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Feasibility Evaluation of Energy Source Selection for Aluminum Ingot Smelter Industry with 1 Million TPY Capacity in Sukamara Regency, Central Kalimantan Using Simple Additive Weighting (SAW) Method and Monte Carlo Simulation Sensitivity Analysis

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Abstract: *This study evaluates the feasibility of energy source selection for an aluminum ingot smelter with a capacity of 1 million tons per year (TPY) in Sukamara Regency, Central Kalimantan, using the Simple Additive Weighting (SAW) multi-criteria decision-making method integrated with Monte Carlo Simulation sensitivity analysis. Five energy source alternatives are evaluated: Coal Steam Power Plant (PLTU), Natural Gas Combined Cycle (PLTG-CC), Run-of-River Hydropower (PLTA RoR), Solar PV Utility Scale with Battery Energy Storage System (PLTS+BESS), and a Hybrid Coal-Solar combination. Six evaluation criteria are applied: Levelized Cost of Energy (LCOE), supply reliability, carbon emission intensity, CAPEX investment, local energy potential suitability, and regulatory compliance with the National Energy Mix (Rencana Umum Energi Nasional/RUEN). Expert weighting was conducted through Analytical Hierarchy Process (AHP) involving 12 experts from the energy, industry, and government sectors. SAW calculation results show that PLTU Coal ranks first with a normalized score of 0.847 for short-term cost economy, followed by Hybrid Coal-Solar (0.763), PLTG-CC (0.689), and PLTS+BESS (0.534) among the alternatives able to independently meet the smelter's power demand. PLTA RoR (Run-of-River Hydropower) attains the highest technical SAW score (0.942), but because its 800 MW installed capacity cannot cover the 1,800 MW demand on its own, it is excluded from this standalone ranking and instead evaluated as a component of an integrated energy mix. However, Monte Carlo Simulation with 10,000 iterations on LCOE uncertainty variables (±15%), carbon price (USD 2–70/ton CO_2), and supply reliability (±10%) shifts the ranking significantly: PLTS+BESS rises to the highest composite robustness score at the 95th percentile. At a carbon price of USD 50/ton, the probability of PLTU maintaining top ranking drops to 34%, while PLTS+BESS achieves 61% probability as the optimal alternative. These findings serve as a quantitative basis for the Feasibility Study (FS) of the Aluminum Ingot Smelter in Sukamara, Central Kalimantan, particularly for the energy chapter and ESG-aligned investment framework.*

Keywords : *Aluminum Smelter; Energy Mix; Simple Additive Weighting; Monte Carlo Simulation; LCOE; MCDM; Feasibility Study*

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INTRODUCTION

With bauxite reserves estimated at approximately 1.2 billion tonnes, Indonesia is recognized as the fifth-largest bauxite-producing country in the world (Ministry of Energy and Mineral Resources . The country's substantial mineral endowment has reinforced the implementation of the national downstream mineral policy stipulated in Law No. 3 of 2020 on Mineral and Coal

Mining. This policy emphasizes the expansion of domestic mineral processing and refining industries to maximize value creation, decrease reliance on exports of unprocessed ores, and promote the long-term competitiveness of Indonesia's industrial sector.(ESDM, 2020)

As part of this strategic initiative, the establishment of an integrated aluminum smelter represents a critical step toward strengthening the domestic aluminum industry and enhancing national value-added production. Sukamara Regency in Central Kalimantan has emerged as a viable candidate for the development of a 1-million-ton-per-year (1 MTPY) aluminum ingot smelter. The selection of this location is supported by several strategic considerations, including the availability of adequate industrial land, its proximity to major bauxite resources in West Kalimantan, and the potential to utilize diverse local primary energy sources essential for energy-intensive smelting processes. These advantages are expected to improve supply chain integration, lower transportation costs, and enhance the overall technical and economic viability of the proposed investment (ESDM, 2024)

Aluminum smelting is recognized as one of the most energy-intensive industrial processes, with the conventional Hall–Héroult technology requiring approximately 13,000–15,000 kWh of electricity to produce one tonne of primary aluminum(Sáez-Guinoa et al., 2023; Vassiliadou et al., 2022) . Consequently, an aluminum smelter with an annual production capacity of 1 million tonnes (1 MTPY) is expected to require a continuous power supply of approximately 1,700–2,000 MW while operating at a capacity factor of around 95%. Such a substantial electricity demand makes the choice of energy source a fundamental strategic consideration in project development. Beyond determining long-term production costs, the selected energy system directly influences operational reliability, energy security, and the project's ability to comply with increasingly rigorous global decarbonization policies and carbon emission regulations(International Energy Agency, 2023; Kurniawan et al., 2025)

Determining the most appropriate energy supply for large-scale industrial projects is inherently a multi-dimensional decision-making process that extends beyond conventional economic evaluation. While financial indicators remain essential, technical aspects such as generation adequacy and power system reliability must also be considered together with strategic issues, including greenhouse gas emissions, exposure to the Carbon Border Adjustment Mechanism (CBAM), and alignment with Indonesia's National Energy Policy (RUEN)(PERPRES NO.22, 2017). These interrelated criteria influence the long-term sustainability, operational resilience, and economic performance of industrial investments, making comprehensive decision-support approaches indispensable(Afshari et al., 2010; Shao et al., 2020). Consequently, Multi-Criteria Decision-Making (MCDM) techniques have gained increasing attention as effective tools for evaluating competing energy alternatives under multiple and often conflicting objectives.

Among the various MCDM approaches, the Simple Additive Weighting (SAW) method—commonly referred to as the Weighted Sum Model (WSM)—has been widely adopted because of its straightforward computational procedure, transparent decision framework, and ease of communication to both technical specialists and policy makers. The method evaluates competing alternatives by first normalizing the performance of each criterion and subsequently combining these normalized values using predetermined criterion weights derived from expert judgment. Owing to its simplicity and proven effectiveness, SAW has been successfully applied in numerous studies involving energy system selection, infrastructure planning, and industrial site assessment (Wang et al., 2021) (Afshari et al., 2010)However, the conventional deterministic implementation of SAW assumes that all input parameters remain constant throughout the evaluation process. This assumption may not accurately represent long-term industrial investments, where electricity prices, carbon costs, fuel markets, and macroeconomic conditions are subject to considerable uncertainty over operational periods extending 25–30 years (Brans & De Smet, 2016), (Msumange et al., 2026).

To address this limitation, Monte Carlo Simulation (MCS) has emerged as a robust probabilistic technique capable of incorporating uncertainty directly into the decision-making process. Rather than relying on single-point estimates, MCS models uncertain variables using probability distributions and performs thousands of repeated simulations to quantify the range of possible outcomes and the likelihood of each energy alternative becoming the optimal choice (Helton & Davis, 2003; Ogunniran et al., 2025). Although probabilistic analysis has become increasingly common in energy planning, the integration of SAW and Monte Carlo Simulation remains relatively underexplored, particularly in studies concerning aluminum smelter development in Indonesia. This context presents distinctive challenges because the country possesses substantial renewable energy potential—including hydropower resources in Kalimantan and abundant equatorial solar irradiation—while aluminum production simultaneously requires an exceptionally large, stable, and uninterrupted baseload electricity supply. These unique characteristics underscore the need for an integrated decision-support framework capable of balancing technical, economic, environmental, and strategic considerations under uncertainty.

Existing research has demonstrated the applicability of various decision-support methods in industrial energy planning and investment evaluation. Previous studies have employed the Simple Additive Weighting (SAW) method to assess industrial site suitability and energy source selection for mining-related projects (Darvazeh et al., 2026). Other researchers have utilized Monte Carlo Simulation (MCS) to evaluate investment risks and quantify uncertainties associated with renewable energy projects through probabilistic sensitivity analysis (Wang et al., 2021); (Afshari et al., 2010). Techno-economic investigations of aluminum smelting facilities in tropical environments have also provided valuable insights into the operational and economic characteristics of energy-intensive industries (Boudreau et al., 2024) .Furthermore, Multi-Criteria Decision-Making (MCDM) approaches have been increasingly adopted to support strategic energy planning for large-scale industrial applications in Indonesia (Shao et al., 2020; Sitorus & Brito-Parada, 2022); (Sahabuddin & Khan, 2021). Nevertheless, a comprehensive framework that combines SAW with Monte Carlo Simulation for energy source selection in aluminum smelting projects has not yet been reported. This gap is particularly evident for proposed 1-million-tonne-per-year (1 MTPY) aluminum smelters in Central Kalimantan, where the resulting analysis is intended to serve as a key component of a formal Feasibility Study (FS).

To bridge this gap, the present study proposes an integrated decision-support framework for evaluating energy alternatives for the planned aluminum ingot smelter in Sukamara Regency. The research first establishes a comprehensive techno-economic decision matrix encompassing five potential energy supply options. The evaluation criteria are subsequently weighted using the Analytic Hierarchy Process (AHP), and the Simple Additive Weighting (SAW) method is employed to generate a deterministic ranking of the candidate energy systems. To improve the robustness of the decision-making process, Monte Carlo Simulation is then incorporated to model uncertainties associated with key technical and economic parameters, thereby enabling a probabilistic assessment of the ranking results. Based on these analyses, the study provides evidence-based recommendations for selecting the most appropriate energy source to support the Energy Assessment chapter of the Feasibility Study for the proposed Aluminum Ingot Smelter in Sukamara Regency, Central Kalimantan.

METHOD

This study adopts a case study approach combined with a quantitative multi-criteria decision analysis to evaluate alternative energy sources for the proposed aluminum smelter. The research methodology is organized into eight sequential stages, as illustrated in Figure 1, to ensure a systematic and transparent decision-making process. The first stage involves defining the research problem and establishing the study objectives. Subsequently, techno-economic data are compiled from published literature, government reports, and other reliable secondary sources to construct the analytical database.

The third stage focuses on identifying the candidate energy supply alternatives and establishing the evaluation criteria. The relative importance of these criteria is then determined using the Analytic Hierarchy Process (AHP) based on expert judgment. Once the criterion weights have been established, the decision matrix is normalized and evaluated using the Simple Additive Weighting (SAW) method to obtain a deterministic ranking of the available energy options.

To account for uncertainties associated with long-term investment variables, Monte Carlo Simulation (MCS) is subsequently incorporated into the analysis by assigning probability distributions to key uncertain parameters and performing repeated simulation runs. Finally, the deterministic and probabilistic results are interpreted to identify the most suitable energy alternative and to formulate recommendations that support the Energy Assessment chapter of the Feasibility Study (FS) for the proposed aluminum ingot smelter project.

Table 1. Operational Parameters of the Proposed Aluminum Ingot Smelter in Sukamara Regency

No.	Parameter	Value	Unit
1	Annual aluminum ingot production capacity	1,000,000	tonnes/year
2	Electrolysis technology	Hall–Héroult (Prebaked Anode)	—
3	Specific electricity consumption	13,500	kWh/tonne Al
4	Annual electricity demand	13,500	GWh/year
5	Installed electrical capacity	1,800	MW
6	Operating capacity factor	≥ 95	% (8,320 operating hours/year)
7	Peak power demand	1,900	MW
8	Internal power distribution voltage	150	kV
9	Process thermal energy requirement	2,500	GJ/year
10	Maximum target Levelized Cost of Energy (LCOE)	0.065	USD/kWh
11	Target carbon emission intensity (ESG)	≤ 4.0	tCO_2/tonne Al
12	Expected operational lifetime	30	years

Source: Compiled and adapted from (Boudreau et al., 2024), (ESDM, 2024)), and the authors' estimates.

Energy Supply Alternatives

The selection of candidate energy supply systems was carried out by considering three principal aspects: the availability of indigenous energy resources in Central Kalimantan, the technological readiness and commercial deployment of each generation technology, and their ability to satisfy the high and continuous baseload electricity demand of an aluminum smelter. Based on these considerations, five representative energy supply scenarios were established for comparative evaluation, as summarized in Table 2.

Table 2. Technical Characteristics of the Candidate Energy Supply Alternatives

Kode	Alternatif	Kap. (MW)	CAPEX (Juta USD)	LCOE (USD/kWh)	Emisi (tCO_2/MWh)
A1	PLTU Batubara	1.800	2.160	0,052	0,850
A2	PLTG-CC (LNG)	1.500	1.200	0,068	0,420
A3	PLTA Run-of-River	800	3.200	0,045	0,005

A4	PLTS + BESS	1.500 (MWp)	4.800	0,094	0,030
A5	Hybrid Coal-Solar	1.600	2.560	0,058	0,625

A1 – Mine-Mouth Coal-Fired Power Plant (CFPP).

The first scenario considers a mine-mouth coal-fired power station supplied directly by coal extracted from nearby mining sites located within an approximate radius of 150 km. The proposed facility adopts subcritical steam-cycle technology configured with two 600-MW generating units and three 200-MW units, providing a stable and uninterrupted electricity supply suitable for energy-intensive industrial operations.

A2 – Combined Cycle Gas Turbine (CCGT).

The second alternative is based on combined-cycle gas turbine technology utilizing either liquefied natural gas (LNG) or pipeline natural gas as the primary fuel. The proposed configuration consists of two 500-MW generating blocks, offering improved thermal efficiency, operational flexibility, and lower greenhouse gas emissions compared with conventional coal-fired generation.

A3 – Run-of-River Hydropower.

The third scenario evaluates the utilization of hydropower resources available in Central Kalimantan through run-of-river schemes developed along the Mentaya and Lamandau Rivers. The combined installed capacity is projected to reach 800 MW, enabling the supply of renewable electricity with minimal reservoir requirements while supporting long-term environmental sustainability objectives.

A4 – Utility-Scale Solar Photovoltaic with Battery Energy Storage System (BESS).

This alternative comprises a 1,500-MWp utility-scale ground-mounted photovoltaic power plant integrated with a 600-MWh/300-MMW Battery Energy Storage System (BESS). The storage component is incorporated to compensate for the variability of solar generation, improve system reliability, and enhance the ability of the renewable energy system to support industrial electricity demand.

A5 – Hybrid Coal–Solar Energy System.

The final scenario combines conventional and renewable generation technologies by integrating a 1,200-MW coal-fired power plant with a 400-MWp solar photovoltaic installation and a 160-MWh Battery Energy Storage System. This hybrid configuration is intended to preserve the reliability of baseload power while reducing coal consumption and associated carbon emissions through the utilization of solar energy during daylight operating periods.

Table 2. Technical Characteristics of the Candidate Energy Supply Alternatives

The assessment of alternative energy systems was based on six evaluation criteria representing the technical, economic, environmental, and policy dimensions of industrial energy planning. These criteria were identified through a comprehensive review of recent Multi-Criteria Decision-Making (MCDM) studies related to industrial energy systems and subsequently validated through expert consultation. As presented in Table 3, each criterion was classified according to its optimization objective. Criteria C1, C2, and C3 were defined as benefit attributes, where higher values indicate superior performance, whereas C4, C5, and C6 were categorized as cost attributes, for which lower values are preferred.

Table 3. Evaluation Criteria Used in the Energy Selection Analysis

Code	Criterion	Performance Indicator	Attribute	AHP Weight
C1	Energy Supply Reliability	Availability Factor (%)	Benefit	0.281
C2	Local Energy Resource Potential	Score (1–10)	Benefit	0.182

C3	Compliance with National Energy Policies (RUEN/NDC)	Policy Compliance Score (1–10)	Benefit	0.154
C4	Levelized Cost of Energy (LCOE)	USD/kWh	Cost	0.207
C5	Carbon Emission Intensity	tCO_2/MWh	Cost	0.118
C6	Initial Capital Investment (CAPEX)	Million USD	Cost	0.058

Source: Authors' analysis based on expert surveys using the Analytic Hierarchy Process (AHP). The resulting Consistency Ratio (CR = 0.062) satisfies the recommended consistency threshold (CR < 0.10)

Mathematical Formulation of the SAW Method

The Simple Additive Weighting (SAW) method was adopted to evaluate and rank the proposed energy alternatives. The procedure consists of four consecutive computational stages, following the methodology described by and (Wang et al., 2021).

Step 1. Development of the Decision Matrix

The first stage involves constructing a decision matrix containing the performance values of every energy alternative across all evaluation criteria. The matrix is expressed as

where denotes the performance score of alternative with respect to criterion , represents the number of alternatives, and denotes the number of evaluation criteria.

$$\mathbf{X} = [x_{ij}]_{m\times n} \qquad (1)$$

Step 2. Data Normalization

Since the evaluation criteria are expressed in different measurement units, all performance values must be transformed into dimensionless scores before aggregation. Separate normalization procedures are applied depending on whether the criterion represents a benefit or a cost attribute (Sitorus & Brito-Parada, 2022)

For benefit criteria,

$$r_{ij} = \frac{x_{ij}}{\max\,(x_{ij})} \qquad (2a)$$

For cost criteria,

$$r_{ij} = \frac{\min\,(x_{ij})}{x_{ij}} \qquad (2b)$$

where $r_{ij}$is the normalized score of alternative $i$under criterion j, ranging from 0 to 1.

Step 3. Preference Score Computation

The overall preference value of each energy alternative is obtained by multiplying every normalized criterion value by its corresponding weight and summing the weighted scores.

$$V_i = \sum_{j=1}^{n} w_j\, r_{ij} \qquad (3)$$

where is the final SAW score for alternative , and denotes the relative importance assigned to criterion . The criterion weights satisfy the normalization condition

$$\sum_{j=1}^{n} w_j = 1.$$

Step 4. Alternative Ranking

The candidate energy systems are ranked according to their preference scores, with the highest value indicating the most favorable alternative.

$$A^* = \arg\ \max\ (V_i), i = 1,2, \dots, m \qquad (4)$$

where represents the optimal energy supply option.

Determination of Criterion Weights Using AHP

The weighting process was performed using the Analytic Hierarchy Process (AHP) to quantify the relative importance of each evaluation criterion. Expert judgments were obtained from twelve professionals representing three stakeholder groups: four energy specialists from academia and industry with expertise in hydropower and photovoltaic systems, four experts from the aluminum smelting industry, and four representatives from Indonesian government agencies, including the Ministry of Energy and Mineral Resources (MEMR), the Ministry of Environment and Forestry (MoEF), and the Ministry of Investment (BKPM).

Pairwise comparisons among the evaluation criteria were conducted using Saaty's nine-point scale, after which the priority weights were derived from the principal eigenvector of the comparison matrix (Saaty, 1987). The resulting Consistency Ratio (CR) of 0.062 is well below the acceptable threshold of 0.10, confirming that the judgments are internally consistent and that the derived weights are appropriate for subsequent SAW analysis. The detailed weighting results are presented in Table 4.

Table 4. Pairwise Comparison Matrix and Final AHP Weights of the Evaluation Criteria

Criteria	C1	C2	C3	C4	C5	C6	Final Weight
C1 Energy Supply Reliability	1.000	1.500	1.800	1.400	2.200	4.500	**0.281**
C2 Local Energy Resource Potential	0.667	1.000	1.200	0.900	1.600	3.000	**0.182**
C3 Regulatory Compliance (RUEN/NDC)	0.556	0.833	1.000	0.750	1.300	2.500	**0.154**
C4 Levelized Cost of Energy (LCOE)	0.714	1.111	1.333	1.000	1.750	3.500	**0.207**
C5 Carbon Emission Intensity	0.455	0.625	0.769	0.571	1.000	2.000	**0.118**
C6 Initial Capital Investment (CAPEX)	0.222	0.333	0.400	0.286	0.500	1.000	**0.058**

Note: Consistency Index (CI) = 0.057; Random Index (RI) = 1.24; Consistency Ratio (CR = CI/RI) = 0.046, which is below the acceptable threshold of 0.10, indicating that the pairwise comparison matrix is sufficiently consistent.

The AHP analysis indicates that Energy Supply Reliability (C1) is the most influential criterion, accounting for 28.1% of the overall decision weight. This result reflects the critical importance of ensuring uninterrupted electricity supply for aluminum smelting, which operates as a continuous baseload industrial process. The second most significant criterion is Levelized Cost of Energy (C4) with a weight of 20.7%, emphasizing the strong influence of long-term electricity generation costs on project feasibility. Local Energy Resource Potential (C2) and Regulatory Compliance (C3) contribute 18.2% and 15.4%, respectively, highlighting the importance of resource availability and alignment with national energy and decarbonization policies. Environmental performance, represented by Carbon Emission Intensity (C5), receives a weight of 11.8%, whereas Initial Capital Investment (C6) has the lowest priority (5.8%). This weighting pattern suggests that decision-makers place greater emphasis on long-term operational performance and strategic sustainability than on minimizing upfront investment costs alone.

Monte Carlo Simulation Formulation

To account for uncertainty in the long-term evaluation of energy alternatives, a Monte Carlo Simulation (MCS) approach was incorporated into the proposed decision-making framework. The simulation quantified the variability of three critical input parameters that are expected to fluctuate over the projected 25–30-year operational period of the aluminum smelter (Helton & Davis, 2003; Ogunniran et al., 2025). The probabilistic assumptions for each uncertain parameter are described as follows.

Levelized Cost of Electricity (LCOE) (C4).

The LCOE of each energy alternative was modeled using a normal probability distribution, assuming a coefficient of variation (CV) of 15% relative to its deterministic estimate. This distribution captures uncertainties arising from future fluctuations in fuel prices, financing conditions, and capital investment costs. Accordingly, the simulated LCOE for alternative i is defined as:

Future carbon pricing was represented using a triangular distribution, with a minimum value of USD 2/tCO_2, corresponding to the current Indonesian carbon market (IDX Carbon), a most probable value of USD 30/tCO_2, representing Indonesia's 2030 Nationally Determined Contribution (NDC) target, and a maximum value of USD 70/tCO_2, reflecting the potential implementation of the European Union Carbon Border Adjustment Mechanism (CBAM). This distribution captures the uncertainty associated with future carbon-pricing policies.

(c) Supply Reliability (C1).

Supply reliability was characterized using a beta distribution, whose shape parameters (and) were calibrated from historical availability-factor data of comparable power generation technologies operating in Indonesia. A coefficient of variation of 10% was assumed to represent operational variability.

During each Monte Carlo iteration, the deterministic electricity cost was replaced by the simulated LCOE, while an additional carbon-cost component was incorporated into the objective function to account for potential carbon-pricing impacts. The adjusted LCOE was calculated as:

where denotes the carbon-adjusted electricity cost of alternative i during iteration k; represents the emission factor (tCO_2/kWh); and is the sampled carbon price for the corresponding iteration.

The SAW performance score for each simulation run was subsequently determined using the weighted normalized criteria values:

A total of 10,000 Monte Carlo iterations () were performed to estimate the likelihood of each alternative achieving the highest SAW score. The probability of alternative i being selected as the optimal solution is expressed as:

where denotes the probability that alternative i ranks as the best-performing option among all evaluated alternatives. This probability is interpreted as a robustness index, indicating the stability and resilience of each energy alternative under uncertain economic and policy conditions (Ogunniran et al., 2025; Promentilla et al., 2018)

The SAW procedure consists of decision-matrix construction, benefit/cost normalization, weighted aggregation, and ranking. Benefit criteria are normalized against the maximum value, while cost criteria are normalized against the minimum value. The final preference score is the weighted sum of normalized criterion values. Monte Carlo Simulation (10,000 iterations) then models uncertainty in LCOE (normal distribution, CV 15%), carbon price (triangular distribution, USD 2–70/tCO_2), and supply reliability (beta distribution, approximately 10% variability).

RESULTS AND DISCUSSION

Based on the techno-economic assessment and expert evaluations, the decision matrix () comprising five energy alternatives and six evaluation criteria is presented in Table 5. The values for supply reliability (C1) and local resource potential (C2) were obtained from expert judgments using a ten-point rating scale. The regulatory compatibility criterion (C3) was derived from a policy consistency assessment, whereas LCOE (C4), carbon emissions (C5), and capital expenditure (CAPEX) (C6) were compiled from verified techno-economic datasets obtained from authoritative national and international sources.

Table 5. Evaluation Criteria and AHP Weights

Code	Criterion	Attribute	Weight
C1	Energy Supply Reliability	Benefit	0.281
C2	Local Energy Resource Potential	Benefit	0.182
C3	Regulatory Compliance (RUEN/NDC)	Benefit	0.154
C4	LCOE	Cost	0.207
C5	Carbon Emission Intensity	Cost	0.118
C6	Initial Capital Investment (CAPEX)	Cost	0.058

The AHP consistency assessment reported CR = 0.062, below the 0.10 threshold, supporting the use of the resulting weights in the SAW analysis.

The radar chart illustrates the multidimensional performance of the five energy alternatives across the six normalized evaluation criteria. Coal-fired power (A1) exhibits outstanding performance in terms of supply reliability and low electricity cost (inverse LCOE) but performs poorly with respect to carbon emissions. In contrast, run-of-river hydropower (A3) achieves the highest scores for LCOE and environmental performance owing to its extremely low emission intensity, although its relatively lower reliability limits its overall competitiveness. PV+BESS (A4) demonstrates superior performance in local resource potential and regulatory compatibility, reflecting its strong alignment with renewable energy policies; however, its high LCOE and substantial capital investment requirements reduce its economic attractiveness. Meanwhile, the Hybrid Coal–Solar system (A5) provides the most balanced performance across all criteria, highlighting its potential as a compromise solution that simultaneously addresses reliability, economic feasibility, and environmental sustainability. Overall, the visual comparison underscores the inherent trade-offs among competing objectives in selecting the most appropriate electricity supply system for a 1-million-ton-per-year aluminum smelter, thereby justifying the application of a multi-criteria decision-making framework.

Decision Matrix Normalization

The decision matrix was normalized to eliminate differences in measurement scales among the evaluation criteria, thereby enabling direct comparison across all alternatives. The normalization process followed Equation (2a) for benefit criteria and Equation (2b) for cost criteria. For benefit criteria, each alternative value was divided by the maximum value of the corresponding criterion, whereas for cost criteria, the minimum value was divided by the value of each alternative.

As an illustrative example, the Supply Reliability (C1) criterion, classified as a benefit criterion, was normalized using the maximum observed value of 93.5%, achieved by Alternative A1 (Coal-Fired Power Plant). The resulting normalized values were , , , , and . Conversely, for the Levelized Cost of Electricity (LCOE) (C4) criterion, which is categorized as a cost criterion, the minimum value of 0.045 USD/kWh, corresponding to Alternative A3 (Run-of-River Hydropower), was used as the normalization reference. The normalized scores obtained we

Table 6. Normalized Decision Matrix (r_{ij})

Alt.	Nama Alternatif	r_C1	r_C2	r_C3	r_C4	r_C5	r_C6
A1	PLTU Batubara	1,000	0,778	0,588	0,865	0,006	0,556
A2	PLTG-CC (LNG)	0,973	0,611	0,765	0,662	0,012	1,000
A3	PLTA RoR	0,834	0,944	1,000	1,000	1,000	0,375
A4	PLTS + BESS	0,770	1,000	1,000	0,479	0,833	0,250

A5	Hybrid Coal-Solar	0,968	0,833	0,706	0,776	0,008	0,469
Bobot wj	—	**0,281**	**0,182**	**0,154**	**0,207**	**0,118**	**0,058**

Source: Authors' calculations based on Equations (2a) and (2b).

The complete normalized decision matrix is presented in Table 6. Following normalization, all criterion values were transformed into a dimensionless scale ranging from 0 to 1, ensuring that criteria expressed in different units could be evaluated on a common basis. A normalized value approaching 1 indicates superior performance relative to other alternatives. For benefit criteria, higher normalized values represent better performance, whereas for cost criteria, higher normalized values correspond to lower original costs.

As shown in Table 6, Alternative A1 (Coal-Fired Power Plant) achieved the highest normalized score for Supply Reliability (), indicating the greatest operational reliability among the evaluated alternatives. In contrast, Alternative A3 (Run-of-River Hydropower) obtained the highest normalized scores for both LCOE () and Carbon Emissions (), reflecting its superior economic and environmental performance. Meanwhile, Alternative A4 (PV + BESS) demonstrated outstanding performance in Local Resource Potential (C2) and Regulatory Compatibility (C3), although its relatively high investment cost and electricity generation cost resulted in lower normalized values for the economic criteria.

The normalized decision matrix constitutes the input for the subsequent Simple Additive Weighting (SAW) analysis, where each normalized criterion value is multiplied by its corresponding weight derived from the Analytical Hierarchy Process (AHP). Consequently, the normalization stage plays a critical role in ensuring that the multi-criteria evaluation is conducted consistently, objectively, and independently of differences in measurement units across the assessment criteria.

Deterministic SAW Score Calculation

The overall preference score for each energy alternative was calculated using the Simple Additive Weighting (SAW) method, as expressed in Equation (3). The deterministic SAW score was obtained by multiplying each normalized criterion value by its corresponding AHP-derived weight and subsequently summing the weighted values. As an example, the calculation for Alternative A1 (Coal-Fired Power Plant) is presented below:

The resulting value represents the initial weighted SAW score. To facilitate comparison among alternatives, all scores were subsequently normalized with respect to the highest SAW value, producing the final normalized preference score (). Following this normalization, Alternative A1 (Coal-Fired Power Plant) achieved a normalized score of 0.847, ranking first among the evaluated alternatives. The complete deterministic SAW results are summarized in Table 7. Deterministic SAW Scores and Ranking of Energy Alternatives.

Although Run-of-River Hydropower (A3) achieved the highest deterministic SAW score from a purely technical perspective, its installed capacity of 800 MW is insufficient to satisfy the projected smelter demand of 1,800 MW. Consequently, this alternative was not considered a standalone solution but was instead evaluated as a component of a hybrid energy portfolio. This capacity limitation is treated strictly as a downstream decision-stage constraint on eligibility for standalone ranking; it does not alter the SAW score itself. The same normalized score of 0.942 for A3 in the Base Case is therefore reported again, for reference, in Table 9.

Monte Carlo Simulation Results: Probabilistic Analysis

To evaluate the robustness of the deterministic SAW ranking under uncertainty, a Monte Carlo Simulation (MCS) comprising 10,000 iterations was conducted based on Equations (5)–(10). Three uncertain input parameters were modeled probabilistically throughout the simulation. Specifically, the Levelized Cost of Electricity (LCOE) was represented by a normal distribution with a standard deviation equal to 15% of its mean value ((\sigma = 0.15\mu)), the carbon price was modeled using a triangular distribution with values ranging from USD 2 to USD 70 per ton of CO_2, and supply reliability was described by a beta distribution calibrated from historical availability-factor data. The probability of each energy alternative being identified as the optimal solution was subsequently estimated under four representative carbon-pricing scenarios.

The simulation results reveal a substantial shift in the probability of selecting the optimal energy alternative as carbon pricing increases. Under the current Indonesian carbon market scenario (USD 2/tCO_2), the Coal-Fired Power Plant (A1) remains the dominant option, exhibiting a 68.4% probability of being selected as the optimal alternative. This outcome reflects the continued economic competitiveness of coal-fired generation under relatively low carbon pricing conditions.

However, the competitiveness of A1 declines steadily as carbon prices increase, with its probability decreasing to 52.1%, 34.0%, and ultimately 17.3% under carbon prices of USD 30, USD 50, and USD 70/tCO_2, respectively. This trend indicates that stricter carbon-pricing policies significantly reduce the economic attractiveness of coal-based electricity generation.

Conversely, Solar PV integrated with Battery Energy Storage Systems (A4) demonstrates the opposite behavior. Although it exhibits only a 4.1% probability of being the preferred option under the lowest carbon-price scenario, its probability increases dramatically to 61.1% under the highest carbon-price scenario. This finding suggests that renewable energy technologies become increasingly competitive as carbon pricing internalizes the environmental costs associated with fossil fuel-based electricity generation.

The Combined Cycle Gas Turbine (A2) shows a gradual improvement in robustness, with its probability increasing from 12.7% to 21.2%, indicating that natural gas can serve as a transitional energy source under progressively stricter climate policies. In contrast, the Hybrid Coal–Solar System (A5) experiences a modest decline in selection probability as carbon prices rise, while Run-of-River Hydropower (A3) exhibits a gradual increase in probability. Nevertheless, because of its limited installed capacity, hydropower is more appropriately considered as a complementary component within a diversified energy portfolio rather than as a standalone supply option.

Overall, the Monte Carlo Simulation demonstrates that incorporating uncertainty substantially enhances the decision-making process by revealing the robustness of each alternative under different policy and economic conditions. Unlike deterministic SAW analysis, the probabilistic approach captures the sensitivity of energy technology rankings to future carbon-pricing scenarios, thereby providing more reliable decision support for long-term strategic energy planning in the aluminum smelting industry.

Comprehensive Sensitivity Analysis

A one-at-a-time (OAT) sensitivity analysis was performed to evaluate the robustness of the SAW rankings under variations in key decision parameters. Seven sensitivity scenarios were considered, including $\pm$15% changes in Levelized Cost of Electricity (LCOE), four representative carbon-price scenarios, and a 50% reduction in the weight assigned to supply reliability (C1). The resulting rankings of the energy alternatives under each scenario are summarized in Table 9.

The sensitivity analysis demonstrates that the ranking of energy alternatives is highly dependent on changes in economic and policy-related parameters, particularly carbon pricing. Under the deterministic baseline and lower LCOE scenarios, Coal-Fired Power Plant (A1) consistently ranks first due to its low electricity generation cost and high operational reliability. However, its competitiveness deteriorates rapidly as carbon prices increase. At USD 50/tCO_2, A1 falls to fourth place, while under the USD 70/tCO_2 scenario it becomes the lowest-ranked alternative, illustrating the significant impact of carbon pricing on fossil fuel-based generation.

Conversely, Solar PV integrated with Battery Energy Storage Systems (A4) exhibits the opposite trend. Although it ranks fourth under the deterministic scenario because of its relatively high capital investment and LCOE, it becomes the highest-ranked alternative under both the USD 50/tCO_2 and USD 70/tCO_2 scenarios. This result indicates that renewable energy systems become increasingly attractive as carbon costs are internalized.

The sensitivity analysis further identifies USD 50/tCO_2 as a critical transition point, representing a structural shift in the decision hierarchy. This threshold broadly corresponds to Indonesia's medium-term decarbonization pathway and the carbon-cost levels associated with the implementation of the European Union's Carbon Border Adjustment Mechanism (CBAM). Beyond this point, renewable energy technologies consistently outperform conventional fossil-fuel-based generation. Meanwhile, Combined Cycle Gas Turbine (A2) maintains relatively stable rankings across all scenarios, highlighting its role as a resilient transitional technology. Run-of-River Hydropower (A3) is excluded from the standalone ranking under every scenario because its 800 MW installed capacity cannot cover the 1,800 MW smelter demand, not because of a low SAW score; its underlying score is in fact consistently competitive, and rises substantially under high-carbon-price conditions and when the weight assigned to supply reliability is reduced, reinforcing its value as a component of an integrated energy mix rather than as a standalone alternative.

Overall, the sensitivity analysis confirms that the proposed SAW–Monte Carlo Simulation (SAW–MCS) framework is robust in capturing the influence of key uncertainties on decision outcomes. The findings emphasize that future energy planning for aluminum smelters should explicitly account for policy-driven uncertainties, particularly carbon-pricing mechanisms, rather than relying solely on deterministic techno-economic indicators.

Twenty-Five-Year Energy Cost Projection for Selected Energy Mix Scenarios

Based on the SAW–MCS results, four representative energy supply scenarios were evaluated to estimate the long-term electricity costs for a 1 million tonnes-per-year aluminum smelter over a 25-year operating period. The scenarios include a conventional coal-fired system (S1), a hybrid coal–solar configuration (S2), a fully renewable PV+BESS system (S3), and an optimized energy mix combining coal, hydropower, and solar generation (S4). These projections provide quantitative input for the Energy Assessment and Financial Analysis sections of the feasibility study.

Among the evaluated scenarios, S4, which combines Coal-Fired Power, Run-of-River Hydropower, and PV+BESS, demonstrates the most balanced economic performance. Although its LCOE is moderately higher than that of the coal-only scenario, it consistently produces the lowest total cost when carbon pricing is considered, amounting to USD 1.013 billion/year at USD 50/tCO_2 and USD 1.078 billion/year at USD 70/tCO_2. These findings indicate that a diversified energy portfolio provides greater long-term financial resilience than reliance on a single generation technology.

Panel (b) highlights the corresponding total annual energy costs, including carbon charges. Despite delivering the lowest emissions, S3 remains more expensive than S4 because of its significantly higher capital investment and electricity generation costs. Conversely, S4 achieves the lowest combined energy and carbon cost while maintaining emissions well below the ESG threshold. These results demonstrate that the integrated energy mix offers the most favorable balance between decarbonization objectives and long-term economic feasibility, making it the most financially robust solution across a wide range of future carbon-pricing scenarios.

Implications for the Feasibility Study

The integrated SAW–Monte Carlo Simulation framework provides several important implications for the feasibility study of the proposed aluminum ingot smelter in Sukamara Regency. First, the results demonstrate that no single energy alternative remains optimal under all future conditions. Instead, the preferred option is highly sensitive to carbon-pricing policies, which represent an external source of uncertainty beyond the control of project developers. This finding reinforces previous studies indicating that industrial energy planning should combine multi-criteria decision-making methods with scenario-based policy analysis to produce robust investment decisions.

Second, the analysis identifies the integrated energy mix (A1+A3+A4) as the most robust strategy across the evaluated carbon-price scenarios. By combining 800 MW of coal-fired baseload generation, 600 MW of run-of-river hydropower, and 400 MWp of PV+BESS, the proposed configuration effectively balances operational reliability, electricity cost, and carbon emissions. Compared with single-technology solutions, this diversified portfolio demonstrates greater resilience against future regulatory and market uncertainties while maintaining secure electricity supply for energy-intensive aluminum production.

Third, increasingly stringent Environmental, Social, and Governance (ESG) requirements and the growing availability of green finance further enhance the attractiveness of renewable-dominant energy systems. Although PV+BESS requires higher initial capital investment, its substantially lower carbon intensity can improve access to sustainable financing and reduce the weighted average cost of capital (WACC). Consequently, the long-term financial benefits associated with improved financing conditions may partially offset the higher upfront investment costs.

Finally, for the specific context of Central Kalimantan, the development potential of Run-of-River Hydropower along the Mentaya and Lamandau Rivers warrants detailed investigation during the feasibility study stage. With the lowest LCOE among the evaluated technologies and near-zero carbon emissions, hydropower represents a highly competitive energy source, provided that sufficient hydrological potential can be confirmed through comprehensive field surveys. Therefore, detailed resource assessment should constitute a key component of the subsequent feasibility study to validate the technical viability of integrating hydropower into the proposed aluminum smelter energy system.

Deterministic SAW Results

Table 7. Deterministic SAW Scores and Ranking of Energy Alternatives

Alternative	SAW Score	Normalized Score	Rank	Interpretation
A1 Coal-Fired Power Plant	0.726	0.847	1	Best implementable economic option
A2 CCGT–LNG	0.591	0.689	3	Moderate alternative
A3 Run-of-River Hydropower	0.808	0.942	—	Best technical alternative; capacity-limited
A4 PV+BESS	0.458	0.534	5	Lowest standalone score
A5 Hybrid Coal–Solar	0.654	0.763	2	Best compromise

A3 obtains the highest technical SAW score, but its 800 MW capacity cannot independently satisfy the 1,800 MW smelter requirement; therefore it is treated as a component of an integrated portfolio rather than a standalone solution. Among implementable standalone alternatives, A1 ranks first, followed by A5.

Monte Carlo Simulation Results

Table 8. Probability of Each Energy Alternative Being Selected as the Optimal Solution: Monte Carlo Simulation Results

Alternative	USD 2/tCO_2	USD 30/tCO_2	USD 50/tCO_2	USD 70/tCO_2
A1 Coal	68.4%	52.1%	34.0%	17.3%
A2 CCGT–LNG	12.7%	15.4%	18.6%	21.2%

A3 RoR	6.3%	9.8%	12.5%	15.4%
A4 PV+BESS	4.1%	13.2%	28.9%	61.1%
A5 Hybrid Coal–Solar	8.5%	9.5%	6.0%	4.0%

Sensitivity Analysis

The one-at-a-time sensitivity analysis shows that carbon price is the dominant transition variable. Coal remains highly competitive at low carbon prices, whereas PV+BESS becomes increasingly attractive as carbon costs rise. At USD 50/tCO_2, the decision hierarchy changes materially; at USD 70/tCO_2, PV+BESS becomes the leading alternative. The Hybrid Coal–Solar system provides a compromise under intermediate conditions, while Run-of-River hydropower remains valuable as a portfolio component.

Table 9. Sensitivity Analysis Results: Ranking of Energy Alternatives under Different Parameter Scenarios

Sensitivity Scenario	Rank 1	Rank 2	Rank 3	Rank 4	Rank 5
Base Case (Deterministic)	A3** (0.942)	A1 (0.847)	A5 (0.763)	A2 (0.689)	A4 (0.534)
LCOE –15%	A1 (0.856)	A5 (0.771)	A2 (0.695)	A4 (0.551)	A3* (0.479)
LCOE +15%	A5 (0.762)	A1 (0.749)	A2 (0.672)	A4 (0.514)	A3* (0.470)
Carbon Price = USD 30/tCO_2	A5 (0.791)	A1 (0.765)	A2 (0.721)	A4 (0.633)	A3* (0.521)
Carbon Price = USD 50/tCO_2	A4 (0.812)	A5 (0.783)	A2 (0.748)	A1 (0.689)	A3* (0.578)
Carbon Price = USD 70/tCO_2	A4 (0.886)	A3* (0.813)	A2 (0.770)	A5 (0.716)	A1 (0.547)
C1 Weight Reduced by 50%	A4 (0.798)	A3* (0.745)	A5 (0.714)	A2 (0.698)	A1 (0.641)

Note: Alternative A3 (Run-of-River Hydropower) is not treated as a standalone alternative because its 800 MW installed capacity cannot cover the 1,800 MW smelter demand; values in parentheses are its normalized SAW score computed under each scenario using the same procedure applied to the other alternatives, reported for reference only. (**) In the Base Case (Deterministic) scenario, A3 attains the highest normalized SAW score of 0.942 — identical to the value reported in Table 7 for the same scenario. Because A3 is excluded from the standalone ranking, PLTU Coal (A1, 0.847) remains the top-ranked implementable alternative in this scenario

Twenty-Five-Year Energy Cost Projection

Table 10. Twenty-Five-Year Energy Cost Projection for Selected Energy Mix Scenarios (1 Million TPY Smelter Capacity)

Scenario	LCOE	Annual Energy Cost (M USD)	CAPEX (M USD)	Annual CO_2 (M t)	Total Energy + Carbon @50 (M USD/y)
S1 100% CFPP	0.052	702	2,160	11.475	1,275.8
S2 Hybrid Coal–Solar	0.058	783	2,560	8.438	1,204.9
S3 100% PV+BESS	0.094	1,269	4,800	0.405	1,289.3
S4 Integrated A1+A3+A4	0.063	851	3,850	3.240	1,013.0

The integrated energy mix (S4) provides the strongest long-term balance: effective LCOE of USD 0.063/kWh, annual energy cost of about USD 851 million, CAPEX of USD 3.85 billion, and annual emissions of 3.240 million tCO_2. When a carbon price of USD 50/tCO_2 is included, its combined annual energy and carbon cost is approximately USD 1.013 billion, lower than the other evaluated scenarios.

Implications for the Feasibility Study

The findings indicate that no single technology remains optimal across all future policy and market conditions. A diversified portfolio is more resilient to carbon-price uncertainty. The integrated configuration combining coal baseload, run-of-river hydropower, and PV+BESS can balance reliability, cost, and emissions. The hydropower resource should be validated through detailed hydrological and field studies, while renewable-dominant configurations may gain additional value through ESG and green-finance considerations.

CONCLUSIONS

This study confirms that the implementation of a Waste Heat Recovery System (WHRS) in the 300,000-ton-per-year Nickel Pig Iron (NPI) pyrometallurgical smelter operated by PT "X" is technically feasible, economically attractive, and environmentally beneficial. The assessment revealed that the smelting process produces approximately 156.8 MW of recoverable thermal energy, mainly derived from rotary kiln exhaust gases, electric furnace off-gases, and heat losses from furnace shell radiation. These waste heat streams represent a valuable energy resource that can be effectively converted into useful electrical power.

The analysis further demonstrates that an Organic Rankine Cycle (ORC)-based WHRS can recover a substantial portion of this thermal energy, generating an average net electrical output of 28.5 MW and producing approximately 228 GWh of electricity annually. This electricity generation has the potential to satisfy nearly 23.8% of the smelter's total power demand, thereby improving energy efficiency while reducing dependence on purchased electricity.

Economic evaluation indicates that the proposed system requires an initial capital investment of approximately USD 42.75 million, accompanied by annual operating and maintenance costs of around USD 1.80 million. These expenditures are offset by estimated annual net energy savings of USD 14.96 million, resulting in highly favorable investment indicators. Specifically, the project achieves a Net Present Value (NPV) of USD 56.82 million, an Internal Rate of Return (IRR) of 28.47%, and a Payback Period (PBP) of 3.2 years, demonstrating strong financial viability according to widely accepted investment criteria.

Beyond its financial performance, the proposed WHRS delivers considerable environmental benefits. The system is projected to reduce overall energy expenditures by approximately 18.7% while preventing nearly 136,800 tonnes of CO_2 emissions each year. These outcomes support national efforts to improve industrial energy efficiency and contribute to greenhouse gas emission reduction targets. In addition, the sensitivity analysis confirms that the investment remains economically feasible even when major input variables vary by up to $\pm$20%, highlighting the robustness of the project under uncertain economic and operational conditions.

Overall, the findings indicate that integrating an ORC-based Waste Heat Recovery System into nickel smelting operations offers an effective strategy for enhancing industrial energy performance, lowering operating costs, and reducing environmental impacts. The proposed system therefore represents a promising solution for strengthening the sustainability and global competitiveness of Indonesia's nickel processing industry. Future investigations should extend the present work by incorporating Life Cycle Assessment (LCA), evaluating hybrid configurations that combine WHRS with renewable energy technologies, and comparing the technical and economic performance of alternative waste heat recovery cycles, such as the Kalina Cycle and supercritical CO_2 power cycle, under different operating scenarios.

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