Onwosi, C. O., Ozoegwu, C. G., Nwagu, T. N., Nwobodo, T. N., Eke, I. E., Igbokwe, V. C., Ugwuoji, E. T., & Ugwuodo, C. J. (2022). Cattle manure as a sustainable bioenergy source: Prospects and environmental impacts of its utilization as a major feedstock in Nigeria. *Bioresource Technology Reports*, *19*, 101151.
Osman, A. I., Fang, B., Zhang, Y., Liu, Y., Yu, J., Farghali, M., Rashwan, A. K., Chen, Z., Chen, L., Ihara, I., & et al. (2024). Life cycle assessment and techno-economic analysis of sustainable bioenergy production: a review. *Environmental Chemistry Letters*.
Pérez-Cutiño, M. A., Valverde, J. S., & Díaz-Báñez, J. M. (2022). Detecting broken Absorber Tubes in CSP plants using intelligent sampling and dual loss. *arXiv*, arXiv:2211.14077.
Sambodo, M. T., Yuliana, C. I., Hidayat, S., Novandra, R., Handoyo, F. W., Farandy, A. R., Inayah, I., & Yuniarti, P. I. (2022). Breaking barriers to low-carbon development in Indonesia: deployment of renewable energy. *Heliyon*, *8*.
Sarkar, S., & Fitzgerald, B. (2022). Fluid inerter for optimal vibration control of floating offshore wind turbine towers. *Engineering Structures*, *266*, 114558.

Schroeder, R. E., Loots, I., Van Dijk, M., & Coetzee, G. L. (2023). Development of a procedure and tool for retrofit hydropower evaluation at South African dams. *Water SA*, *49*, 230-238.

Secretary General of the National Energy Council (Ed.). (2023). *Indonesia's energy outlook*. National Energy Council.

Shouman, E. R. M. (2020). Global prediction of wind energy market strategy for electricity generation. In *Modelling, Simulation and Optimisation of Wind Farms and Hybrid Systems*. IntechOpen.

Siciliano, G. (2023). Hydropower, climate change and sustainable energy transitions. In *Handbook on Climate Change and Technology*. Edward Elgar Publishing.

Singh, Y. D., & Satapathy, K. B. (2018). Conversion of lignocellulosic biomass to bioethanol: an overview with a focus on pretreatment. *International Journal of Engineering & Technology*, *15*, 17-43.

Sulaeman, I., Simatupang, D. P., Noya, B. K., Suryani, A., Moonen, N., Popovic, J., & Leferink, F. (2021). Remote microgrids for energy access in indonesia-part i: Scaling and sustainability challenges and a technology outlook. *Energies*, *14*, 6643.

Surya, B., Muhibuddin, A., Suriani, S., Rasyidi, E. S., Baharuddin, B., Fitriyah, A. T., & Abubakar, H. (2021). Economic evaluation, use of renewable energy, and sustainable urban development of mamminasata metropolitan, Indonesia. *Sustainability*, *13*, 1165.

Teh, J. S., Teoh, Y. H., How, H. G., Le, T. D., Jason, Y. J. J., Nguyen, H. T., & Loo, D. L. (2021). The potential of sustainable biomass producer gas as a waste-to-energy alternative in Malaysia. *Sustainability, 13*, 3877.

Tephiruk, N., Jamjang, P., Taweesap, A., & Hongesombut, K. (2022). Hybrid energy storage system to enhance efficiency of renewable energy usage. In *Proceedings of the 2022 19th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON)* (pp. 1-4). IEEE.

Terrén-Serrano, G., & Martínez-Ramón, M. (2021). Kernel learning for intra-hour solar forecasting with infrared sky images and cloud dynamic feature extraction. *Renewable and Sustainable Energy Reviews*, *175*, 113125.

Tiawon, H., & Miar, M. (2023). The role of renewable energy production, energy efficiency and green finance in achieving sustainable economic development: evidence from Indonesia. *International Journal of Energy Economics and Policy*, *13*, 250-260.

Troldborg, M., Heslop, S., & Hough, R. L. (2014). Assessing the sustainability of renewable energy technologies using multi-criteria analysis: Suitability of approach for national-scale assessments and associated uncertainties. *Renewable and Sustainable Energy Reviews*, *39*, 1173-1184.

Worighi, I., Maach, A., Hafid, A., Hegazy, O., & Van Mierlo, J. (2019). Integrating renewable energy in smart grid systems: Architecture, virtualisation and analysis. *Sustainable Energy, Grids and Networks*, *18*, 100226.

Xu, R., Zeng, Z., Pan, M., Ziegler, A. D., Holden, J., Spracklen, D. V., & Wood, E. F. (2023). A global-scale framework for hydropower development incorporating strict environmental constraints. *Nature Water*, *1*, 113-122.

Yelmanchli, G. (2018). Smart Solutions and Opportunities for Key Challenges in Renewables Integration and Electric Vehicles Integration to a Conventional Grid. In *ISGW 2017: Compendium of Technical Papers: 3rd International Conference and Exhibition on Smart Grids and Smart Cities* (pp. 237-249). Springer.

Zeraibi, A., Balsalobre-Lorente, D., & Murshed, M. (2021). The influences of renewable electricity generation, technological innovation, financial development, and economic growth on ecological footprints in ASEAN-5 countries. *Environmental Science and Pollution Research*, *28*, 51003-51021.

Zhang, L., Zhou, P., Newton, S., Fang, J. X., Zhou, D. Q., & Zhang, L. P. (2015). Evaluating clean energy alternatives for Jiangsu, China: An improved multi-criteria decision making method. *Energy*, *90*, 953-964.