The Selection of Energy Storage in the Southern Sulawesi Electricity System with AHP-TOPSIS Method

Peri Indriyanto
School of Interdiciplinary Management and Technology
Institut Teknologi Sepuluh Nopember
Surabaya, Indonesia
6047222014@student.its.ac.id

Vita Lystianingrum
School of Interdiciplinary Management and Technology
Institut Teknologi Sepuluh Nopember
Surabaya, Indonesia
vita@ee.its.ac.id

***Abstract*— In the fourth quarter of 2023, a power deficit of up to 600 MW was observed in the Southern Sulawesi (Sulbagsel) electricity system due to the prolonged El Nino that affected hydropower plants. Based on the 2021-2030 RUPTL, the Sulbagsel system does not allow the addition of renewable energy (RES) plants, except with a battery firming scheme while the construction of fossil-based power plants is limited by the government. One potential mitigation strategy for PLN (Perusahaan Listrik Negara) is to evaluate the potential application of Energy Storage Systems (ESS) in the Sulbagsel system. The purpose of this research is to evaluate the selection of ESS in the South Sulawesi electricity system through a combination of AHP (Analytical Hierarchy Process) and TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution). The AHP-TOPSIS method is an optimal choice for this evaluation due to its capacity to address complex evaluation scenarios by considering a multitude of comprehensive criteria and conducting weighting analyses to ascertain accuracy and identify optimal solutions. The evaluation criteria encompass technical, economic, environmental, and social considerations, with a total of 15 sub-criteria. The alternatives to be evaluated are PHES (Pumped Hydro Energy Storage), BESS (Battery Energy Storage System), and HESS (Hydrogen Energy Storage System). The results of the evaluation demonstrate that PHES is the optimal alternative, with a preference value of 0.655. BESS is ranked second with a preference value of 0.404, while HESS is ranked third with a preference value of 0.224.**

Keywords: AHP, ESS, Sulbagsel, TOPSIS.

I. INTRODUCTION

In the third quarter of 2023, most areas in Indonesia experienced El Nino which resulted in drought in various regions and impacted the VRE (Variable Renewable Energy) plant. Consequently, the South Sulawesi electricity system which is managed by Perusahaan Listrik Negara (PLN) experienced a power deficit of up to 600 MW.

The power deficit problem in the Sulbagsel system can be solved with the construction of additional power plants, the optimization of operating patterns, load management, the effective scheduling of plants, the interconnection with other sub-systems, the establishment of a partnership with an IPP (Independent Power Producer) and the utilization of Energy Storage System (ESS). From the perspective of PLN, one of the proposed mitigations is to evaluate the performance of VRE plants and RES (Renewable Energy Source) plants, which will require the installation of ESS in the future. Solutions to address grid issues include the development of more advanced ESS technologies, integration of ESS with RES, and optimization of energy management [1].

The Sulbagsel electricity system has a VRE generation capacity of 33.4% with a peak load of 1,903 MW and a total generation capacity of 2,478 MW. The consequence of a high percentage of VRE is the risk of reliability disruption during intermittency and seasonal variations caused by climate change. In order to overcome these obstacles, the role of ESS is needed. On the other hand, the quota for additional VRE plants in the Sulbagsel system is full, except for VRE plants equipped with batteries as firming, and financially no more than 7 cent/kWh [2]. Additionally, the construction of fossil-based plants has been subject to constraints imposed by the government.

The implementation of ESS has been shown to improve system reliability, particularly intermittency issues in renewable energy system integration. In New England, the implementation of ESS has had the impact of improving the efficiency and stability of the solar power plant and wind power plant [3]. Incorporating ESS with sufficient capacity into the Sulbagsel system can mitigate the potential power shortfalls caused by seasonal variations and intermittency, thereby improving system reliability.

In the context of ESS, Sulbagsel demonstrates considerable potential depending on its resource endowment, topographical characteristics and geographical location. The presence of RES, including solar, wind, hydro, biomass and geothermal, can be utilized in the production of hydrogen for use in ESS and power generation in South Sulawesi [4]. The need for energy storage solutions is paramount to facilitate the integration of RES in Indonesia. It can be posited that regions with high solar intensity, such as East Nusa Tenggara and Sulawesi, may prove to be optimal for the establishment of hydrogen-producing solar power plants [5].

The implementation of ESS has a significant impact on maintaining the reliability of systems with a high VRE ratio, where the influence of intermittency becomes very risky to cause disturbances in the system. The large capacity of energy storage also has an impact, as it allows ESS to handle unstable load peaks and provide sufficient reserves that do not need to be supplied by power plant generation. With sufficient energy storage capacity, potential power shortages in the system will be reduced. In addition, numerous studies have underlined the importance of integrating ESS technologies into power systems to facilitate the integration of VRE plants [6].

 How to cite: Indriyanto, P., Lystianingrum, V. (2025). The Selection of Energy Storage in the Southern Sulawesi Electricity System with AHP-TOPSIS Method. *JAREE (Journal on Advanced Research in Electrical Engineering), 9(2).*

Research in the field of ESS is currently concentrated on improving the efficiency and cost-effectiveness of these systems, with the aim of integrating them as essential part of the forthcoming energy landscape. In addition, the significant capital costs associated with the selected technology types, such as LIB (Lithium Ion Battery) and HFC (Hydrogen Fuel Cell) have been identified as a significant barrier to their adoption [7].

Pumped Hydro Energy Storage (PHES) dominated the global market, accounting for about 92% of total energy storage in 2020 [8]. PHES potential in Indonesia with a head value of more than 200 meters is spread across Papua, Central Sulawesi and Nangroe Aceh Darussalam [9]. Indonesia has 26,000 sites with PHES potential, with a total capacity of up to 821,000 GWh, which is far greater than the amount needed to support a 100% RES [10]. While PHES has great potential for renewable energy integration, there are challenges in terms of cost and geographical location that limit its application [11].

Battery Energy Storage System (BESS) is becoming a popular technology in the renewable energy penetration market as it has many models and specification options and is widely available in the market compared to others. In Indonesia, hydrogen production has been initiated by PLN from 2023 using its power plants, and green hydrogen projects will continue to be developed in various regions. Although large-scale battery storage has the potential to increase the efficiency and profitability in RES, its presence is not always necessary to achieve 100% renewable energy targets [12].

Hydrogen is emerging as a promising technology in various fields, including industry, transport, power generation and as an ESS. Hydrogen Energy Storage Systems (HESS) are seen as a potential solution for energy storage with large power and capacity requirements, especially in countries where hydroelectric resources are dominant. For HESS, attention to capacity attenuation characteristics is critical in the development of more efficient hydrogen storage systems [13].

Research on ESS in an electricity system in Indonesia has not shown tangible results, therefore this study will discuss the selection of ESS specifically in the Sulbagsel system. Table I shows the state of the art of this research, where several previous studies used various methods such as AHP (Analytical Hierarchy Process), TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution), TEA (Techno Economic Assessment), IULCWA (Intuitionistic Uncertain Language Choquet ordered Weighted Aggregation operator), VIKOR (Vise Kriterijumska Optimizacija Kompromisno Resenje) and NDEA (Neutrosophic Data Envelopment Analysis) and evaluated various alternatives such as PHES, CAES (Compressed Air Energy Storage), various types of BESS technology, FWES (Fly Wheel Energy Storage), SCES (Super Capacitor Energy Storage), SMES (Superconducting Magnetic Energy Storage), HESS and Hybrid Energy Storage System. The criteria evaluated are also diverse with many variables. This paper will focus on evaluating with a combination of AHP and TOPSIS methods, selecting three alternatives that are relevant to the conditions of the South Sulawesi system and selecting 4 main criteria and 15 sub criteria.

TABLE I. STATE OF THE ART

No	Reference	Method	Alternatives	Criteria
1	(Balezentis et al., 2021)	TOPSIS	8 (Hydrogen, CAES, PHES, Molten Salt, Lead Acid, Na-Ion, Li-Ion NMC, VRB	4 (Technical, Economic, Environmental, Social) 18 Variables
2	(Alonso et al., 2024)	TEA	3 (BESS, HESS, H2ESS)	3 (Technical, Economic, Environmental) 7 Variables
3	(Pang et al., 2021)	MCDM, IULCWA	3 (Lead Acid, NaS, Li-Ion)	4 (Technical, Economic, Environmental, Social)
4	(Çolak & Kaya, 2020)	AHP, VIKOR	9 (PHES, CAES, FWES, SCES, SMES, HESS, Li-Ion, VRB, NaS)	4 (Technical, Economic, Environmental, Social-Politics)
5	(Tapia et al., 2022)	NDEA	8 (PHES, SCES, CAES, FWES, Lead Acid, NiCd, Li-Ion, NaS)	2 (Techno and Economic)
6	This paper	AHP-TOPSIS	3 (PHES, BESS, HESS)	4 (Technical, Economic, Environmental, Social) 15 Variables

In previous studies there were several research gaps, the analysis carried out focused on general criteria so that it was often not specific to certain locations [14], the dominant factors in the criteria that were considered from the selection of alternatives were cost variables and economic value [15], lack of empirical data used in evaluations can reduce the accuracy of analysis results [16], in addition, sensitivity testing is required to understand the impact of variable changes on evaluation results [17].

The article is presented in a sequential format, with Section II presenting the research methods used, Section III discussing the results of the analysis, and Section IV outlining the conclusions of this study.

II. METHODS

The AHP-TOPSIS method was selected for this research project because of its ability to facilitate objective and subjective evaluation of the selected alternatives by considering a range of factors and criteria. Furthermore, the combined AHP-TOPSIS method is characterized by a high degree of complexity in the evaluation and weighting analysis, which serves to determine the accuracy and selection of the optimal solution. The combined AHP-TOPSIS method is considered more effective in minimizing subjectivity in decision making and producing more consistent decisions [18].

A. Analytical Hierarchy Process

In the AHP method, the weighting assessment is derived from experts by providing assessment contexts, opinions, and assumptions. The aforementioned information was mainly provided by management experts and specialists at PLN, who outlined the criteria and alternatives that were evaluated in the selection of the ESS, as well as the overall condition of the South Sulawesi electricity system. It is crucial to involve relevant stakeholders and consider a wider range of perspectives in the decision-making process [19], especially when evaluating indicators that are unclear and require expert opinion [20].

Important criteria to consider in selecting energy storage technologies include economic, technical, social, and political aspects [21]. Clear policies, regulations and support from government and policy makers are needed to support the development of renewable energy [22]. Sustainability is an important consideration, particularly in relation to carbon emissions [14]. Environmental criteria are also an important consideration, as the essence of implementing renewable energy technology is to create a good environment and for the sustainability of nature.

Figure 1 illustrates the AHP hierarchy used in this study, which consists of four main criteria: technical including power rating, energy rating, efficiency and lifetime. Economic criteria include investment cost, O&M (Operational and Maintenance) cost, and energy cost. Environmental criteria include supply chain, waste management, carbon emissions and ecological impact. Social criteria include social acceptance, human rights, regulation and social impact.

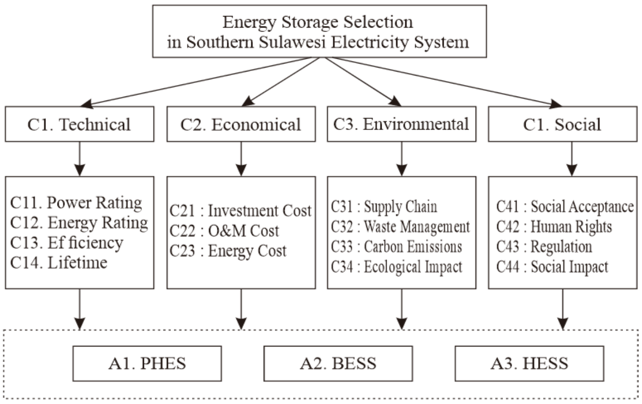

Fig. 1. AHP hierarchy

The pairwise comparison matrix is filled with the importance scale according to Saaty's scale. The Saaty scale is used to give a value or level of importance between criteria. The comparison matrix in the AHP method is denoted by Equation 1, which shows the comparison between criteria and sub-criteria.

$$\begin{bmatrix} b_{11} & b_{12} & b_{13} & \dots & b_{1n} \\ \frac{1}{b_{12}} & b_{11} & b_{11} & \dots & b_{2n} \\ \vdots & \vdots & \vdots & \dots & \vdots \\ \frac{1}{b_{1n}} & \frac{1}{b_{2n}} & \frac{1}{b_{23}} & \dots & b_{nn} \end{bmatrix} \tag{1}$$

TABLE II. PAIRWISE COMPARISON MATRIX BETWEEN MAIN CRITERIA

Main Criteria	C1	C2	C3	C4
C1	1	2	4	7
C2	0.5	1	4	5
C3	0.25	0.333	1	4
C4	0.143	0.2	0.25	1

Table II shows the pairwise comparison matrix between the main criteria, in which the technical criteria are given priority in the evaluation process. The economic criteria are the second priority, the environmental criteria are the third priority and the social criteria are the last priority. The ranking is based on expert judgement and the empirical conditions of the Sulbagsel system.

Table III shows the pairwise comparison matrix between the sub-criteria relating to the technical criteria, where the sub-criterion performance is given the highest priority in the evaluation process, followed by energy rating, efficiency and lifetime.

TABLE III. PAIRWISE COMPARISON MATRIX BETWEEN SUB CRITERIA ON TECHNICAL CRITERIA

Sub Criteria	C11	C12	C13	C14
C11	1	3	5	6
C12	0.333	1	2	4
C13	0.2	0.5	1	2
C14	0.167	0.25	0.5	1

Table IV shows a matrix of pairwise comparisons between the sub-criteria within the economic criteria, with investment cost being the highest priority in the evaluation process.

TABLE IV. PAIRWISE COMPARISON MATRIX BETWEEN SUB CRITERIA ON ECONOMICAL CRITERIA

Sub Criteria	C21	C22	C23
C21	1	9	4
C22	0.111	1	0.333
C23	0.25	3	1

Table V shows the comparative analysis between the environmental sub-criteria, with the carbon emissions sub-criterion taking a primary position in the evaluation process. This is followed by the supply chain, ecological impact and waste management sub-criteria.

TABLE V. PAIRWISE COMPARISON MATRIX BETWEEN SUB CRITERIA ON ENVIRONMENTAL CRITERIA

Sub Criteria	C31	C32	C33	C34
C31	1	6	0.333	2
C32	0.167	1	1.143	0.333
C33	3	7	1	6
C34	0.5	3	0.167	1

Table VI shows the comparative analysis between the sub-criteria related to the social criteria, where the regulation sub-criterion is given the highest priority, followed by social impact, human rights and social acceptability.

TABLE VI. PAIRWISE COMPARISON MATRIX BETWEEN SUB CRITERIA ON SOCIAL CRITERIA

Sub Criteria	C11	C12	C13	C14
C11	1	0.5	0.2	0.25
C12	2	1	0.35	0.5
C13	5	4	1	3
C14	4	2	0.333	1

Once the pairwise criteria matrix has been calculated, it is normalised by dividing each matrix component by the number of matrix components per column, according to equation 2. The local weighted criteria are then calculated as the average of each matrix component in each normalised row, according to Equation 3. Consistent evaluation of the decision matrix is indicated by a Consistency Ratio (CR) of less than 0.1. The CR is calculated according to equation 4, considering the Random Index (RI) coefficient, while the Consistency Index (CI) is calculated according to equation 5.

$$b_{ij} = \frac{b_{ij}}{\sum_{j=1}^{n} b_{ij}} \quad (2)$$

$$\omega_{ij} = \frac{\sum_{j=1}^{n} b_{ij}}{n} \quad (3)$$

$$CR = \frac{CI}{RI} \quad (4)$$

$$CI = \frac{\lambda max - n}{n - 1} \quad (5)$$

Table VII shows the results of the global weighting of the criteria where the power rating sub-criterion is identified as the main consideration, with a global weight of 0.282 followed by the investment cost sub-criterion with a global weight of 0.218 and the energy cost sub-criterion with a global weight of 0.118. It should be noted that although the other sub-criteria have insignificant weights, they are still important considerations in the evaluation.

TABLE VII. GLOBAL WEIGHTING OF CRITERIA

Criteria	Local weight of criteria	Sub-criteria	Local weight of sub criteria	Global weight of sub criteria
C1	0.497	C11	0.567	0.282
		C12	0.237	0.118
		C13	0.124	0.061
		C14	0.072	0.036
C2	0.301	C21	0.726	0.218
		C22	0.074	0.022
		C23	0.201	0.060
C3	0.146	C31	0.246	0.036
		C32	0.054	0.008
		C33	0.576	0.084
		C34	0.123	0.018
C4	0.055	C41	0.079	0.004
		C42	0.136	0.007
		C43	0.535	0.029
		C44	0.249	0.014

B. *Ranking of Alternatives using TOPSIS*

The TOPSIS method constructs a decision matrix by entering the alternative performance values obtained from a variety of references and other sources. Table VIII shows the decision matrix with alternative performance values.

TABLE VIII. DECISION MATRIX WITH ALTERNATIVE PERFORMANCE VALUES

Main Criteria	Sub Criteria	A1 : PHES	A2 : BESS	A3 : HESS	Unit
C1	C11	5,000	750	260	MW
	C12	120,000	3287	1,000	MWh
	C13	85	90	40	%
	C14	60	15	30	Year
C2	C21	1,000	200	550	US$/kW
	C22	1	1	2	%
	C23	50	150	200	US$/MWh
C3	C31	1	1	2	Scale (1 to 3)
	C32	1	2	1	Scale (1 to 3)
	C33	15	125	200	g CO_2/kWh
	C34	1	1	1	Scale (1 to 3)
C4	C41	3	2	2	Scale (1 to 3)
	C42	1	1	1	Scale (1 to 3)
	C43	2	1	2	Scale (1 to 3)
	C44	1	1	2	Scale (1 to 3)

The South Sulawesi system's alternative performance values are justified based on expert evaluation, which indicates that PHES in South Sulawesi has great potential. This is due to the presence of numerous existing reservoirs and dams with substantial capacity and high head. For instance, the Bilibili dam has a reservoir storage capacity of up to 290 million cubic meters and a maximum head height of 50.71 meters. The implementation of HESS can be seamlessly integrated with existing VRE plants, such as the Sidrap and Tolo wind farms, which can be utilized for hydrogen production. Additionally, BESS technology offers a high degree of flexibility for implementation in various locations.

The alternative performance values of the power rating and energy rating sub criteria are taken from existing projects in the world, namely Vistra's BESS in Moss Landing (California) with specifications of 750 MW / 3,000 MWh, the PHES project from the Queensland government with specifications of 5GW / 120 GWh. Efficiency is taken from the maximum value of the reference, PHES reaching 85%, BESS 90% and HESS 40%, while the lifetime of PHES is up to 60 years, BESS 15 years and HESS 30 years [23].

The value of alternative performance on economic criteria is taken from IRENA (International Renewable Energy Agency) which states that PHES has a minimum investment cost of 1,000 US$/kW, O&M (Operational and Maintenance) cost of at least 1% and LCOE (Levelized Cost of Energy) or energy cost of at least 50 US$/kW. For BESS, the minimum investment cost is 200 US$/kW, O&M cost is at least 1% and LCOE or energy cost is at least 150 US$/kW. As for HESS, the minimum investment cost is 550 US$/kW, the O&M cost is at least 2% and the LCOE or energy cost is at least 200 US$/kW [24].

In environmental criteria, the alternative performance value of the carbon emission sub-criteria obtained data that PHES has carbon emissions of around 15 g CO_2/kWh, BESS around 125 g CO_2/kWh and HESS around 200 CO_2/kWh [23]. HESS has the potential for zero carbon emissions if the process uses green energy or 100% renewable energy. Alternative performance values from PHES obtained supply chain with scale 1, waste management with scale 1, ecological impact with scale 1 and at BESS obtained supply chain with scale 1, waste management with scale 2, ecological impact with scale 1 and at HESS obtained supply chain with scale 2, waste management with scale 1, ecological impact with scale 1 [14].

Alternative performance values from PHES obtained human rights with a scale of 1, social impact with a scale of 1 and at BESS obtained human rights with a scale of 1, social impact with a scale of 1 and at HESS obtained human rights with a scale of 1, social impact with a scale of 2 [14]. For social acceptance based on the evaluation of experts, in Indonesia, especially the Sulbagsel system, it still requires a deeper survey, but in this case it is assessed that in PHES there may be a lot of rejection so that the scale is 3, while for BESS and HESS it is neutral with a scale of 2. In terms of regulation, both PHES, BESS and HESS there are no regulations and policies in Indonesia that discuss more specifically, in this case the experts assessed related regulations on PHES and BESS at level 1 and HESS at level 2.

As the values of the elements are not identical, it is necessary to normalize them in order to equalize the proportion of each variable and ensure a balanced comparison between the sub-criteria. The normalization is calculated using Equation 2. Table IX shows the normalization of the decision matrix for each sub-criterion in relation to the alternatives.

$$a_{ij} = \frac{b_{ij}}{\sqrt{\sum_{i=1}^{n} {b_{ij}}^2}} \quad (6)$$

TABLE IX. NORMALISATION OF THE DECISION MATRIX

Main Criteria	Sub Criteria	A1 : PHES	A2 : BESS	A3 : HESS
C1	C11	0.988	0.148	0.051
	C12	1.000	0.027	0.008
	C13	0.653	0.692	0.307
	C14	0.873	0.218	0.436
C2	C21	0.863	0.173	0.475
	C22	0.408	0.408	0.816
	C23	0.196	0.588	0.784
C3	C31	0.408	0.408	0.816
	C32	0.408	0.816	0.408
	C33	0.063	0.529	0.846
	C34	0.577	0.577	0.577
C4	C41	0.728	0.485	0.485
	C42	0.577	0.577	0.577
	C43	0.667	0.333	0.667
	C44	0.408	0.408	0.816

After obtaining the normalized alternative performance value, the weighting is calculated by multiplying the alternative performance value with the global weight obtained from the AHP method analysis according to the sub-criteria. The weighting of the normalized decision matrix is very important to obtain results and decisions that are more accurate, fair and in line with the main objectives of the evaluation. By weighting the normalized decision matrix, each criterion can be ranked according to its priority or importance, so that alternatives can be taken based on predetermined priorities. Without weighting, each criterion will be considered equally important, leading to inappropriate judgements, especially if there are criteria that are actually more critical for proportional results or decisions. Table X shows the results of weighting the normalized decision matrix.

TABLE X. THE RESULT OF WEIGHTING THE NORMALISED DECISION MATRIX

Main Criteria	Sub Criteria	Global Weight	A1 : PHES	A2 : BESS	A3 : HESS
C1	C11	0.114	0.112	0.017	0.006
	C12	0.306	0.306	0.008	0.003
	C13	0.024	0.016	0.017	0.008
	C14	0.054	0.047	0.012	0.024
C2	C21	0.219	0.189	0.038	0.104
	C22	0.022	0.009	0.009	0.018
	C23	0.060	0.012	0.036	0.047
C3	C31	0.036	0.015	0.015	0.029
	C32	0.008	0.003	0.006	0.003
	C33	0.084	0.005	0.044	0.071
	C34	0.018	0.010	0.010	0.010
C4	C41	0.004	0.003	0.002	0.002
	C42	0.008	0.004	0.004	0.004
	C43	0.030	0.020	0.010	0.020
	C44	0.014	0.006	0.006	0.011

Once the normalized weights have been calculated, the next step is to determine the positive ideal solution and the negative ideal solution. The positive ideal solution, as defined in equation 7, is the sum of all the optimal values that can be achieved for each attribute. In contrast, the negative ideal solution, as defined in equation 8, consists of all the least optimal values achieved for each attribute. Table XI shows the results of the positive and negative ideal solutions.

$$V^{+} = \{v_1^{+} + v_2^{+} + \cdots + v_3^{+}\} \quad (7)$$

$$V^{-} = \{v_1^{-} + v_2^{-} + \cdots + v_3^{-}\} \quad (8)$$

TABLE XI. THE RESULT OF POSITIVE IDEAL SOLUTION AND NEGATIVE IDEAL SOLUTION

Main Criteria	Sub Criteria	V+	V-
C1	C11	0.112	0.006
	C12	0.306	0.003
	C13	0.017	0.008
	C14	0.047	0.012
C2	C21	0.038	0.189
	C22	0.009	0.018
	C23	0.012	0.047
C3	C31	0.015	0.029
	C32	0.003	0.006
	C33	0.005	0.071
	C34	0.010	0.010
C4	C41	0.002	0.003
	C42	0.004	0.004
	C43	0.010	0.020
	C44	0.006	0.011

Furthermore, the Euclidean distance to the positive ideal solution is calculated according to equation 9, the Euclidean distance to the negative ideal solution according to equation 10 and the preference value according to equation 11. The preference value that is the highest or closest to 1 is the optimal alternative of the evaluation. Table XII shows the calculated preference values and the results of the ranking of the alternatives.

$$Ed^{+} = \left[\sum_{j=1}^{n} (V_{ij} - V_j^{+})^2\right]^{0,5} \quad (9)$$

$$Ed^{-} = \left[\sum_{j=1}^{n} (V_{ij} - V_j^{-})^2\right]^{0,5} \quad (10)$$

$$P_s = \frac{Ed_i^{-}}{Ed_i^{+} + Ed_i^{-}} \quad (11)$$

TABLE XII. PREFERENCE VALUES AND RANKINGS OF ALTERNATIVE

ALTERNATIF	Ed+	Ed-	Psi	Rank
A1 : PHES	0.151	0.288	0.655	1
A2 : BESS	0.241	0.163	0.404	2
A3 : HESS	0.295	0.085	0.224	3

The TOPSIS evaluation showed PHES as the first ranked alternative, BESS as the second ranked alternative and HESS as the third ranked alternative. These results are based on a weighting evaluation using the AHP method to determine the priority and share of each criterion in the evaluation.

C. Sensitivity Test

Sensitivity tests are carried out to test whether changes in the weights of the criteria in the AHP-TOPSIS analysis can affect the ranking or the final results of the alternatives evaluated. The sensitivity test is used to ensure that the results of the decisions made are robust and remain optimal. If the ranking results change after a small change in weight or are very sensitive to changes in weight, the results or decisions will be less stable.

In the sensitivity test, the weight of each criterion is changed with test values of -15%, -10%, -5%, +5%, +10% and +15%. Table XIII shows the results of the alternative sensitivity test to changes in criteria weights.

TABLE XIII. ALTERNATIVE SENSITIVITY TEST RESULTS

Alternatif	Test Value	Rank		
		A1 : PHES	A2 : BESS	A3 : HESS
C1	-15%	1	2	3
	-10%	1	2	3
	-5%	1	2	3
	5%	1	2	3
	10%	1	2	3
	15%	1	2	3
C2	-15%	1	2	3
	-10%	1	2	3
	-5%	1	2	3
	5%	1	2	3
	10%	1	2	3
	15%	1	2	3
C3	-15%	1	2	3
	-10%	1	2	3
	-5%	1	2	3
	5%	1	2	3
	10%	1	2	3
	15%	1	2	3
C4	-15%	1	2	3
	-10%	1	2	3
	-5%	1	2	3
	5%	1	2	3
	10%	1	2	3
	15%	1	2	3

The test values applied to each criterion show that the final result has not changed and PHES remains the first ranked alternative, BESS becomes the second ranked alternative and HESS becomes the third ranked alternative.

III. RESULTS AND DISCUSSION

A. Empirical Data of Sulbagsel Electricity System

Based on empirical data obtained from PLN, in 2023 the power plant in the Sulbagsel system is dominated by IPP or private plants with a total production of 6,578,778 MWh or equivalent to 55.49% and PLN's power plants produced only 5,276,273 MWh or 44.51%. In the regulation of electricity sales transaction contracts between IPPs and PLN, the majority of IPPs or private parties have a TOP (Take or Pay) scheme, so that in their operations, IPP plants are always maximized to achieve contract power, even though economically it will be a burden in the amount of electricity BPP (Biaya Pokok Penyediaan) or cost of supply.

TABLE XV. PRODUCTION OF POWER PLANT TYPES IN THE SULBAGSEL SYSTEM IN 2023

Type of Power Plant	Capability (MW)	Production (MWh)	Capacity Factor (%)
Coal	1,021.03	6,177,360	69.07
Hydro	851.33	3,565,545	47.81
Gas	315.00	1,106,608	40.10
VRE	143.00	479,764	38.30
Fuel	275.65	428,532	17.75
Fuel (MFO)	62.20	124,180	22.79
TOTAL IPP	**1,443.00**	**6,578,778**	**52.04**
TOTAL PLN	**1,146.21**	**5,276,273**	**52.55**

Table XV shows the production by generation type in the Sulbagsel system. Among the generation types in the Sulbagsel system, coal-fired power plants still dominate as the largest producer supplying the system in 2023 with a total production of 6,177,360 MWh. In second place are hydroelectric plants with a total production of 3,565,545 MWh, although during this period many hydroelectric plants were affected by El Niño and their production was not optimal. The role of VRE plants, consisting of wind and solar power plants, is 479,764 MWh, where VRE plants are very vulnerable to intermittency and natural conditions.

In the Sulbagsel system, there are wind power plants with high intermittency, such as Sidrap 70 MW and Tolo 60 MW, both of which do not yet have firming batteries, so the production fluctuates and greatly affects the reliability of the system. In terms of load profile, wind power plants experience a decrease in daily production at night and annual production in the fourth semester in accordance with seasonal conditions that greatly affect wind discharge.

The capacity of VRE's hydropower plants in the Sulbgasel system reaches 852.9 MW, with large capacity hydropower plants such as Poso 515 MW, Malea 90 MW and Bakaru 126 MW. The hydropower plants are operated as peak load generators and their production is maximized at peak load times or only when needed. In the case of a power deficit in 2023, the condition of the hydropower plant experienced a decrease in capacity and water discharge due to El Nino, when the condition of other plants entered a period of maintenance and disruption, so that the hydropower plant could not meet the load demand, especially during peak load. At that time, the deficit of the Sulbagsel system reached 600 MW, although all the existing plants were operating optimally.

The lessons learnt from the power deficit of the Sulbagsel system in 2023 led PLN to re-evaluate the management of system operation and power plant operation so that the same incident would not be repeated in 2024. However, in October 2024, the Sulbagsel system was again in a critical period with no power reserves. This was due to a plant suddenly leaving the system due to a fault.

B. Best Alternative in Sulbagsel Electricity System

The results of the weighting in the AHP method are shown Table VII, obtained three sub-criteria that have the highest weight, namely power rating with a weight of 0.282, investment cost with a weight of 0.218 and energy rating with a weight of 0.118. The final result of the TOPSIS method evaluation shown in Table XII, PHES is the first ranked alternative with a preference value of 0.655, while BESS has a preference value of 0.404 and HESS has a preference value of 0.224. The evaluation results were then subjected to a sensitivity test and based on Table XIII, the final results did not change and PHES remained the first ranked alternative, BESS became the second ranked alternative and HESS became the third ranked alternative.

An ideal capacity of the ESS depends on the needs of its use, such as smoothing or firming to overcome short-term system fluctuations with a capacity of around 10-20% of VRE generation, balancing or balancing daily loads with a capacity of 20-30% of VRE generation, or deeper penetration with a capacity of up to 100% of VRE generation capacity. The ESS required in the Sulbagsel system, based on load profile evaluation and expert opinion, has a minimum capacity of 200 MWh for safe system conditions. This capacity is related to the largest VRE generating unit and system conditions that have experienced deficits of up to 600 MW, so that at least 30% of the power is required.

In the ESS scenario required in the Sulbagsel system of 200 MWh, an investment of 200 million US dollars is required or at the rupiah exchange rate against the US dollar on November 14th, 2024 (1 US dollar = Rp 15,882.95), the required investment cost is about Rp 3.18 trillion, although this figure can be reduced due to natural factors in the Sulbagsel system where there are already existing reservoirs that can be used as PHES, so the construction is half complete.

Technically, PHES is implemented together with existing hydropower plants that have reservoirs or water source reservoirs such as the Poso, Bilibili or Bakaru. Bilibili hydropower plant, for example, with a reservoir storage capacity of up to 290 million cubic metres and a maximum head height of 50.71 meters can be used as a PHES that can handle power fluctuations in the Sulbagsel system. This scheme still needs more specific research related to water sources, water utilization and environmental assessment.

PHES as the best ESS alternative in the Sulbagsel power system is based on system conditions that require a high-capacity ESS, in addition to the geographical potential of the Sulbagsel system supporting the existing reservoirs that can be utilized. PHES is technically proven to have a very large power and energy capacity and has the potential to be used to support system reliability with high VRE. Economically, PHES requires a high cost to develop, but the Sulbagsel system already has the potential, so the cost can be reduced.

System stability and reliability will be met with the implementation of ESS during the lean season and annual seasonal variations in the South Sulawesi system. Generation management planning and load management will become very important to ensure sufficient power supply to the system and to optimize BPP to keep it to a minimum.

The implementation of PHES will have an impact on the achievement of the Government's energy mix and NZE (Net Zero Emission) targets, as ESS can support VRE and renewable energy plants to reduce reliance on fossil fuel or high carbon emission plants. PHES does not use chemicals, so there is no risk of waste, and with long lifetimes of up to 60 years and high efficiencies of up to 85%, ESS solutions are economical and sustainable in the long term.

In addition to the opportunities for system stability and increasing the renewable energy mix, the implementation of PHES in the Sulbagsel system has local economic and tourism benefits. The construction of reservoirs or dams can provide water sources for the community's needs for drinking water, irrigation and industry. Reservoirs and dams can also be used for flood control, aquaculture and even as a promising nature tourism facility for the surrounding community.

The implementation of PHES in the Sulbagsel system also faces several challenges in terms of financing, regulation and operation. High investment costs are the main obstacle to the development of PHES, and long-term funding is needed either from investors, international financial institutions or the government, with economic risks that need to be carefully considered. Government policies on renewable energy and ESS are still not legally regulated and need to be accelerated to support the implementation of PHES in the Sulbagsel system or nationally. Regulations are needed to address ESS licensing, environmental impact analysis and tariff setting, as well as incentives for investment in renewable energy. One of the operational challenges is the availability of water sources, which is strongly influenced by seasonality and climate change, the potential of each region and its geographical conditions greatly affect long-term operations. The integration of PHES into the electricity system is also a challenge, as the location of PHES requires the construction of a transmission network and must be adapted to the needs of the system.

IV. Conclusion

Based on the research result, the best ESS alternative to be implemented in the South Sulawesi Electricity System is PHES with a preference value of 0.655, BESS is in second place with a preference value of 0.404 and HESS is in last place with a preference value of 0.224. The sensitivity test shows that the decision is robust because the ranking of the alternatives remains the same, namely PHES first, BESS second and HESS third, even if the weight of each criterion is changed by a value of -15%, -10%, -5%, +5%, +10% and +15% of the decided weight.

References

[1] M. Faisal, M. A. Hannan, P. J. Ker, A. Hussain, M. Bin Mansor, and F. Blaabjerg, “Review of energy storage system technologies in microgrid applications: Issues and challenges,” *IEEE Access*, vol. 6, pp. 35143–35164, 2018, doi: 10.1109/ACCESS.2018.2841407.

[2] PLN, “Rencana Usaha Penyediaan Tenaga Listrik (RUPTL) PT PLN (Persero) 2021-2030.,” *Rencana Usaha Penyediaan Tenaga List. 2021-2030*, pp. 2019–2028, 2021.

[3] S. Freeman and E. Agar, “The impact of energy storage on the reliability of wind and solar power in New England,” *Heliyon*, vol. 10, no. 6, p. e27652, 2024, doi: 10.1016/j.heliyon.2024.e27652.

[4] Indonesia Fuel Cell and Hydrogen Energy (IFHE), “Indonesia Hidrogen Roadmap,” *IFHE Press*, 2023.

[5] Z. Arifin, “Peluang Pemanfaatan Energy Storage berbasis Hydrogen / NH 3 di Sistem Ketenagalistrikan di Indonesia Dr . Zainal Arifin,” no. June, 2021, doi: 10.13140/RG.2.2.24483.78884.

[6] X. Luo, J. Wang, M. Dooner, and J. Clarke, “Overview of current development in electrical energy storage technologies and the

application potential in power system operation," *Appl. Energy*, vol. 137, pp. 511–536, 2015, doi: 10.1016/j.apenergy.2014.09.081.

[7] M. Liaqat, Y. Y. Ghadi, M. Adnan, and M. R. Fazal, "Multicriteria Evaluation of Portable Energy Storage Technologies for Electric Vehicles," *IEEE Access*, vol. 10, pp. 64890–64903, 2022, doi: 10.1109/ACCESS.2022.3183105.

[8] S. Serag, A. Echchelh, and B. Morrone, "Hydroelectric and Hydrogen Storage Systems for Electric Energy Produced from Renewable Energy Sources," *Energy Eng.*, vol. 0, no. 0, pp. 1–10, 2024, doi: 10.32604/ee.2024.054424.

[9] M. A. and F. A. Rahmanta, "Study on the potential and technology of pumped storage hydropower (PSH) in Indonesia," vol. 2646, no. 1, 2023, doi: https://doi.org/10.1063/5.0113762.

[10] M. Stocks, A. ; Blakers, C. Cheng, and B. Lu, "Towards 100% renewable electricity for Indonesia: the role for solar and pumped hydro storage," *Int. Conf. Technol. Policies Electr. Power Energy*, 2019, doi: 10.1109/IEEECONF48524.2019.9102581.

[11] M. Maio, E. Marrasso, C. Roselli, M. Sasso, N. Fontana, and G. Marini, "An innovative approach for optimal selection of pumped hydro energy storage systems to foster sustainable energy integration," *Renew. Energy*, vol. 227, no. November 2023, p. 120533, 2024, doi: 10.1016/j.renene.2024.120533.

[12] M. Yuan, P. Sorknæs, H. Lund, and Y. Liang, "The bidding strategies of large-scale battery storage in 100% renewable smart energy systems," *Appl. Energy*, vol. 326, no. August, p. 119960, 2022, doi: 10.1016/j.apenergy.2022.119960.

[13] J. Li *et al.*, "Modeling of Large-Scale Hydrogen Storage System Considering Capacity Attenuation and Analysis of Its Efficiency Characteristics," *Energy Eng. J. Assoc. Energy Eng.*, vol. 121, no. 2, pp. 291–313, 2024, doi: 10.32604/ee.2023.027593.

[14] T. Balezentis, D. Streimikiene, and I. Siksnelyte-Butkiene, "Energy storage selection for sustainable energy development: The multi-criteria utility analysis based on the ideal solutions and integer geometric programming for coordination degree," *Environmental Impact Assessment Review*, vol. 91. 2021. doi: 10.1016/j.eiar.2021.106675.

[15] A. M. Alonso, D. Costa, M. Messagie, and T. Coosemans, "Techno-economic assessment on hybrid energy storage systems comprising hydrogen and batteries: A case study in Belgium," *Int. J. Hydrogen Energy*, vol. 52, pp. 1124–1135, 2024, doi: 10.1016/j.ijhydene.2023.06.282.

[16] F. Sitorus and P. R. Brito-Parada, "The selection of renewable energy technologies using a hybrid subjective and objective multiple criteria decision making method," *Expert Syst. Appl.*, vol. 206, no. May 2021, p. 117839, 2022, doi: 10.1016/j.eswa.2022.117839.

[17] A. Kumar *et al.*, "A review of multi criteria decision making (MCDM) towards sustainable renewable energy development," *Renew. Sustain. Energy Rev.*, vol. 69, no. October 2016, pp. 596–609, 2017, doi: 10.1016/j.rser.2016.11.191.

[18] F. Zoma and M. Sawadogo, "A multicriteria approach for biomass availability assessment and selection for energy production in Burkina Faso: A hybrid AHP-TOPSIS approach," *Heliyon*, vol. 9, no. 10, p. e20999, 2023, doi: 10.1016/j.heliyon.2023.e20999.

[19] N. Pang, Q. Meng, and M. Nan, "Multi-Criteria Evaluation and Selection of Renewable Energy Battery Energy Storage System-A Case Study of Tibet, China," *IEEE Access*, vol. 9, pp. 119857–119870, 2021, doi: 10.1109/ACCESS.2021.3107192.

[20] W. Chanpuypetch, J. Niemsakul, W. Atthirawong, and T. Supeekit, "An integrated AHP-TOPSIS approach for bamboo product evaluation and selection in rural communities," *Decis. Anal. J.*, vol. 12, no. May, p. 100503, 2024, doi: 10.1016/j.dajour.2024.100503.

[21] M. Çolak and İ. Kaya, "Multi-criteria evaluation of energy storage technologies based on hesitant fuzzy information: A case study for Turkey," *J. Energy Storage*, vol. 28, no. January, 2020, doi: 10.1016/j.est.2020.101211.

[22] S. W. Chisale and H. S. Lee, "Evaluation of barriers and solutions to renewable energy acceleration in Malawi, Africa, using AHP and fuzzy TOPSIS approach," *Energy Sustain. Dev.*, vol. 76, no. July, p. 101272, 2023, doi: 10.1016/j.esd.2023.101272.

[23] IRENA, *Electricity storage and renewables: Costs and markets to 2030*, no. October. 2017. [Online]. Available: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Oct/IRENA_Electricity_Storage_Costs_2017.pdf

[24] IRENA and IEA-ETSAP, "Technology Brief - Electricity Storage," no. April, p. 28, 2012.