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Optimizing The Transition: Strategic Prioritization for Early Retirement of Coal-Fired Power Plants (CFPP) In Java-Madura-Bali

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Abstract – *The Paris Agreement has driven global efforts to reduce greenhouse gas (GHG) emissions, with early retirement of Coal-Fired Power Plants (CFPP) identified as a key strategy. As one of the largest CFPP users, particularly in the Java, Madura, and Bali (JAMALI) regions, Indonesia has developed an energy transition roadmap to reach Net Zero Emissions (NZE), incorporating early CFPP retirement. This research aims to determine the priority order of CFPP to be retired in the JAMALI electricity systems based on Indonesia's roadmap to NZE through a combination of MCDM (Multi-Criteria Decision Making) methods: Analytic Network Process (ANP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). The criteria used in this study were derived from literature reviews and expert Focus Group Discussions (FGDs). The weights of each criterion were obtained by averaging the questionnaire responses using the Weighted Geometric Mean Method (WGMM), and the results were simulated using the Super Decisions Software. The TOPSIS approach was then utilized to formulate the ranking. The following CFPPs were ranked in order of early retirement by the ANP-TOPSIS combination: CFPP A, E, D, F, C, and B. Power flow simulation and expert assessment indicate that CFPP E is considered viable for implementation by 2033.*

Keywords - *Coal-Fired Power Plant (CFPP), Early Retirement, MCDM, ANP, TOPSIS*

I. INTRODUCTION

The 21st session of the Climate Change Conference (COP 21), also known as the Paris Agreement, is a gateway to massive global efforts to minimize global warming to less than 2°C [1]. This agreement became the basis for countries that are members of the United Nations (UN) to participate in the mission of reducing greenhouse gas (GHG) emissions. One of the most effective strategies to reduce GHG is by implementing the early retirement of Coal-Fired Power Plants (CFPPs). In its Emissions Gap Report 2023, the United Nations Environment Programme provides updated data on the level of commitment required by countries to reduce GHG emissions. A reduction of 42 percent is needed by 2030 and 57 percent by 2035 to remain on track for the 1.5°C target [2]. GHG emissions are driven by a range of activities and result from various economic sectors.

One of the sectors, the electricity sector, was the largest source of GHG emission increases contributing 26% of total carbon dioxide ($GtCO_2e$) in 2023 [2]. Several studies have stated that CFPPs are considered the most significant source of greenhouse gas emissions from the electricity sector. In line with these findings, the energy sector has accounted for 70% of total CO_2 emissions over the previous sixty years, primarily due to coal combustion [3],[4],[5],[6]. Therefore, effective strategies to reduce CO_2 emissions are required.

A critical short-term strategy to mitigate the effects of global warming is to rapidly eliminate coal from the mix of energy sources [3],[5],[6],[7]. Early retirement policies are highly feasible due to the availability of cleaner and more affordable alternative fuels, such as renewable energy [4]. Indonesia, as one of the major coal users, is actively participating in the transition toward NZE by 2060. The commitment is articulated in Presidential Regulation No. 112 of 2022 [8]. In which the government encourages the development of renewable energy in the production of electricity and lessens reliance on fossil fuels through a planned roadmap for accelerating the early retirement of CFPP. PT PLN (Persero), as the state-owned electricity company of Indonesia, plays an active role in advancing the national commitment to energy transition. PLN forecasts an accumulated increase of 42.6 GW in renewable power generation capacity by 2034. This accelerated effort supports the company's commitment to achieving NZE by 2060, with a targeted energy mix of 41.5% variable renewables and 58.5% non-variable renewables [9]. To achieve this target, Indonesia has established a long-term Energy Transition Roadmap, extending from

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2021 until 2060, with the first phase of early retirement scheduled for 2031–2035 and followed by the second phase in 2036–2040.

Through this study, an early retirement order preference CFPPs will be developed using a combination of Multi-Criteria Decision Making (MCDM) methods, specifically the Analytic Network Process (ANP) combined with Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) for the ranking method. The ANP is an extended and more comprehensive form of the Analytic Hierarchy Process (AHP), formulated by Saaty in 1980 [10]. On the other hand, TOPSIS is considered relatively simple and easy to apply in a variety of decision-making contexts, offering clear results that are easy for decision-makers to interpret [11].

This study employs three main criteria for selecting CFPP candidates for early retirement. The first is the technical criterion, which includes the sub-criteria of plant age, efficiency, technology, plant factor (PF), and location. The second is the economic criterion, represented by the sub-criterion of fuel cost. The third is the environmental criterion, represented by the sub-criterion of CO_2 emissions.

Relationships among the sub-criteria necessitate the use of the Analytic Network Process (ANP) for weighting, as the technology sub-criterion is considered to influence other sub-criteria, namely efficiency, PF, fuel cost, and CO_2 emissions. The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is then applied to rank the CFPPs. Combining ANP with a ranking approach such as TOPSIS improves flexibility and accuracy in identifying the best options [12]. These two methods support the identification and prioritization of plants that meet the criteria for early retirement. The objectives to be achieved in this research are:

1. To formulate the factors and criteria that determine the early retirement process of CFPPs in support of the NZE policy while still considering the fulfillment of customer needs.
2. To determine the priority order scheme for CFPPs to be early retired based on Power System Control operational data.

II. LITERATURE REVIEW

A. Electricity Business Sustainability

The electricity sector is often seen as a major contributor to declining air quality and accounts for a significant share of national CO_2 emissions [4]. Implementing early retirement policies is a practical option, given the presence of cleaner and more cost-effective energy sources such as renewable energy [5]. As previously discussed, early retirement is a legitimate approach that can be employed to reduce the impact of CO_2 emissions. Therefore, many countries have developed studies on early retirement of CFPPs, including Germany, the United States, Japan, China, and India [13]. Previous studies have employed various methods to identify power plants for early retirement, including the Global Change Analysis Model (GCAM) [3], multidimensional weighting and ensemble index approaches [5], random forest regression [14], AHP - Entropy Weighted Method (EWM) - Linear Probability Model (LPM) [15], and the AHP–PROMETHEE method [16]. This study utilizes a combination of the ANP and TOPSIS methodologies, informed by the literature review and practical application considerations.

B. Analytic Network Process (ANP)

The Analytic Network Process (ANP), developed by Saaty (1999), is a generalization of the Analytic Hierarchy Process (AHP) designed to address complex decision problems involving interdependent and feedback relationships among decision elements [17]. Unlike AHP's strict hierarchy, ANP allows for more realistic modeling through network structures, where elements may influence each other within and across clusters. ANP is especially useful when:

1. Criteria are interdependent.
2. Feedback loops exist between elements.

The ANP process generally follows four steps:

1. Model construction and identification of clusters and elements.
2. Pairwise comparisons to determine local priorities using Saaty's 1–9 scale.
3. Supermatrix formation, capturing all relationships.
4. Limit matrix derivation to obtain global priorities.

C. Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)

The TOPSIS method, introduced by Hwang and Yoon (1981), is a classical Multi-Criteria Decision Making (MCDM) technique based on the concept of a Positive Ideal Solution (PIS) and a Negative Ideal Solution (NIS) [18]. The optimal alternative is the one closest to the PIS and furthest from the NIS. TOPSIS offers several key advantages:

1. Simplicity and efficiency.
2. The ability to rank alternatives based on both benefit and cost criteria.
3. Clear interpretability of results. The decision problem requires non-linear structuring.

The standard procedure of TOPSIS includes:

1. Normalizing the decision matrix.
2. Applying weights to form a weighted normalized matrix.
3. Determining PIS and NIS
4. Calculating the Euclidean distances to PIS and NIS
5. Computing a relative closeness coefficient to rank alternatives

III. METHODOLOGY

This study employed a combined MCDM framework that utilized ANP for weighting criteria [17] and TOPSIS for ranking alternatives [18]. Criteria and sub-criteria were developed through literature review and validated using Focus Group Discussions (FGD) with senior experts from PT PLN (Persero) Unit Induk Pusat Pengatur Beban Jawa, Madura, dan Bali (UIP2B Jamali), known as a power system control in Java, Madura, and Bali region. The analysis in this study is restricted to power plant evaluation within the context of power system control. The three main criteria were considered:

1. Technical: Age, efficiency (Specific Fuel Consumption), technology (subcritical/supercritical), plant factor, location (western, central, eastern).
2. Economic: Fuel Cost
3. Environmental: CO_2 emissions

Based on that sub-criteria, the technology used in CFPP influences efficiency, plant factor, fuel cost and CO_2 emissions. Therefore, this study employs ANP instead of AHP. Fig 1. illustrates the interrelationship among the sub-criteria.

Fifty-five units of CFPP are in operation in the Jamali area. From these, six units were shortlisted based on specific criteria such as connection to 500 kV transmission lines, expected to be under 30 years of age by 2031, and utilization of subcritical or supercritical technologies. The 500 kV transmission lines were selected because these power plants do not serve as backbone facilities in their respective subsystems. The age threshold of 30 years was adopted based on the Director Regulation of PT. PLN (Persero) [19], this regulation defines the typical maximum operational lifespan for CFPP. Subcritical and supercritical technologies were chosen as they represent the two oldest CFPP technologies, while ultrasupercritical units were excluded as their emissions are considered to remain within tolerable limits [20]. Due to the presence of confidential data, the six power plants used in this study are referred to as CFPP A, CFPP B, CFPP C, CFPP D, CFPP E, and CFPP F.

A questionnaire was used to gather the level of importance based on the Saaty scale. The study included 10 participants who had a minimum of 10 years of experience at PT PLN Persero in the Power System Control Unit. The questionnaire results were averaged using the Weighted Geometric Mean Method (WGMM) and used as input for analysis to obtain the global weight for each criterion.

The Analytic Network Process (ANP) was implemented through Super Decisions Software to determine global weights with interdependencies among technology, efficiency, PF, fuel cost, and CO_2 emissions. These weights were applied in the TOPSIS model to generate a priority ranking of CFPP units for retirement. The results of the ANP–TOPSIS combination will be validated by three experts from the Power System Control Unit of PLN.

To evaluate the viability of early retirement scenarios for CFPPs in the Jamali region, this study employed the Power System Simulator for Engineering (PSSE) Software. The objective of the simulation was to evaluate the stability of the system's frequency and system stiffness under various retirement conditions, particularly in response to major system contingencies. Three experts from the Power System Control Unit of PLN will validate the outcomes of the PSSE simulation's results.

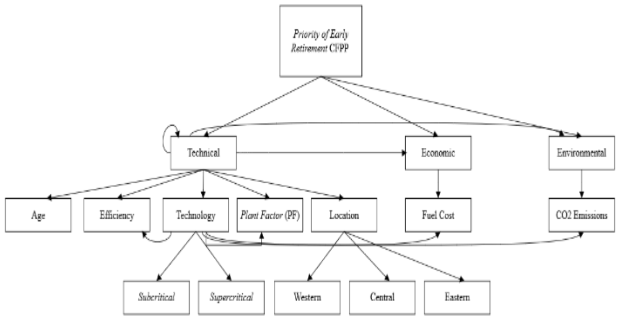

Figure 1 ANP Model of Early Retirement CFPP

IV. FINDINGS AND DISCUSSION

A. Prioritization Results Using ANP-TOPSIS

The integration of the ANP and TOPSIS resulted in a structured prioritization of six CFPP units located in the Java, Madura, and Bali (Jamali) region. The prioritization process was based on a comprehensive framework that took into account technical, economic, and environmental criteria. The ANP global weights showed the most important criteria were:

- Fuel Cost (0.2471): high operational expenses contribute significantly to retirement candidacy.
- CO_2 Emissions (0.0665): shows the plant's environmental impact.
- Plant Factor (PF) (0.0588): Shows the efficiency of capacity utilization.
- Efficiency (SFC) (0.0414): Less efficient units are more likely to be retired.
- Location (0.0185): Regions with lower electricity demands are more likely to be considered for early retirement. In terms of demand levels, the order from lowest to highest is Central, Eastern, and Western.

Using these weights, the TOPSIS method ranked the six candidate units as CFPP A, CFPP E, CFPP D, CFPP F, CFPP C, and CFPP B. The analysis confirmed that the top-ranked units exhibit less favorable performance in most indicators compared to other units. The rankings suggest that CFPP A and CFPP E are the best options for early retirement, primarily due to their age, higher fuel cost, and emission intensity. Furthermore, both CFPP areas encounter transfer limitations due to the transmission system's inability to meet the N-1 contingency criterion. The TOPSIS method relies on operational data from the Power System Control Unit. Operational data such as plant age, specific fuel consumption, technology type, plant factor, fuel cost, and CO_2 emissions were gathered from official PLN Power System Control Annual Reports (Annual Operational Evaluation and Annual Operational Plan). The capacity of each CFPP is shown in Table 1.

Table 1 Capacity of Power Plant

CFPP	Capacity (MW)
A	625
B	625
C	660
D	614
E	830
F	660

B. Early Retirement CFPP Scheme

The early retirement scheme was designed using the available data in the Electricity Supply Business Plan (RUPTL) 2025–2034 period [9], where reserve margin is maintained within the range of 33-35% during the 2031-2035 period. This RM range is considered operationally adequate for the system. If RM exceeds this range, the system becomes more robust. However, the utility must bear the consequence of paying capacity charges for generation readiness that is not directly dispatched. Among the years in that period, 2033 is the only year with a RM above 35%, at 36.4%, which presents an opportunity to consider early retirement of CFPP. Table 2 shows the RM during 2030-2034 and Equation (1) presents the calculation of the reserve margin.

$$\text{Reserve Margin} = (\text{Capacity} - \text{Peak Load}) / \text{Peak Load} \quad (1)$$

Several early retirement scenarios were formulated and assessed based on reserve margin (RM) impacts. The reserve margin is very important for making sure that the electricity supply is reliable during peak load conditions. Table 3 presents the results of the reserve margin calculation.

Table 2 Reserve Margin During 2030-2034

	2030	2031	2032	2033	2034
Capacity (MW)	57,100	59,148	61,759	64,713	65,803
Peak Load (MW)	42,448	44,095	45,708	47,436	49,167
RM (MW)	14,652	14,853	15,851	17,077	16,526
RM (%)	34.5%	34.1%	35.1%	36.4%	33.8%

Table 3 Retirement Scenarios

	Basecase	Single Smallest	Single Largest	Single Top-Ranked
Retired (MW)	-	614	830	625
Capacity (MW)	64,713	64,099	63,883	64,088
Peak Load (MW)	47,436	47,436	47,436	47,436
RM (MW)	17,277	16,663	16,447	16,652
RM (%)	36.4%	35.1%	34.7%	35.1%
Summary	X	X	V	X

	Basecase	Two Smallest	Two Largest	Two Top-Ranked
Retired (MW)	-	1,239	1,490	1,455
Capacity (MW)	64,713	63,474	63,223	63,258
Peak Load (MW)	47,436	47,436	47,436	47,436
RM (MW)	17,277	16,038	15,787	15,822
RM (%)	36.4%	33.8%	33.3%	33.4%
Summary	X	V	V	V

Six retirement scenarios were modeled as follows:

1. Retirement of a single smallest capacity unit (CFPP D)
2. Retirement of a single largest unit (CFPP E)
3. Retirement of the top-ranked unit (CFPP A)
4. Retirement of the two smallest units (CFPP A and D)
5. Retirement of the two largest units (CFPP E and C)
6. Retirement of the top two ranked units (CFPP A and E)

The Results showed that:

- Scenarios 1 and 3 had RM levels higher than the recommended RM range (33–35%), which made them less desirable.
- Scenarios 2, 4, 5, and 6 maintained RM within the acceptable range. Scenario 2 (retiring CFPP E) was the most operationally balanced and technically feasible.

C. System Stability Assessment

To assess the feasibility of early retirement scenarios for CFPPs, this study used Power System Simulator for Engineering (PSSE) software. The goal of the simulation was to assess the frequency stability and system stiffness under various retirement scenarios, particularly in the event of a major system contingency. Simulation Objectives as follows:

- To evaluate the impact of CFPP retirement on frequency deviation during a disturbance
- To ensure that the system remains stable under N-1 contingency conditions, where the largest CFPP (1000 MW) trips unexpectedly
- To determine which retirement scenario has the least impact on grid reliability and reserve margin.

The scenario with a system stiffness value nearest to the base case was selected, as it indicates the most secure condition for the electricity system, preserving stability under standard operational contingencies. The results were validated through interviews with three experts in Operation System. The experts agreed with the prioritization and simulation results that CFPP E should be the first to retire due to its limited dispatch capability because of transmission issues. Retiring both CFPP A and D requires further voltage and protection system analysis, because of the two units are located in different regions (Western and Central Java). The simulation outcomes are shown in the Table 4, Table 5 and Fig. 2.

Table 4 ΔFrequency from PSSE

Scenario	Retired Unit	Capacity (MW)	ΔFreq (Hz)
Base case	-	-	0.6148
2	CFPP E	830	0.6167
4	CFPP A and E	1455	0.6178
5	CFPP E and C	1490	0.6183
6	CFPP A and D	1239	0.6173

Table 5 System Stiffness Result from PSSE

Scenario	Retired Unit	Capacity (MW)	System Stiffness (MW/Hz)
Base case	-	-	1626.48
2	CFPP E	830	1621.43
4	CFPP A and E	1455	1618.58
5	CFPP E and C	1490	1617.34
6	CFPP A and D	1239	1620.00

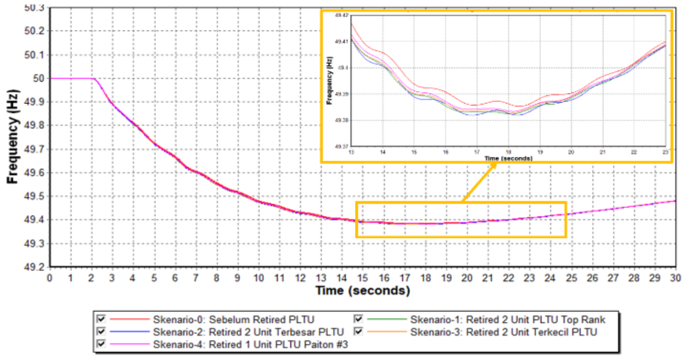

Figure 2 Frequency Stability

V. CONCLUSION

This study presents a comprehensive and data-driven framework for prioritizing the early retirement of CFPPs in Java, Madura, and Bali power systems by integrating the ANP and TOPSIS methods. The study effectively determines the most feasible CFPP units for early retirement based on technical, economic, and environmental criteria. Interdependence among criteria, such as the impact of technology type on fuel cost, emissions, and efficiency. At the same time, TOPSIS made it easy to rank the options in a clear and understandable way. The study showed that CFPP A and CFPP E are the best candidates for early retirement because they cost more to run, are less efficient, and have a bigger impact on the environment than other units.

In addition to the ranking procedure, the study used reserve margin forecasts from the PT PLN Persero Electricity Supply Business Plan 2025–2034 Period to examine the viability of retirement scenarios. This ensures that any proposed retirement does not compromise supply adequacy. The integration of PSSE-based simulations provided an additional layer of validation, which verified that the system would behave very similarly to the base case if CFPP E were retired in 2033. This scenario supported the system's technical and operational viability by keeping frequency variations and system stiffness within safe operating thresholds. The feasibility of the suggested strategy was confirmed by expert validation with senior engineers from PT PLN (Persero), who specifically pointed out that CFPP E runs under dispatch limitations because of transmission constraints, further supporting for the early retirement of CFPP E.

Achieving NZE by 2060 requires the Government and PLN to harmonize and update the Electricity Supply Business Plan as the foundational step of the CFPP early-retirement roadmap. In parallel, system simulations using JROS and DIgSILENT could be conducted to quantify fuel costs and transmission losses arising from early-retirement implementation, thereby clarifying operational and economic trade-offs. Moreover, the proposed framework can be extended to identify candidates among mothballed CFPPs, which are aging, non-operational units that are still maintained.

In conclusion, the proposed ANP-TOPSIS framework, which is improved by simulation and alignment with regulations, can be used for making decisions in countries that are going through an energy transition. It not only helps Indonesia's commitment to the NZE 2060 target, but also ensures that transition measures are technically robust, economically viable, and operationally secure.

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