www.rericjournal.ait.ac.th

Identifying Coal-fired Power Plants for Early Retirement in Java Island - Indonesia

Suksmo Satriyo Pangarso*, [1], Jaka Aminata*, and Nugroho Sumarjiyanto B.M.*

ARTICLE INFO

Article history:
Received 24 March 2025
Received in revised form
07 October 2025
Accepted 27 October 2025

Keywords:
Coal
Early retirement
Indonesia
Net-zero emission
Power plant

ABSTRACT

The Indonesian government has already announced the early retirement of coal power plants as a part of its goal to achieve net-zero emissions (NZE) by 2060 or earlier. However, there has been no in-depth study related to (1) how to choose a power plant that will be retired early and (2) the priority of the power plant that will be retired. This research will provide information about the priority of a coal power plant (CFPP) on Java Island, which is proposed to be retired early by using the fuzzy analytical hierarchy process method. The criteria used in this study are age, performance, generation cost, release of CO2, the number of people affected and the distance of CFPP to a renewable energy source. This study informs that CFPP that is prioritized for early retirement, is the closest power plant to alternative renewable energy sources. The age of the plant and the resulting emissions are the second and third considerations, respectively. Then, we tested the method on 10 sample CFPP (with range capacity 500-1000 MW) on Java Island. The result shows that CFPP-C will be the most prioritized powerplant to be retired first.

1. INTRODUCTION

The 2021 energy balance issued by the Central Bureau of Statistics shows that fossil energy still dominates energy needs in Indonesia. Electricity statistics for 2021 show that the value of per capita electricity consumption is 1,122.60 GWh. The national electricity needs are served by power plants with an installed capacity of 74,532.94 MW. The largest composition of the power plant is a coal-fired power plant (CFPP) with total capacity of 32,705.36 MW [1]. In 2021, CFPP production amounted to 191,122 GWh, or about 66% of national electricity production. About 74% of these power plants are on the island of Java [2]. Based on these data, the success of the energy transition, especially power plants in Java, has a significant effect on the success of the energy transition in Indonesia.

The dominance of CFPP in the electricity system in Indonesia is strongly influenced by the price of electricity from Independent Power Producer (IPP) which is lower than the generation cost of PT PLN (Persero). Figure 1 shows to the generation cost versus PPA tariff for several powerplants in Indonesia. The electricity tariff of CFPP in Indonesia is cheaper than the price of electricity from other plants caused by the price of coal in the country is cheap due to the subsidization policy through the Domestic Market Obligation (DMO) provision. DMO provision provides lower coal prices for power generation purposes. Indonesian Government has issued the regulation which concerning the fulfilment of domestic coal needs in 2021 stated that the selling price of coal for the provision of power plants for public use is USD 70 per metric ton [3]. The price is much cheaper when compared with the price of coal that has the same specifications which are stated another regulation which stipulated the reference of coal prices for July 2023. The regulation set a price of USD 191.60 per metric ton for similar coal[4].

1.1 Net-zero Policy in Indonesia

Indonesia launched the energy transition roadmap towards carbon neutrality at the 26th Conference of Parties (COP) at the Indonesia Pavilion, Glasgow, UK in October 2020 [5]. The roadmap targets that Indonesia will be able to reach net zero emissions (NZE) by 2060 or earlier. The Ministry of Energy and Mineral Resources (MEMR) stated that the principle towards NZE was through several pillars, namely: (1) to increase the use of new and renewable energy, (2) to reduce the use of fossil energy, (3) to increase the use of electric vehicles, (4) to increase the electricity consumption in households and industries, and (5) to utilize the carbon capture and storage (CCS)[6]. The International Energy Agency (IEA) proposes short-term pillars towards NZE by 2060 in the form of efficiency, renewable resources, and electrification [7]. The Institute for Essential Services Reform (IESR) said that the early retirement program of CFPP and replacing it with renewable energy power plants is the most effective thing to achieve NZE by 2060 [8].

DOI: https://doi.org/10.64289/iej.25.0412.6293854

*Doctoral Program in Economics, Universitas Diponegro, Semarang, Indonesia.

[1]Corresponding author:
Email: satriyo.pangarso@gmail.com

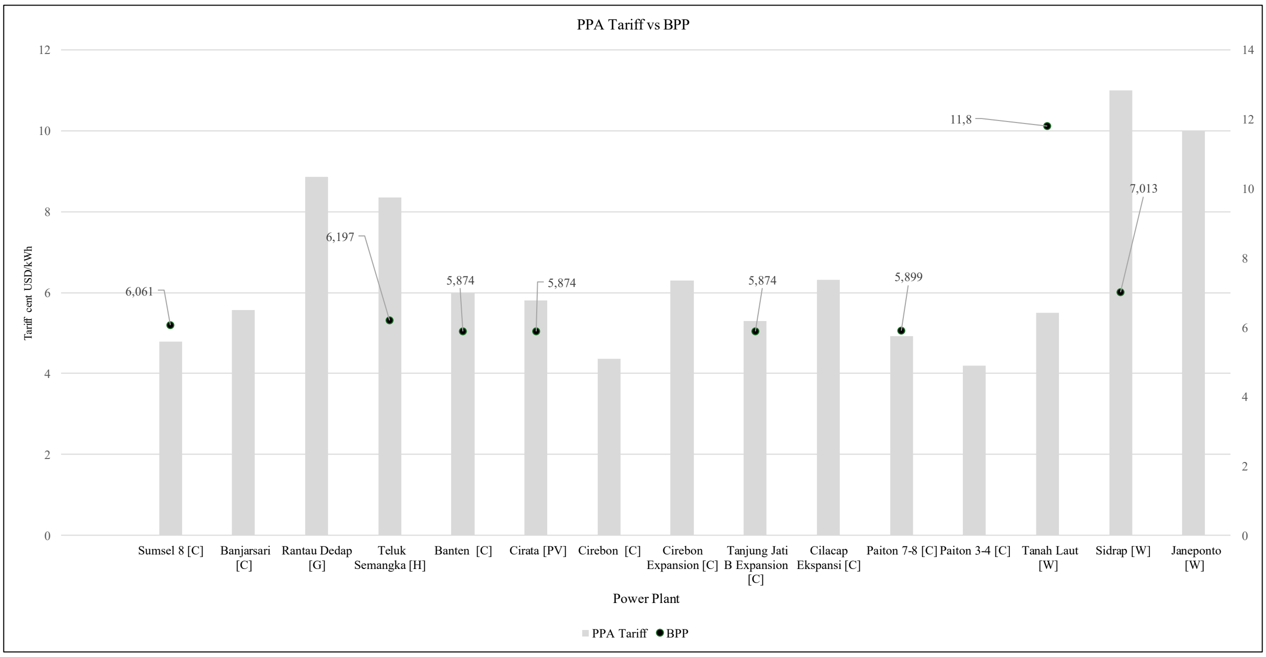

Fig. 1. Electricity tariffs referring to PPA.

Note: C = coal, G=geothermal, H =hydropower, PV = photovoltaic, w =wind

1.2 Early Retirement of Coal Power Plant Policy in Indonesia

Coal phase-out or early retirement for the CFPP program is considered the most prominent option to achieve net-zero emission conditions in Indonesia. However, the program cannot be implemented optimally because there is no roadmap issued by the government [9].

Government of Indonesia has already issued Presidential Regulation concerning the accelerating the development of renewable energy for electricity supply which mentioned the criteria to be concerned regarding early retirement of CFPP of PT PLN (Persero) [10].

1.2.1 Early retirement of coal power plant policy in Indonesia List of CFPP for early retirement program

One of the things that must be agreed upon by stakeholders in the formulation of a roadmap related to the early retirement program is the criterion for power plants that are included in the list of early retirement programs. This needs to be done considering the many proposals for which power plants will be retired early. Energy Transition Partnership (ETP) in their study, which cites an exposure from the MEMR, said that there are 32 power plants throughout Indonesia are eligible for early retirement. Meanwhile, ETP said that there are 12 power plants have met the criterion for early retirement [11].

1.2.2 Criteria to determine CFPP to be retired from previous research

We have analyzed reports and studies proposed to determine the criterion for power plants included in the early retirement program. However, the majority do not explain in detail why these criteria were chosen, how to conduct the selection process, or only highlight one criterion. Research by Edianto *et al*, for example, shows that the resulting CO_2 emissions are the most important factor in the early retirement process of coal-fired power plants in China, the United States, and other countries [12].

Maamoun *et al* rank the order of early retirement of coal-fired power plants based on the age, carbon emissions, and potential air pollution which used data on 2,143 power plants globally [13]. Another research of Maamoun compares the criterion in identifying coal power plants criterion related to early retirement programs based 7 variables divided into 2 sectors, namely the economic–technical sector (age, O&M variable cost, generation efficiency, and distance to coal mines), and the environmental sector (population affected by power plant emissions in India and water usage levels) [14]. The other research uses age, operating costs, and pollution as criterion to prioritize early retirement CFPP globally. Based on this research, the average age of CFPP that is included in the criterion is around 21 years [15].

The research by Cui *et al* uses technical, economic, and environmental criterion. The technical criterion used in this research are age, capacity, combustion technology, application, annual gross profit, CO2, local air pollution, and impacts related to water needs [16].

The Climate Investment Funds (CIF) provide complete input related to the criterion for eligible CFPP in retirement. Starting from aspects of performance (age, installed capacity, type, heat rate, ramp rate, force outage, local electricity conditions, electricity tariffs), contract and licensing aspects (emissions generated, Power Purchase Agreement, Coal Supply Agreement), and environmental and social aspects (CO_2 generated and the economic impact caused) [17].

Table 1 compiles the criteria to determine CFPP to be retired referring to previous research.

Table 1. PPA tariff versus BPP to be PPA tariff versus generation cost.

	Criteria	References
C1	Age	[13][14][18][17]
C2	Performance	[17]
C3	Generation cost	[14][18][17][15]
C4	Released amount of CO_2	[13][14][17][15]
C5	The number of people affected	[13][14][17]
C6	The distance of the CFPP to a renewable energy source	[18][17]

2. RESEARCH METHODOLOGY

2.1 Research Aim

This research aims to determine the criteria that are considered the most decisive in the early retirement program of CFPP. The study began with a literature study to obtain a reference criterion used for the determination of early retirement CFPP. Based on the literature study, there are 6 criteria selected to be tested in this study. The criteria are age, performance, cost of generation, the annual amount of CO_2 released, the number of people affected, and the distance of the CFPP to renewable sources.

2.2 Research Framework

Data was obtained from the questionnaire using Google Forms. We invited 20 respondents who work at 20 CFPPs spread across Indonesia. The respondents have at least 5 years of experience related to CFPP.

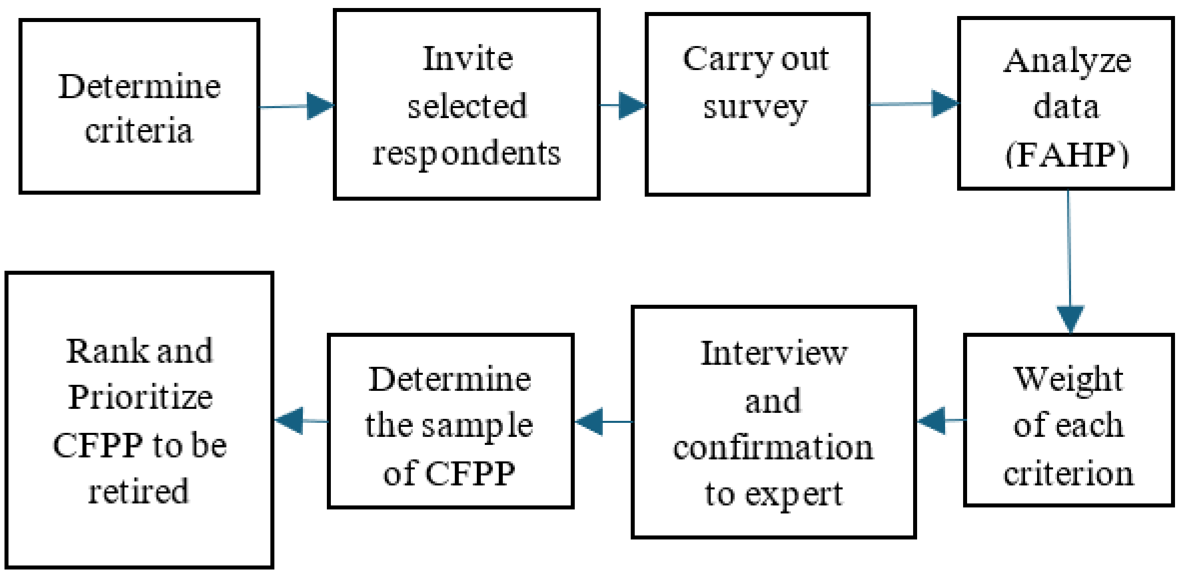

Fig. 2. Research framework.

2.2 Fuzzy Analytical Hierarchy Process

Data is processed using the Fuzzy Analytical Hierarchy Process (FAHP). FAHP is a development of the AHP method developed by Chang [19]. FAHP method is a combination of the AHP method and the Fuzzy concept. FAHP can cover the shortcomings of the AHP method, namely the great subjectivity of each respondent. The Fuzzy method in FAHP can be used to solve the problem of preference equation that may appear in a method that uses a combination of qualitative and quantitative analysis [20].

The main principle of the FAHP method is the extension of the AHP method. The steps of the preparation of the FAHP method start from the preparation of hierarchy, prioritization, and calculation of the consistency ratio (CR). Pairwise Comparison matrix if it has a value of CR<0.1000, then the inconsistency of opinion of decision-making can be accepted, and if the value is not met then the assessment must be repeated. The next process after the consistency condition is met is to do the weighting of TFN, as stated by Chang [19].

The CR calculation refers to Equations 1 and 2:

$$\mathrm{CI} = \frac{\lambda max \ - n}{n - 1} \tag{1}$$

$$\mathrm{CR} = \frac{CI}{RI} \tag{2}$$

where: CI is the consistency index, λ max is the largest principal eigenvalue of a positive reciprocal pairwise comparison matrix, while "n" is a number of criterion and RI is a random index. The value of RI is referred to in Table 3 [21].

Table 2. Random index.

n	2	3	4	5	6	7
RI	0	0,58	0,9	1,12	1,24	1,32

3. EMPIRICAL RESULTS AND DISCUSSIONS

3.1 Validity and Reliability Testing

The most important features of a tool or any measurement instrument are reliability and validity. [22]. In this research, the validity test uses the Pearson Product Moment method, where the data is declared valid if r-count> r-table. While the reliability test uses the Spearman-Brown and Cronbach Alpha method. Calculation using Microsoft Excel software. [23].

Table 4 shows the reliability test results using Spearman-Brown and Cronbach Alpha methods. The data is considered reliable if the value of Alpha Cronbach > 0.700. [24] . While Otavia *et al* categorized the data as " reliable-adequate" if the Alpha Cronbach value is 0.7-0.799 [23].

Table 3. Validity testing using Pearson method.

	C1	C2	C3	C4	C5	C6	Total
X1	5	5	5	4	5	5	29
X2	5	5	5	4	3	3	25
X3	4	5	5	5	5	1	25
X4	1	5	5	3	5	2	21
X5	5	5	5	5	5	5	30
X6	4	3	2	4	4	4	21
X7	5	5	4	4	3	3	24
X8	4	5	5	3	3	4	24
X9	4	4	4	4	3	4	23
X10	4	5	5	4	3	2	23
X11	3	5	3	5	5	2	23
X12	3	4	5	3	4	5	24
X13	2	5	5	5	5	5	27
X14	5	5	5	5	5	5	30
X15	4	4	4	4	4	4	24
X16	3	4	4	5	5	5	26
X17	4	5	4	5	4	5	27
X18	5	5	5	5	5	5	30
X19	3	3	3	4	4	4	21
X20	3	5	4	4	4	3	23
r-count	0,545	0,494	0,546	0,593	0,467	0,580	
r-table	0,444	0,444	0,444	0,444	0,444	0,444	
	Valid	Valid	Valid	Valid	Valid	Valid	

Table 4. Reliability testing using Spearman-Brown and Cronbach Alpha method.

r-count	0,630	Variance	5,3
Spearman	0,773	Total variance	8,84211
r-table	0,444	Alpha Cronbach	0,7994
r-count> r-table			
Conclusion: Reliable			

It can be concluded that the data used is valid and reliable. The data can be used for further research.

3.2 Consistency ratio

The CR calculation process starts with finding the priority vector. Based on (Matrix A) the priority vector of each variable can be obtained. Table 5 shows the value of the priority vector (PV) in each variable (C1-C6). The next step is to find the eigenvalue which is the matrix multiplication between Matrix A with PV. The CR value is 0.035, so the data is consistent.

3.3 Pairwise Comparison matrix, Geomean, and Fuzzy Weight

The first stage of data processing using FAHP is to make a pairwise comparison matrix and find the geometric mean (geomean) of the existing data. This is to reduce the deviation that may occur due to the use of many respondents. Table 6 shows the ranking of each criterion, where criterion 6 (C6: distance to renewable energy source) is the most prioritized criterion for early retirement. The table also shows the weight or score of each criterion.

Table 5. Pairwise matrix, normalization, and priority vector.

	Matrix (A)						Normalization (B)						Sum (B)			(C)	(A x C)	
	C1	C2	C3	C4	C5	C6	C1	C2	C3	C4	C5	C6		PV		λ		
C1	1,0	2,2	1,6	1,3	1,4	1,0	0,2	0,2	0,2	0,2	0,2	0,3	1,2	0,204	1,265	6,2	λ_{max}	6,220
C2	0,4	1,0	0,5	0,3	0,6	0,3	0,1	0,1	0,1	0,0	0,1	0,1	0,4	0,073	0,446	6,1	C1	0,044
C3	0,6	2,0	1,0	0,5	1,0	0,4	0,1	0,1	0,1	0,1	0,1	0,1	0,7	0,119	0,732	6,2	R1	1,240
C4	0,8	3,4	2,1	1,0	0,6	0,4	0,2	0,3	0,2	0,1	0,1	0,1	1,0	0,166	1,025	6,2	CR	0,035
C5	0,7	1,8	1,0	1,7	1,0	0,3	0,2	0,1	0,1	0,2	0,1	0,1	0,9	0,146	0,928	6,3		
C6	1,0	3,2	2,4	2,4	2,9	1,0	0,2	0,2	0,3	0,3	0,4	0,3	1,8	0,292	1,845	6,3		
Sum	4,6	13,6	8,6	7,2	7,4	3,5	1,0	1,0	1,0	1,0	1,0	1,0	6,0	1,0	6,2			

Table 6. Matrix x priority vector.

	C1			C2			C3			C4			C5			C6		
C1	1,0	1,0	1,0	1,9	2,2	2,5	1,3	1,6	1,9	1,1	1,3	1,5	1,2	1,4	1,6	0,9	1,0	1,1
C2	0,4	0,4	0,5	1,0	1,0	1,0	0,4	0,5	0,6	0,2	0,3	0,4	0,6	0,6	0,7	0,3	0,3	0,4
C3	0,5	0,6	0,8	1,7	2,0	2,3	1,0	1,0	1,0	0,4	0,5	0,6	0,8	1,0	1,2	0,4	0,4	0,5
C4	0,7	0,8	0,9	2,9	3,4	4,1	1,7	2,1	2,5	1,0	1,0	1,0	0,5	0,6	0,7	0,4	0,4	0,5
C5	0,6	0,7	0,8	1,5	1,8	2,1	0,9	1,0	1,2	1,4	1,7	2,0	1,0	1,0	1,0	0,3	0,3	0,4
C6	0,9	1,0	1,2	2,8	3,2	3,6	2,0	2,4	2,8	2,0	2,4	2,8	2,4	2,9	3,4	1,0	1,0	1,0

Table 7. Fuzzy weight, normalized, and rank.

	Fuzzy Weight			Mi	Normalized	Rank
C1	0,16	0,21	0,27	0,21	21%	2
C2	0,06	0,07	0,1	0,07	7%	6
C3	0,09	0,12	0,16	0,12	12%	5
C4	0,12	0,16	0,21	0,16	16%	3
C5	0,11	015	0,19	0,15	15%	4
C6	0,23	0,3	0,38	0,30	29%	1

3.4 How to Assess

This study used 10 CFPPs as samples to be tested. We start to assess using criterion and categorization is informed in Table 8. The oldest power plant, the worst performance, the highest generation cost, the greatest emissions produced, the largest number of residents affected and the nearest location to a source of renewable energy, will obtain the maximum points, which is 10.

The points earned by each power plant will be multiplied by the weight of each criterion to get the final score.

3.5 Powerplant Data

The age of the CFPP is calculated from the moment the power plant enters the Commercial Operation Date (COD). We used the average Equivalent Availability Factor (EAF) to show the performance of the power plant [25]. The assumption of EAF for each power plant was taken from the interview to the respondents. While the assumption of emission emitted refers to data of PT PLN (Persero) [26].

Table 8. Criterion, categorization, and final score.

	Criterion	Weight	Categorization		Final score
1	Age	21%	The eldest	Obtain max point (10)	Weight x point
2	Performance	7%	The worst		
3	Generation Cost	12%	The most expensive		
4	Emission	16%	The highest		
5	Affected of Population	15%	The largest		
6	Distance of renewable energy resource	29%	The nearest		

Table 9. Age, EAF, generation cost, and yearly CO_2 emissions.

No	CFPP	No of unit	Total capacity (MW)	Province	Age (yrs)	EAF	Rp/kWh	tCO_2/year
1	A	2	660	Banten	14	79,24%	605	3,149
2	B	3	945	Banten	12	80,81%	533	4,756
3	C	3	1050	West Java	10	76,38%	446	5,151
4	D	3	990	West Java	13	79,46%	469	5,29
5	E	2	660	Central Java	9	74,39%	459	3,269
6	F	1	600	Central Java	18	80,16%	518	2,566
7	G	2	630	Central Java	13	85,41%	434	2,323
8	H	2	560	East Java	11	75,65%	435	2,629
9	I	2	700	East Java	9	75,46%	457	4,068
10	J	2	800	East Java	31	91,92%	447	4,871

3.6 Affected Population

Before the CFPP development process, developers are required to make an environmental impact assessment (EIA). The EIA is a requirement for obtaining an environmental permit [27]. It is undeniable that the main pollutants from CFPP have a significant impact, especially on the health of local communities. Such major pollutants include CO_x, SO_x, NO_x, PM, and heavy metals.[28]. For example, $PM_{2.5}$, Ozone, and NO_x released by CFPP cause asthma.[29]. Meanwhile, the process of indiscriminate disposal of fly ash around CFPP leads to a decrease in the quality of agricultural land and groundwater [30].

The Government of Indonesia has already issued regulation concerning the limit of SO_2, NO_x, PM, and Hg which can be emitted by thermal power plant [31]. In this research, the number of affected populations is indicated by the emission inventory. The emission inventory describes the level of pollution in an area. The higher the level of pollution, it is considered the greater the impact on the area [32]. Table 10 shows the emission inventory in nearby cities.

3.7 Distance from Another Renewable Resource

There are many renewable sources in Java Island, mostly in scattered locations and having a small capacity. We refer to The Business Plan for the Provision of Electricity of PT Perusahaan Listrik Negara (Persero) (RUPTL) for 2021-2031, 2021 [34] and choose the location which has potential and proven capacity of at least 30 MW.

Table 10. Emission inventory in nearby city.

	Nearby city	SOx	NOx	PM
CFPP A	Pandeglang	1.467	978	74
CFPP B	Tangerang	1.333	859	228
CFPP C	Sukabumi	2.200	1.933	315
CFPP D	Indramayu	3.600	5.867	725
CFPP F	Cilacap	4.267	4.133	504
CFPP E	Cilacap	4.267	4.133	504
CFPP G	Rembang	445	1.783	317
CFPP H	Pacitan	357	3.000	183
CFPP I	Tuban	3.700	7.633	1.033
CFPP J	Probolinggo	2.500	6.233	352

SOx: Sulphur oxide; NOx: Nitrogen oxide; PM: Particulate matter. *Source: [33]*

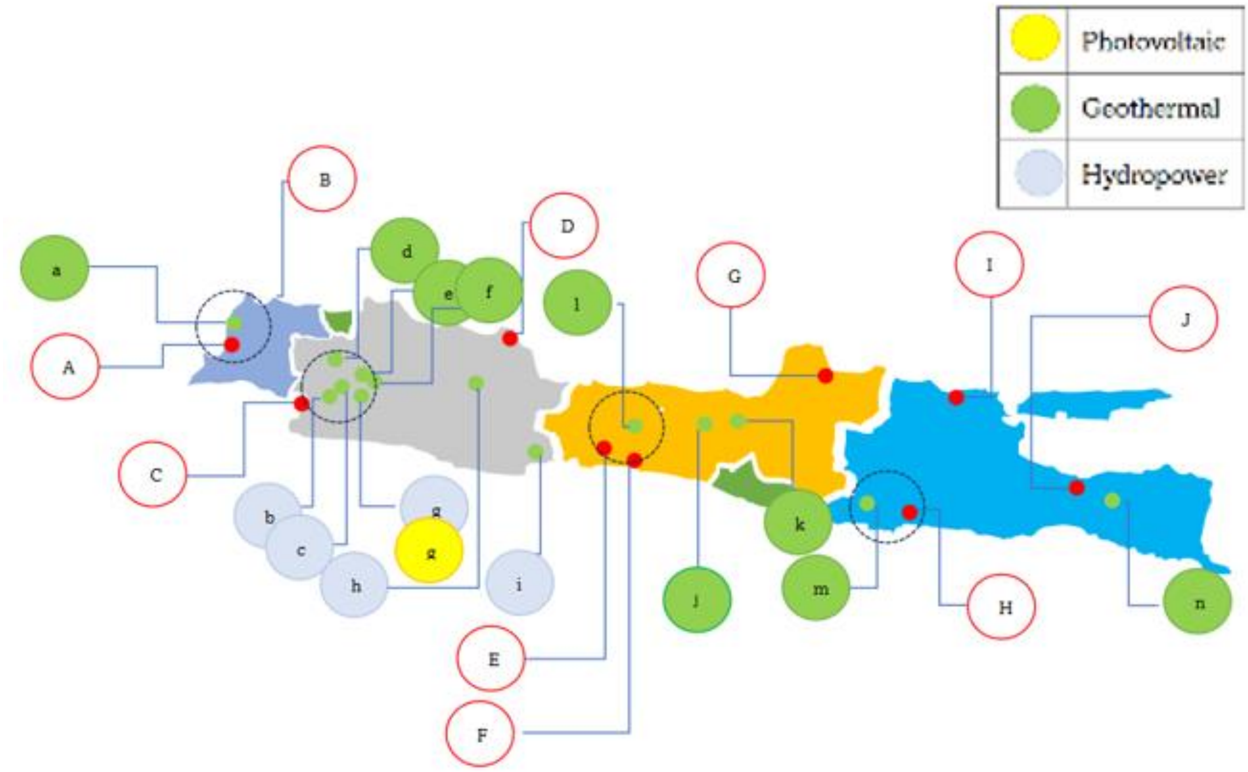

Fig. 3. Distance to renewable energy sources.

Table 11. Nearby renewable energy sources.

	Name	Type	Capacity	Status
a	Rawadano	Geothermal	110 MW	Exploration
b	Rajamandala	Hydropower	47 MW	Operation
c	Upper Cisokan	Hydropower	4x260 MW	Construction
d	Salak	Geothermal	287 MW	Operation
			55+15 MW	Expansion+Binary cycle
e	Patuha	Geothermal	60 MW	Operation
			2 x 55 MW	Expansion
f	Wayang Windu	Geothermal	230 MW	Operation
			60 MW	Expansion
g	Cirata	Hydropower Floating PV	1008 MW	Operation
			192 MWp	
h	Jatigede	Hydropower	110 MW	Construction
i	Matenggeng	Hydropower	4 x235 MW	Development
j	Dieng	Geothermal	60 MW	Operation
			2x55 MW	Expansion
k	Ungaran	Geothermal	55 MW	Exploration
l	Baturaden	Geothermal	75 MW	Exploration
m	Ngebel	Geothermal	55 MW	Exploration
n	Ijen	Geothermal	2x55 MW	Construction

3.8 Result

The result of FAHP analysis show that the criterion of proximity of the CFPP to renewable energy sources is the criterion with the highest weight. Meanwhile, power plant performance is the criterion with the lowest weight. Follow up interview with respondent revealed there is a tendency for early retirement of CFPP to be balanced with the availability of renewable energy as a substitute (in this case, the closest renewable energy source).

We then multiply the points and weights of each criterion for each CFPP (Table 12). The calculation results show that CFPP-C is the powerplant that gets the highest score and is prioritized for early retirement. Successively, CFPP-H and CFPP-G became the next prioritized power plants.

CFPP-C is an area with abundant renewable energy potential, especially geothermal and hydropower. Furthermore, the power plant's age is another key factor for early retirement.

Table 12. Final score.

CFPP	Age		EAF		Rp/kWh		tCO_2/ year		Affected Population		Distance		Final Score	Rank
	21%		7%		12%		16%		15%		29%			
	P	S	P	S	P	S	P	S	P	S	P	S		
CFPP A	8	1,68	6	0,42	10	1,2	4	0,64	1	0,16	2	0,58	4,68	4
CFPP B	5	1,05	3	0,21	9	1,08	7	1,12	1	0,16	10	2,9	6,52	8
CFPP C	3	0,63	7	0,49	3	0,36	9	1,44	5	0,8	1	0,29	4,01	1
CFPP D	6	1,26	5	0,35	7	0,84	10	1,6	9	1,44	9	2,61	8,10	10
CFPP F	9	1,89	4	0,28	8	0,96	2	0,32	7	1,12	3	0,87	5,44	6
CFPP E	1	0,21	10	0,7	6	0,72	5	0,8	7	1,12	4	1,16	4,71	5
CFPP G	6	1,26	2	0,14	1	0,12	1	0,16	4	0,64	8	2,32	4,64	3
CFPP H	4	0,84	8	0,56	2	0,24	3	0,48	3	0,48	5	1,45	4,05	2
CFPP I	1	0,21	9	0,63	5	0,6	6	0,96	10	1,6	7	2,03	6,03	7
CFPP J	10	2,1	1	0,07	4	0,48	8	1,28	6	0,96	6	1,74	6,63	9

3.9 Discussion

As an implementation of Presidential Regulation No. 112/2022, the Indonesian Government issued another regulation states that the Government uses 10 criteria using the Analytical Hierarchy Process (AHP) method to determine which CFPP will be retired early [35]. The regulation states that the most important criterion in early retirement of CFPP is the availability of financial support. However, to date, there has been no example of a CFPP roadmap that has been created and widely published.

The main objective of this study was to obtain a prioritized CFPP for early retirement, according to predetermined criterion. The results showed that the distance between CFPP and renewable sources as a substitute gained the greatest weight (29%) followed by the age of the plant (21%).

The assumption of location, capacity, and certainty of commercial operation date (COD) renewable sources replacement is still unproven. Especially for geothermal, many are still in the exploration stage. Location certainly is a consideration in determining the distance to the CFPP that will be replaced. Certainty of capacity and COD will be a consideration in determining how many CFPPs will be retired early.

On the other hand, we also found that the age of the power plant does not always correlate with the performance of the generator. For example, CFPP-J is 31 years old, but still performs very well compared to younger CFPP (See Table 12). CFPP-J shows better EAF and lower generation cost.

This study also shows that respondents' backgrounds will determine the weighting of each criterion. In this study, respondents selected from CFPP occupations may have limited understanding of financial issues as the impact of early retirement program. Therefore, selecting respondents with diverse backgrounds should be considered in future studies.

The future study also should consider coal phase down program which has been launched by Government of Indonesia, instead of early retirement of CFPP. To maintain electrical energy security while reducing emissions at CFPP, the Government is implementing a control scenario for the addition of coal-fired power plants and fuel conversion using biomass or ammonia fuels (using cofiring or retrofitting methods)[36].

4. CONCLUSION

This research can provide input on how to determine which CFPP is prioritized for early retirement. Based on criterion of age, performance, cost of generation, the amount of CO_2 released each year, and the distance CFPP to renewable resource. The results showed that CFPP-C is a plant that deserves to be prioritized for early retirement at this time.

ACKNOWLEDGMENTS

The authors acknowledge colleagues at CFPP in Indonesia for their support during this study.

AUTHOR CONTRIBUTIONS

S.S.; Conceptualization, methodology, formal analysis, writing-original draft, J.A.; supervision, writing-review and N.S.; supervision, writing-review administration, validation. All authors have read and agreed to the published version of the manuscript.

FUNDING

The authors received no financial support for this study, authorship, and/or publication of this article.

REFERENCES

[1] Indonesian Central Bureau of Statistic, 2023. *Energy Balances of Indonesia 2017-2021* (Volume 25 Number 2, 2023). Jakarta, Indonesia: Central Bureau of Statistic of Indonesia. (BPS Publication Number: 05300.2332).

[2] Indonesian Ministry of Energy and Mineral Resources, 2024. *Electricity Statistic 2023* (37th edition). Jakarta, Indonesia: Directorate General of Electricity of Ministry of Energy and Mineral Resources. (DGE-MEMR Electricity Statistic No. 37-2023).

[3] Government of Indonesia, 2020. *The Regulation of The Minister of Energy and Mineral Resources concerning the fulfilment of domestic coal needs in 2021*. Jakarta, Indonesia. (Decree No. 255.K/30/MEM /2020).

[4] Government of Indonesia, 2023. *The Regulation of The Minister of Energy and Mineral Resources concerning Reference Metal Mineral Prices and Reference Coal Prices for July 2023*. Jakarta, Indonesia. (Decree Number 183.K/MB.01/MEM.B/2023).

[5] Indonesian Minister of Finance., 2021. Press release of Ministry of Finance of Indonesia: ETM Indonesia's new step to accelerate clean energy. Retrieved 12 January 2024 from the website of Ministry of Finance of Indonesia https://www.kemenkeu.go.id/informasi-publik/publikasi/berita-utama/etm-langkah-baru-indonesia-akselerasi-energi-bersi.

[6] Wanhar, 2021. Carbon Trading Trial at Coal-Fired Power Plants. In *Webinar on the Economic Value of Carbon in the Electricity Subsector*. Jakarta, Indonesia, 2 December.: Indonesian Ministry of Energy and Mineral Resources, Directorate of Electricity.

[7] International Energy Agency, 2022. *An Energy Sector Roadmap to Net Zero Emissions in Indonesia*, Paris, France: International Energy Agency. (IEA Special Report 2022).

[8] Cui R., Tumiwa F., Zhao A., Arinaldo D., Wiranegara R., Cui D., Dahl C., Myllyvirta L., Squire C., Simamora P., and Hultman N., 2022. *Financing Indonesia's coal phase-out: A just and accelerated retirement pathway to net-zero.* Jakarta, Indonesia: Joint Research of Center for Global Sustainability, University of Maryland and Institute for Essential Services Reform (IESR).

[9] E. Hamdi and P. Adhiguna. 2021. *Putting PLN's net zero ambition into context: The numbers will need to add up.* Jakarta, Indonesia: The Institute for Energy Economics and Financial Analysis (IEEFA).

[10] Government of Indonesia, 2022. *The Regulation of Presidential of Republic of Indonesia concerning accelerating the development of renewable energy for electricity supply*. Jakarta, Indonesia. (Presidential Regulation number 112/2022).

[11] Hartree, Neyen, and Sakti C.B., 2022. *Study on the financial implications of the early retirement of coal-fired power plants in Indonesia*. Jakarta, Indonesia: UNOP and Energy Transition Partnership (Deliverable 2).

[12] Edianto A., Trencher G., Manych N., and Matsubae K., 2023. Forecasting coal power plant retirement ages and lock-in with random forest regression. *Patterns* 4(7). doi: 10.1016/j.patter.2023.100776.

[13] Maamoun N., Kennedy R., Jin X., and Urpelainen J., 2020. Identifying coal-fired power plants for early retirement. *Renewable and Sustainable Energy Reviews* 126 (April). doi: 10.1016/j.rser.2020.109833.

[14] Maamoun N., Chitkara P., Yang J., Shrimali G., Busby J, Shidore S., Jin Y., and Urpelainen J., 2022. Identifying coal plants for early retirement in India: A multidimensional analysis of technical, economic, and environmental factors. *Applied Energy* 312(11): Art. no. 118644.

[15] Maamoun N., Kennedy R., Peng W., D'souza D., Gray M., Lavelle S., Chau L., Jiménez N.G., Ehrenheim V., Joseph M., and Urpelainen J., 2023. Multi-dimensional and region-specific planning for coal retirements. *iScience*, 26(6): Art. no. 106739.

[16] Cui R.Y., Hultman N., Cui D., McJeon H., Yu S., Edwards M.R., Sen A., Song K., Bowman C., Clarke L., Kang J., Lou J., Yang F., Yuan J., Zhang W., and Zhu M., 2021. A plant-by-plant strategy for high-ambition coal power phaseout in China. *Nature Communication* 12(1): Art. no. 1468.

[17] The Climate Investment Funds, 2023. *A simplified guide to repurpose coal assets*. Washington DC, USA: The CIF Technical Assistance Facility Report.

[18] Jindal A. and G. Shrimali. 2022. Cost–benefit analysis of coal plant repurposing in developing countries: A case study of India. *Energy Policy* 164(January): 112911. doi: 10.1016/j.enpol.2022.112911.

[19] Chang D.Y., 1996. Applications of the extent analysis method on fuzzy AHP. *European Journal of Operational Research* 95(3): 649–655. doi: 10.1016/0377-2217(95)00300-2.

[20] Hossen M.M., Kang S., and Kim J., 2015. Construction schedule delay risk assessment by using combined AHP-RII methodology for an international NPP project. *Nuclear Energy Technology* 47(3): 362–379. doi: 10.1016/j.net.2014.12.019.

[21] Wedley W.C., 1993. Consistency prediction for incomplete AHP matrices. *Mathematical Compution Modeling* 17(4–5): 151–161. doi: 10.1016/0895-7177(93)90183-Y.

[22] Mohajan H., 2017. Two criteria for good

measurements in research: validity and reliability. *Annals of Spiru Haret University* 17(3): 58–82.

[23] Oktavia R., Irwandi I., Rajibussalim T., Mentari M., and Mulia I.S., 2018. Assessing the validity and reliability of questionnaires on the implementation of Indonesian curriculum K-13 in STEM education. *Journal of Physics: Conference Series* 1088. doi: 10.1088/1742-6596/1088/1/012014.

[24] Taber K.S., 2018. The use of Cronbach's Alpha when developing and reporting research instruments in science education. *Research in Science Education* 48(6): 1273–1296. doi: 10.1007/s11165-016-9602-2.

[25] IEEE, 2007. Standard Definitions for Use in Reporting Electric Generating Unit Reliability, Availability, and Productivity. in *IEEE Std 762-2006 (Revision of IEEE Std 762-1987).* pp.1-75. doi: 10.1109/IEEESTD.2007.335902.2007.

[26] PLN, 2023. *Operation Plan 2024 for Java, Madura & Bali Electricity Grid. Internal Document* (unpublished). System Operations Planning Team of Load Dispatcher of Java, Madura and Bali of PT PLN (Persero). Jakarta, Indonesia.

[27] Government of Indonesia, 2021. *Regulation of Minister of Environment and Forestry concerning forestry planning, changing in forest area designation and function, and forest area use*. Jakarta, Indonesia. (Regulation number 7/2021).

[28] Munawer M.E., 2018. Human health and environmental impacts of coal combustion and post-combustion wastes. *Journal of Sustainable Mining* 17(2): 87–96. doi: 10.1016/j.jsm.2017.12.007.

[29] Anenberg S.C., Henze D.K., Tinney V., Kinney P.L., Raich W., Fann N., Malley C.S., Roman H., Lamsal L., Duncan B., Martin R.V, Donkelaar A.V., Brauer M., Doherty R., Jonson J.E., Davila Y., Sudo K., and Kuylenstierna J.K.I., 2018. Estimates of the global burden of ambient PM2:5, ozone, and NO2 on asthma incidence and emergency room visits. *Environmental Health Perspectives* 126(10): Art. no. 3766.

[30] Khan I. and R. Umar. 2019. Environmental risk assessment of coal fly ash on soil and groundwater quality, Aligarh, India. *Groundwater for Sustainable Development* 8: 346–357. doi: 10.1016/j.gsd.2018.12.002.

[31] Government of Indonesia, 2019. *Regulation of the Minister of Environment and Forestry concerning quality standards for thermal power plants*. Jakarta, Indonesia. (Regulation number P.15/2029).

[32] Lestari P., Damayanti S., and Arrohman M.K., 2020. Emission Inventory of Pollutants (CO, SO2, PM2.5, and NOx) in Jakarta Indonesia. IOP Conference Series: Earth and Environmental Science 489(5): Art. no. 012014.

[33] Indonesian Ministry of Forestry, 2024. Online Inventory Emission. Retrieved 10 February 2024 from the website of the Ministry of Environment and Forestry of Indonesia, https://ditppu.menlhk.go.id/simpel/gis/bebanemisi.

[34] Indonesian Ministry of Energy and Mineral Resources, 2021. *The Business Plan for the Provision of Electricity of PT Perusahaan Listrik Negara (Persero) (RUPTL) for 2021-2030*. Jakarta, Indonesia: RUPTL of PT PLN (Persero) 2021-2030.

[35] Government of Indonesia, 2025. *Regulation of Minister of Energy and Mineral Resources concerning Roadmap of Energy Transition of Electricity Sector*. Jakarta, Indonesia. (Regulation number 10/2025).

[36] Indonesian Ministry of Energy and Mineral Resources, 2021. *The Business Plan for the Provision of Electricity of PT Perusahaan Listrik Negara (Persero) (RUPTL) for 2025-2034*. Jakarta, Indonesia: RUPTL of PT PLN (Persero) 2025-2034.