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Mitigation of the Stranded Asset Risk Due to the Implementation of Coal Plants Early Retirement in Indonesia Using Analytical Hierarchy Process

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Abstract

Based on Presidential Regulation Number 112 of 2022 concerning the Acceleration of Renewable Energy Development for the Supply of Electric Power, Indonesia has a road map in which there is a strategy program for accelerating the end of the operational period of PLTUs. In implementing early retirement, there is a risk of stranded assets that needs to be mitigated. Appropriate decision-making strategies and effective mitigation are needed to reduce the impact of stranded asset risk. Using the Anaytical Hierarchy Process (AHP), this study tries to analyze the implementation of the PLTU early retirement strategy by taking into account the risk of stranded assets and finding appropriate mitigation in reducing the level of impact of the risk of stranded assets that needs to be implemented by stakeholders. The results show that effective mitigation requires comprehensive planning and stakeholder involvement, which can substantially ease the financial transitions from coal to renewable energy sources. The findings suggest that integrating economic and policy considerations into the early retirement planning of coal-fired power plants is crucial for managing the transition effectively and minimizing potential financial losses. This approach ensures a smoother transition to sustainable energy sources, contributing significantly to both national and global decarbonization goals.

Keywords: early retirement; coal plant; stranded asset; risk.

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1. Introduction

The energy industry is a significant source of greenhouse gas emissions worldwide, responsible for almost 90% of carbon dioxide emissions and 75% of total greenhouse gas emissions in industrialized nations. Power plants and refineries are accountable for 50% of these emissions due to combustion operations. (Jeon et al., 2010) Dependence on coal as a main energy source worsens this problem. Using just coal for electricity generation can result in greenhouse gas emissions of up to 1.03 kg of carbon dioxide equivalent per kilowatt-hour produced during the whole lifespan. (Froese et al., 2010).

Focusing on Indonesia, the situation is particularly critical. The country's energy production is heavily reliant on fossil fuels, with gas and coal accounting for 83% of the electrical mix. This reliance places Indonesia as the tenth largest producer of greenhouse gases in the world (Silalahi et al., 2023) Moreover, Greenpeace's research suggests a concerning forecast for Indonesia's carbon footprint. Approximately 22,000 MW of electricity—60% of the country's total—will be generated by coal-fired power stations, contributing significantly to greenhouse gas emissions. Between 2019 and 2030, it is estimated that 2,000 MW of these coal-fired power stations alone will produce around 10.8 million tons of carbon emissions annually. If the government's plans for coal power plants in 2019 are realized, the emissions could reach a staggering 1.3 Giga Tons, severely increasing greenhouse gas concentrations (Maskun et al., 2022)

The global shift towards rapid decarbonisation, primarily in the energy sector, underscores the urgency of early retirement for fossil fuel power plants to mitigate the adverse effects of climate change. According to studies by (Kefford et al., 2018) and (Fofrich et al., 2020), achieving significant reductions in CO2 emissions necessitates the near-complete decarbonization of the electric power sector, with a particular emphasis on the substantial early retirement of coal plants. This strategy aligns with the goal of avoiding dangerous climate change by substantially

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reducing fossil fuel emissions, as coal plants must undergo a drastic 99% capacity reduction from 2014 to 2060 to meet the 2°C Scenario (2DS) targets. However, this transition poses challenges, including potential impacts on energy market stability, system reliability, and energy security (Rahmani et al., 2016).

The coal plant early retirement program is not without obstacles, coal early retirement raises new issues related to stranded assets. To achieve the mitigation goals outlined in the Paris Agreement, some countries will need to retire their coal-fired power plants prematurely, meaning before their expected operational lives are completed. This action can result in large amounts of stranded assets (Bruschin et al., 2022). In addition, early retirement of PLTUs can produce residual value on the operating company's balance sheet due to premature termination of operations and carried out before full depreciation. This situation causes the asset to be considered abandoned and needs to be written off, causing financial losses for investors. Additionally, eroding revenues and asset devaluation can force operators to raise prices, adversely affecting consumers, in an effort to recoup their lost investments (Czyzak & Wrona, 2021).

Stranded assets can result in financial losses for generator owners, resulting in asset owners opposing the policy. This is a challenge in itself in implementing early retirement (Angelika et al. 2023). In developing countries, the use of old technology that damages the environment may end up in stranded assets, which means the country spends money on goods that they cannot use or sell, while developing countries may end up being stuck with these stranded assets if the country -rich countries provide them with technology that is outdated and environmentally unfriendly (Bos et al. 2019). Stranded asset risk can affect the amount of money investors are willing to spend on various types of projects, especially those involving fossil fuels such as coal, oil and gas. If investors think that these fossil fuel projects will not make money in the future because of climate change regulations, they may not want to invest in them Curtin et al. (2019). Harrop (2022) states that the implications of stranded assets for the fossil fuel industry are a devaluation of 37% to 50% or 13 to 17 trillion dollars. This could be a strong reason for fossil fuel producers to reject climate stabilization.

To mitigate economic repercussions, a conservative approach to preferential retirement is assumed, aiming to minimize stranded capital and adjust end-of-life retirement rates accordingly. Indonesia, aligning with these global efforts, has initiated policies under Presidential Regulation Number 112 of 2022 to accelerate renewable energy development and phase out coal-fired power plants (PLTU) by 2035, aiming for a zero operational capacity by 2050 (Taufik, 2022). This move is part of Indonesia's commitment to reducing greenhouse gas (GHG) emissions significantly, with targets set in its Updated and Enhanced Nationally Determined Contributions (NDCs), highlighting the country's endeavor to contribute to global decarbonization efforts with and without international support.

The purpose of this study was to address the following research questions: What is the suitable strategy for minimizing the magnitude of stranded asset risk that stakeholders should implement? This study also motivated by the pressing need for a global shift towards rapid decarbonization, particularly in the energy sector, to mitigate the adverse effects of climate change. It draws inspiration from the urgency of implementing early retirement strategies for fossil fuel power plants, and the specific challenges faced by countries like Indonesia. This study is based on the opinions of experts who are experienced in the subject of early retirement coal plants to gain strategic mitigation of stranded asset risk. Furthermore, this study does not calculate in depth quantification of the risk of stranded assets themselves.

2. Literature Review

2.1. Early retirement

Early retirement refers to decommissioning of power-generating assets before reaching their expected physical life. This concept is implied in the context of changing environmental regulations, technological innovations, and market developments that influence the operational lifespan and utilization of power plants (Rode et al., 2017). Meanwhile, according to Guivarch and Hood (2011), early retirement of a power plant refers to the closure of the plant before the end of its technical life. Implementing early retirement of fossil fuel power plants, including coal power plants, is critical to achieving the goals of the Paris agreement on climate change, but this poses economic challenges and can result in stranded assets worth billions. Early retirement of a power plant refers to the process of stopping or decommissioning a power plant before its expected operational life. This often occurs for various reasons, such as technological advances, changes in energy policy, economic factors, or environmental concerns. Power plant retirements can be influenced by factors such as age, carbon emissions, potential air pollution, and industry competitiveness. In the context of reducing greenhouse gas emissions, phasing out coal-fired power plants is considered important to reduce carbon emissions and switch to more environmentally friendly energy sources. The retirement of nuclear power plants can also be influenced by factors such as deregulation, economic feasibility, and safety concerns. The decision to retire a power plant is usually based on a combination of economic, environmental, and regulatory considerations. (Fofrich et al., 2020); (Maamoun et al., 2020); (Rothwell, G., 2000); Baldwin, C. J., Hoffman, C. H., & Jeynes, P. H., 1961); Johnson, N., 2015).

To achieve the Paris Agreement goals and mitigate climate change, early retirement of coal-fired power plants is one option. Many countries, including advanced developing countries, face the challenge of phasing out coal-fired power plants before their normal lifespan ends. A country's capacity is a strong predictor of coal retirement, and countries have used strategies such as regulatory enforcement, buy-outs or compensation, and market dynamics to retire coal-fired power plants prematurely. Future research needs to explore the most promising strategies for different regions and countries, considering their political structures and their implications for global mitigation efforts (Brutschin et al., 2022). A retirement index based on age, carbon emissions, and potential air pollution identifies factories facing retirement in China, India, and South Korea, which account for a significant portion of global operating capacity (Maamoun et al., 2020). Ambitious climate mitigation scenarios require drastic changes in the operating and shutdown schedules of electricity infrastructure, with coal-fired power plants idling earlier than historically expected ((Fofrich et al., 2020). In the United States, most coal plants have been retired, and three-quarters of coal generation capacity is expected to be retired in the next twenty years (Davis et al., 2022); (Zhang & Qin, 2016).

Early Retirement, or PLTU Early retirement is one of the schemes in the Carbon Reduction Facility program in ETM. Indonesia, through the Ministry of Energy and Mineral Resources, is currently preparing a road map regarding the early retirement of this PLTU in accordance with Article 3 of Presidential Regulation Number 112 of 2022 concerning the Acceleration of Renewable Energy Development for the Supply of Electric Power. The Indonesian government is collaborating with a private company appointed as the ETM Country Platform Manager, where the company will create a financing and investment framework for the ETM program. The private company will work with strategic partners to implement the energy transition strategy in Indonesia. A transition away from coal-fired power plants is necessary for global climate stability, and the early retirement of coal-fired power plants is critical to this transition. However, the selection of units for early retirement must consider carbon emissions, age, and potential air pollution to maximize environmental benefits (Maamoun et al., 2020). In addition, implementing early retirement of fossil fuel power plants, including coal power plants, is critical to achieving the goals of the Paris agreement on climate change, but this poses economic challenges and can result in billions of stranded assets (Kefford et al., 2018).

Early retirement implementation strategies need to be carried out appropriately. Policies that target the early retirement of coal-fired power plants, such as replacing small and inefficient units with larger and more efficient units, can result in significant reductions in CO_2 emissions. However, the shutdown of newly built coal-fired power plants may cause economic losses and carbon lock-in effects, highlighting the need for careful policy design (Zhang & Qin, 2016). It is hoped that the right strategy can help reduce a country's emissions and be in line with development plans. A detailed strategy for the retirement of high-ambition coal-fired power plants in China suggests that 18% of currently operating coal-fired power plants will soon be phased out due to poor performance in technical, economic, and environmental criteria (Mo et al., 2021). Determining when to implement early retirement is also quite crucial. Climate mitigation scenarios that include early retirement of coal-fired power plants require drastic changes in operating schedules and/or the shutdown of electricity infrastructure. To meet international climate targets, coal-fired power plants may need to be retired one to three decades earlier than their historical operational lifetime (Fofrich et al., 2020).

2.2. Stranded asset

The concept of stranded assets poses significant risks in the early retirement of coal plants, as detailed by various studies. (Ben et al., 2014) highlight how environmentally unsustainable assets face premature devaluation, becoming stranded when they are retired before their intended economic lifespan, leading to financial losses. (Miller et al., 2013) discusses how stranded assets can pressure operators to increase prices, impacting consumers. (Edwards et al., 2022) note the role of climate regulations in stranding new coal plant assets. The importance of strategic planning to mitigate these risks, through anticipating regulatory, technological, and market shifts, is underscored by (Curtin et al., 2019). (Kefford et al., 2018) provide stark figures, estimating up to $773 billion in stranded asset values due to early retirements, underscoring the financial magnitude of the issue. This comprehensive view reveals the multifaceted challenge of managing stranded assets and costs in transitioning to sustainable energy sources. Incorporating the insights from (Baron & Fischer, 2015), the financial implications of stranded assets due to early coal plant retirements are further magnified. They estimate the potential stranded assets for fossil fuel plants could range from $50 billion to $120 billion by 2035, contingent on compensation through capacity markets.

2.3. Analytical Hierarchy Process

AHP is a multi-criteria approach to decision-making for situations that do not have a component-by-component structure and involve complex or complicated problems. Discovered by Thomas L. Saaty in 1970, this technique has been applied in various fields. Researchers are particularly interested in AHP because of its easy-to-use data input functionality and powerful mathematical properties. AHP logically integrates personal judgment with the influence of intuition, experience, and knowledge to construct a problem hierarchy based on logic, intuition, experience, and knowledge. A multi-level hierarchical structure consisting of objectives, criteria, sub-criteria, and alternatives is used in this method. The data were obtained by performing a series of pairwise comparisons. Through this comparison, determining the weight for the level of importance in the decision criteria and the relative performance of each alternative in relation to certain decision criteria can be done. When inconsistencies arise in comparisons, AHP has implemented mechanisms to improve consistency. (Kousalya et al., 2012) AHP facilitates the transformation of qualitative data, including preferences and priorities, into quantitative data using pairwise comparisons. This process then reveals the importance of these priorities. Because the initial data that is converted is qualitative, AHP places great emphasis on data sources, where respondents must be experts in the subject area being investigated. As a result, AHP is both limited and inclusive. In addition, AHP is adaptive because it can be used independently or combined with other tools (Darko et al., 2019)

(Samanaseh et al., 2023) define the Analytical Hierarchy Process (AHP) as a multifaceted decision-making approach that arranges factors hierarchically, emphasizing its effectiveness in evaluating decisions that combine qualitative and quantitative elements. (Sankaranarayanan & Mala, 2022) define AHP as a structured method for complex decision making. The study emphasizes the application of AHP in various industries, including power generation, to overcome various problems that include qualitative and quantitative elements. In addition, (Sankaranarayanan & Mala, 2022) underscore the effectiveness of AHP in reducing bias through numerical assignment to subjective judgments, thereby facilitating balanced and informed decisions in complex scenarios. Researchers chose the AHP method as a method to identify and evaluate mitigations that could arise from early retirement decisions for coal plants due to decarbonization. The AHP method was used in this research because it is a fairly good method for processing qualitative data. The AHP method will change the qualitative data into quantitative data.

Many studies related to strategies for implementing early retirement have been carried out around the world, but in Indonesia itself, there are still very few studies that discuss early retirement strategies for coal plants and the risks related to stranded assets. Research conducted by (Suski et al., 2022) discusses the growing reality of phasing out coal-fired power plants in the context of low-cost planning in various countries and emphasizes the complexity of issues that go beyond planning, including commercial contracts, markets, and stranded assets. (Suski et al., 2022) also introduce the Coal Retirement Model (CRM), a new approach to quantifying the economic and financial impact of coal-fired power plant retirements in the context of decarbonization strategies. This model is specifically designed to calculate stranded assets endogenously (originating internally), considering broader commercial and market issues. The aim of the modeling is to maximize net income from coal plants while meeting production targets and considering various scenarios, including economic market-based compensation and power purchase agreements (PPA). This study illustrates CRM modeling with case studies of India, which has a large and aging coal fleet, and the Philippines, which has a smaller and younger coal fleet. The study helps understand the main causes of stranded costs and the implications of decommissioning coal-fired power plants in different contexts.

(Kefford et al., 2018) used economic modeling and scenario analysis to evaluate the impact of decarbonization policies on the viability of fossil fuel power plants and the potential for abandoned assets. This methodology includes a review of policy documents, an analysis of market data, and the application of economic forecasting models to project future scenarios based on different policy frameworks. (Anderson et al., 2021) uses a combination of technical and economic analysis, including technology evaluation options to mitigate emissions at coal-fired power plants, cost-benefit analysis, and multi-criteria decision analysis (MCDA) to prioritize retrofitting or retirement decisions based on economic, environmental, and environmental factors and social. (Spencer et al., 2017) used a combination of policy analysis, statistical modeling, and stakeholder analysis to understand the dynamics of coal-fired power plants in China and the risks of abandoned assets. The methodology used includes data collection on existing coal-fired power plants, analysis of policy documents, and interviews with key stakeholders in the energy sector. (Edwards et al., 2022) applied Integrated Assessment Models (IAM) to estimate the risk of stranded assets under various global warming scenarios. This methodology involves the use of climate models, economic data, and energy demand and supply projections to assess the financial risks to coal-fired power plants in different regions.

(Tohidi et al., 2013) developed a mathematical model based on stochastic programming for simultaneous expansion of generation and retirement planning. This model considers the retirement decisions of aging units, emphasizing the need for detailed modeling to understand retrofitting or retirement decisions under future policy uncertainty. Maamoun et al. (2020) introduced a retirement index that ranks coal-fired power plants based on age, carbon emissions, and air pollution potential. The largest power plants identified for retirement are mostly in China, India, and South Korea, representing 1% of global coal-fired power generation but accounting for 4.5% of global operating capacity. From the research above, there is no research that specifically calculates the economic and financial impact of stopping coal-fired power plants for stakeholders in Indonesia.

This projection highlights the economic stakes involved in transitioning away from fossil fuels, emphasizing the critical need for policies and strategies that address the financial risks of stranded assets and costs in the energy sector's decarbonization efforts.

This research provides a new perspective on the risks and strategies associated with the early retirement of coal-fired power plants. This research addresses a significant gap by combining financial risk assessment with technical components of energy policy, thereby offering a comprehensive perspective on the results of Indonesia's efforts to reduce carbon emissions. This study assesses the effectiveness of current modification policies and their impact on industrial energy, the environment, and surrounding populations, and provides a comparative perspective with a global approach.

3. Research Method and Materials

This research was conducted to answer research questions in the form of: What is the appropriate mitigation for reducing the level of impact of stranded asset risk that needs to be carried out by stakeholders? Therefore, researchers chose case studies as a research method.

Yin (2014) defines case studies as strategic research that focuses on investigating contemporary phenomena in real-life contexts, especially when the boundaries between phenomenon and context are not clearly visible. This method is distinguished by its deep and detailed examination of a problem, designed to explore the complexity and underlying principles that govern real-world situations. Case studies are very suitable for use in this research because making early retirement decisions requires complex considerations regarding the operational and financial sustainability of a coal plant.

The case study was determined by researchers to select mitigation alternatives in the context of implementing the early retirement strategy for coal plants in Indonesia. This research was carried out because of the Indonesian government's program regarding the preparation of a road map regarding coal plant early retirement in accordance with Article 3 of Presidential Regulation Number 112 of 2022 concerning the Acceleration of Renewable Energy Development for the Supply of Electric Power. This research uses qualitative methods to collect primary or secondary data, and uses quantitative methods in the form of Analytical Hierarchy Process to obtain mitigation selection results for stranded asset risks.

3.1. Research Design

To answer the research questions, the stages used in this research are:

Stage 1: Analysis of the condition of the coal plant early retirement program in Indonesia.

At this initial stage, secondary data related to the coal plant early retirement program such as business processes, targets, timelines, procedures, and financing are collected to understand the condition of the PLTU early retirement program.

Stage 2: Determining the factors that influence the selection of stranded asset risk mitigation.

Drawing conclusions regarding the criteria and sub-criteria was carried out by conducting a literature study on research that discussed the risks of stranded assets or early retirement of coal plants. Apart from that, interviews were also conducted with experts at energy companies before making it into a questionnaire.

Stage 3: Analysis of stranded asset risk mitigation options

Further analysis related to predetermined criteria in selecting stranded asset risk mitigation using the Analytical Hierarchy Process (AHP). The AHP method was used in this research because it is a fairly good method for processing qualitative data. The AHP method will change the qualitative data into quantitative data.

Stage 4: Analyze the results

Analyze the results of the ranking criteria resulting from the AHP method.

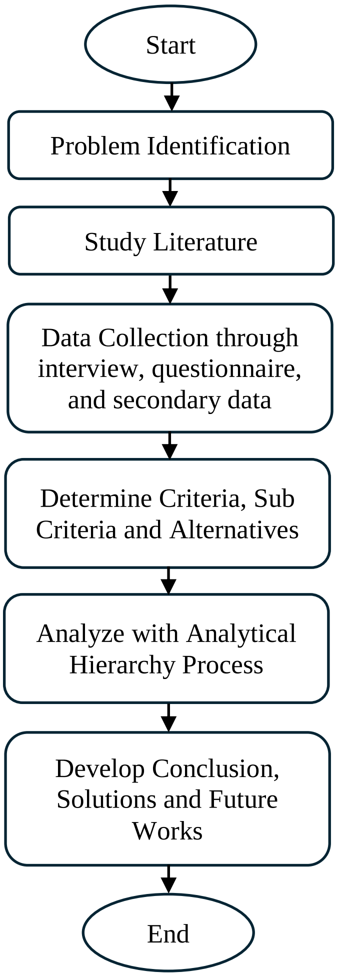

Figure 1. Research Flow Diagram

The case study in this research uses a single case study, with the research object used being PT. XYZ, a state-owned enterprise (BUMN) that operates in the electricity services sector and is responsible for the operation and distribution of electricity in Indonesia. The data used in this research are primary and secondary data, namely data obtained by researchers directly from research informants as well as data indirectly through intermediaries, in the form of information and data obtained from company annual reports, RUPTL 2021-2030, information from the media printed or electronic, official documents related to research. Primary data used in this research was obtained through interviews conducted with PT XYZ, owner and operator of coal-fired power generation facilities. Interviews are the data acquisition method most often used in qualitative research, whether conducted alone or combined with other methods (Yin, 2014). Given the qualitative nature of this research which was driven by research questions, the primary method of data acquisition used was semi-structured interviews. A list of questions was provided to the interviewer in a semi-structured format; however, compliance with these questions is not mandatory (Saunders et al., 2019). As a result, researchers can investigate new ways of inquiry due to the adaptability of semi-structured interviews (Kumarasiri et al., 2020).

PT XYZ was designated as the source for the research object because PT The selected speakers are the highest position holder in the planning department, the second highest position holder in the risk and energy transition and sustainability departments and the third highest position holder in the finance department, where these departments are departments that have accountability in implementing the early program retirement by PT XYZ. Their views are considered relevant and comprehensive for assessing the criteria needed in selecting stranded asset risk mitigation.

Qualitative research covers a broad methodology and can combine various sources of evidence, including participant observation, document analysis, and interview data, both independently and together (Lilis, 2008). Secondary data was also incorporated into this investigation. Secondary data includes information and data obtained through intermediaries, including company annual reports, RUPTL 2021–2030, information from print and electronic media, official documents related to research, published journals, regulations, expert opinions, and books. Secondary data was obtained indirectly by researchers.

The documents and regulations used in this research include:

a. Presidential Regulation (Perpres) 112 of 2022 concerning the Acceleration of Renewable Energy Development for the Supply of Electric Power
b. PT XYZ's exposure regarding early retirement (2022)
c. Exposure of the Directorate General of Financing and Risk Management (DJPPR) Ministry of Finance, 2022
d. Revised Edition of Strategic Management Book, Popy Rufaidah, SE, MBA, Ph.D., 2014
e. PT XYZ 2022 statistics
f. RUPTL 2021-2030
g. Information from electronic media

From these documents, this research can build a big picture to answer related research questions while strengthening the interview results.

3.2. Select mitigation alternatives in the context of implementing the early retirement strategy for coal plants in Indonesia

According to Saaty (1988), in making organized decisions to produce priorities, after explaining the problem and determining the type of study, the following steps need to be outlined:

1) Creating a hierarchy for selecting stranded asset risk mitigation in the early retirement program for coal-fired power plants in Indonesia.

   The electoral hierarchical framework and the objectives of the election that will be held need to be determined objectively from a broad perspective, from the middle level to the lowest level. In this research, determining the criteria and sub-criteria of the hierarchy uses a combination of two approaches, namely using literature studies and expert interviews. From these two approaches, the criteria, sub-criteria, and alternatives are obtained, namely:

Table 1. Literature of Table Criteria

Criteria	Literature
Economic Feasibility Social Acceptability Environmental Impact	Prospective assessment of energy technologies: a comprehensive approach for sustainability assessment (Haase et al. 2022)
Regulatory Compatibility	Sustainable Energy Transition for Renewable and Low Carbon Grid Electricity Generation and Supply (Kabeyi MJB and Olanrewaju OA, 2022)

Table 2. Literature of Table Sub Criteria

Sub Criteria	Literature
Economic consequences Cost effectiveness Effect on jobs and communities dependent Accommodate the shifts in the energy sector Comply with current regulation Robust against future regulatory Certainty of cleaner technologies	Power sector asset stranding effects of climate policies (Saygin et al, 2019), Stranded Costs and Grid Decarbonization (Hammond E & Rossi Jim, 2016

Allignment with decarbonization scenario

Table 3. Literature of Table Alternatives

Alternatives Criteria	Literature
Rein-in	Exploring Enablers for an Ambitious Coal Phaseout (Brutschin et al, 2022)
Buy-out	
Crowd-out	

According to (Brutschin et al., 2022), strategies for early retirement can be divided into three types, namely Rein-in, Buy-out and Crowd-out. Rein-in is Implement strict restrictions and standards on coal-fired power plants with government participation. The aim is to reduce emissions and accelerate the phase-out of coal in the energy sector. This strategy has the ability to rapidly reduce pollution and greenhouse gas emissions. However, this may face resistance from the coal and related industries, which could result in legal disputes and economic turmoil in cities that rely heavily on coal labor. Buy-out Aims to speed up the process of phasing out coal by offering financial incentives or compensation to coal-fired power plant operators in exchange for early retirement of their facilities. This strategy can facilitate the transition for coal-dependent employees and regions, ensuring a smoother and more politically appropriate shutdown. However, this process carries large financial costs and raises concerns about the fairness of using public funds to reimburse private entities for stopping environmentally damaging practices, as well as possible moral hazard. Crowd out is Leverage market dynamics and the competitive advantages of renewable energy sources to gradually reduce the importance of coal in the energy portfolio. This policy aims to stimulate the use of environmentally friendly energy technologies and provide a conducive market environment, thereby facilitating a gradual shift away from the use of coal without requiring direct government action. While this approach has the advantage of being driven by market forces and being flexible, its effectiveness depends on market conditions, which may not be aligned with the urgent need to reduce emissions and may fail to consider the social consequences of phasing out coal, such as providing assistance to workers and affected communities.

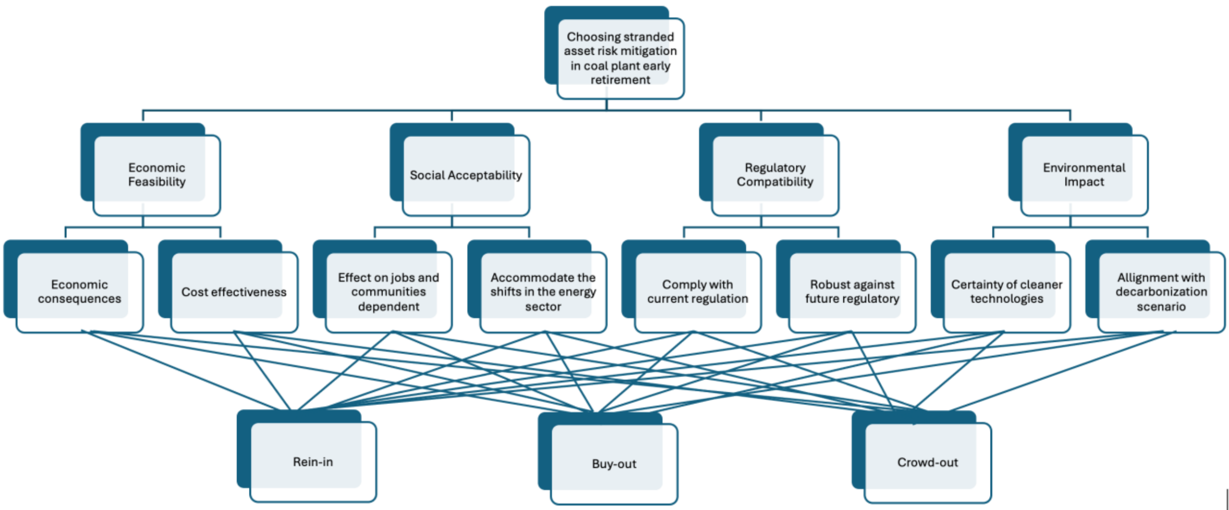

Figure 2. Hierarchy of Selection of Stranded Asset Risk Mitigation

2) Building a comparison matrix

From the list of dominant criteria that have been collected in the previous stage, a comparison matrix design will be created. The number of comparison matrices prepared is n(n-1)/2, where n is the number of criteria to be considered. The AHP Expert Panel will provide a comparison between the criteria that have been identified based on the order of priority for selecting stranded asset risk mitigation in the early retirement program for coal-fired power plants (Figure 1) using the Saaty ratio scale (Table 4).

Table 4. Literature of Table Criteria

Scale	Degree of Preference	Explanation
1	Equally	Two activities contribute equally
3	Moderately	Experience and judgment slightly to moderately favour one activity to another
5	Strongly	Experience and judgment strongly or essentially favour one activity to another
7	Very strongly	One activity is strongly favoured over another and its dominance is showed in practice
9	Extremely	The evidence of favouring one activity over another is of the highest degree possible of an affirmation
2, 4, 6, 8	Intermediate values	Used to represent compromises between the preference in weights 1, 3, 5, 7, and 9
Reciprocals	Opposites	Used for inverse comparisons

3) Determining the weight of criteria and sub-criteria

Criteria weights are calculated using the eigenvalue method:

$$A \cdot = \lambda_{max} \cdot \chi \qquad (1)$$

Where A is a pairwise comparison matrix, χ is a weight vector and λ_{max} is a maximal eigenvalue. In the AHP method, one of the important things that needs to be considered regarding respondents' answers is the consistency of the answers. Consistency in this case means the intensity of the relationship between elements, which is based on certain criteria logically justifying each other. Consistency testing is carried out as a way to see the consistency of the comparison pairs' assessment answers and the hierarchical structure of the problem. This is because reality shows that it is very impossible to obtain absolutely consistent participant answers (Junaidi, M., 2002). The AHP suggests that inconsistency should be less than 10% of the mean for decision matrices, prompting a reassessment if exceeded, ensuring reliable decision-making Eric, F., Lane., William, A., Verdini. (1989). The formulation for calculating the consistency index is as follows:

a. Consistency Index

$$CI = \frac{(\lambda - n)}{(n-1)} \qquad (2)$$

Where n is number of criteria, not respondents and λ is average of consistency vectors

b. Consistency Ratio

$$CR = \frac{CI}{RI} \qquad (3)$$

Where RI is random index.

4) Cumulative preferences

Cumulative preferences use the AIJ method, where individual assessments are aggregated using the weighted geometric mean method (WGMM) to create a group matrix $A^G = (a_{ij}^G)_{nxn}$, and use the eigenvalue method to find priority weights over the matrix.

5) Determination of ranking based on weight

Ranking is determined by the priority weights compared at that level. This is done for each element, and then for each element at the lower level, its respective weight is determined using the weight of the level above it. Then the weights are sorted to obtain global priorities.

6) Data Processing with Expert Choice

AHP facilitates multi-expert decision-making where each expert can apply his knowledge, values, and experience to decompose problems into a hierarchy that can then be solved using AHP steps. Experts will be asked to fill out a questionnaire to find out the weighting of the criteria and the weighting of alternative mitigation options. To assist in the calculation process, Expert Choice software will be used.

4. Results and Discussion

The research was conducted using primary and secondary data from PT XYZ. Primary data was obtained from interviews regarding the implementation of the coal plant early retirement strategy by considering the risk of stranded assets and distributing AHP questionnaires. The criteria for the sources selected in this research are experts in their respective fields and understand early retirement. The selected resource person has a minimum position of Vice President in the company. The resource persons are:

Table 5. List of expert respondent

No	Initial	Position
1	X1	Vice President of Financial Department
2	X2	Director of Planning Department
3	X3	Executive Vice President of Strategic Risk Department
4	X4	Executive Vice President of Energy Transition Department

For Results, provide sufficient detail to allow the results to be meaningful and informative. For Discussion, this should explore the significance of the results of the work, not repeat them. A combined Results and Discussion section is often appropriate. Avoid extensive citations and discussion of published literature.

4.1. Mitigation in reducing the impact of stranded asset risk needs to be implemented by stakeholders.

Risk mitigation is the practice of reducing the impact of potential risks by developing plans to manage, eliminate, or limit setbacks as much as possible. Once management creates and implements the plan, they will monitor progress and assess whether they need to change any actions or not. With Expert Choice 11 the mitigation will be decided.

Table 6. Criteria and Sub Criteria

Factor	Code	Explanation
Economic Feasibility	EF1	Cost effectiveness
	EF2	Economic consequences
Social Acceptability	SA1	effect on jobs and communities dependent
	SA2	accommodate the shifts in the energy sector
Regulatory Compatibility	RC1	Comply with current regulations
	RC2	Robust against future regulatory
Environmental Impact	EI1	Certainty of cleaner technologies
	EI2	Alignment with decarbonization scenario

4.2. Pairwise Comparison Matrix Between Criteria

At this stage, weighting is carried out in pairwise comparisons between criteria. To check whether the pairwise comparisons have been carried out consistently or not, namely using the Incon/Consistency Ratio. In checking the consistency of this data, the error degree of 10% is used, where the data is considered good if the CR value is $\leqslant 0.1$. To check the Incon/Consistency Ratio of respondent data, below the Incon/Consistency Ratio value is displayed in the form of a Pairwise Comparison Matrix image using the Expert Choice 11 application.

Table 7. Pairwise Comparison Between Criteria (Respondent of X3)

Factor	Economic Feasibility	Social Acceptability	Regulatory Compatibility	Environmental Impact
Economic Feasibility		7.0	5.0	5.0
Social Acceptability			7.0	5.0
Regulatory Compatibility				5.0
Environmental Impact	Incon: 0.21			

Table 8. Pairwise Comparison Between Criteria (Respondent of X2)

Factor	Economic Feasibility	Social Acceptability	Regulatory Compatibility	Environmental Impact
Economic Feasibility		7.0	9.0	7.0
Social Acceptability			9.0	7.0
Regulatory Compatibility				9.0
Environmental Impact	Incon: 0.39			

Table 9. Pairwise Comparison Between Criteria (Respondent of X4)

Factor	Economic Feasibility	Social Acceptability	Regulatory Compatibility	Environmental Impact
Economic Feasibility		7.0	9.0	1.0
Social Acceptability			9.0	1.0
Regulatory Compatibility				7.0
Environmental Impact	Incon: 0.37			

Table 10. Pairwise Comparison Between Criteria (Respondent of X1)

Factor	Economic Feasibility	Social Acceptability	Regulatory Compatibility	Environmental Impact
Economic Feasibility		9.0	1.0	3.0
Social Acceptability			3.0	3.0
Regulatory Compatibility				5.0
Environmental Impact	Incon: 0.10			

After the questionnaire results for each respondent are input into Expert Choice 11, then the results of each respondent's questionnaire must be combined into one data unit to continue the AHP (Analytic Hierarchy Process) calculation using Expert Choice 11, each comparison of the same criteria in the third result Pairwise Comparison between criteria in the table 7-10 the geometric mean will be calculated.

Table 11. Pairwise Comparison Between Criteria (Combined)

Factor	Economic Feasibility	Social Acceptability	Regulatory Compatibility	Environmental Impact
Economic Feasibility		7.45391	2.00622	3.20109
Social Acceptability			4.87973	3.20109
Regulatory Compatibility				6.29970
Environmental Impact	Incon: 0.08			

From the Pairwise Comparison Combination results above, the results show that Economic Feasibility has a very important weight when compared with Social Acceptability (7.45391) and quite important when compared with Environmental Impact (3.20109), and quite an important weight when compared with Regulatory Compatibility (2

,00622). This shows that Economic Feasibility is considered much more important than Social Acceptability and Environmental Impact, but not as important as Regulatory Compatibility. Incon/Consistency Ratio 0.08 illustrates that the calculation results are quite consistent.

After the pairwise comparison data (criteria) has been input into Expert Choice 11, the next step is to input the factor comparison data (alternatives). The chosen alternative must meet previously determined criteria. There are alternative risk mitigation scenarios for stranded assets at PT. XYZ, namely Rein-in Scenario, Buy-out Scenario, Crowd-out Scenario.

After the criteria are determined and an assessment is carried out in pairwise comparisons (criteria), then an assessment is carried out to compare the existing factors (alternatives). Alternatives consisting of 3 risk mitigation scenarios are assessed based on these criteria. The following are the results of the questionnaires that have been filled in, combined and translated into a Pairwise Comparison matrix table using Expert Choice 11:

1) Assessment of Alternatives According to Economic Feasibility

Table 12. Pairwise Comparison Based on Economic Feasibility Criteria

Factor	Cost Effectiveness	Economic Consequences
Cost Effectiveness		1.08776
Economic Consequences	Incon: 0.00	

2) Assessment of Alternatives According to Social Acceptability

Table 13. Pairwise Comparison Based on Social Acceptability Criteria

Factor	Cost Effectiveness	Economic Consequences
Effect on jobs and communities dependent		2.81731
accommodate the shifts in the energy sector	Incon: 0.00	

3) Assessment of Alternatives According to Regulatory Compatibility

Table 14. Pairwise Comparison Based on Regulatory Compatibility Criteria

Factor	Cost Effectiveness	Economic Consequences
Comply with current regulations		1.96799
Robust against future regulatory	Incon: 0.00	

4) Assessment of Alternatives According to Environmental Impact

Table 15. Pairwise Comparison Based on Regulatory Environmental Impact

Factor	Cost Effectiveness	Economic Consequences
Certainty of cleaner technologies		4.70488
Allignment with decarbonization scenario	Incon: 0.00	

From the results of the Pairwise Combined Sub Criteria above, the results obtained are Economic Consequences, Alignment with decarbonation scenario, Effect on jobs and dependent communities, and comply with current regulations which are considered the more important criteria among the sub criteria. In checking the consistency of this data, an error degree of 10% is used where the CR value is $\leqslant 0.1$. Based on the image above, you can see that the Incon/Consistent Ratio in the image is 0.00. Thus the calculation results are quite consistent.

4.3. Determination of Pairwise Comparison Weights Between Criteria

After inputting the pairwise comparison data between criteria is complete, it is entered into Expert Choice 11, it will produce a normalization matrix between criteria which will determine the weight of each criterion.

Table 16. Normalization of Pairwise Comparison Matrix Between Criteria

Criteria	Weight
Economic Feasibility	0.322
Social Acceptability	0.057
Regulatory Compatibility	0.508
Environmental Impact	0.113
Inconsistency	0.080

In Table 16, each criterion gets weighting values. The Economic Feasibility criterion received a weight value of 0.322 or 32.2%, the Social Acceptability criterion received a weight value of 0.057 or 5.7%, the Regulatory Compatibility criterion received a weight value of 0.508 or 50.8%, the Environmental Impact criterion received a weight value of 0.113 or 11.3 %. If all these weights are added or added together you will get 0.100 or 100%.

1) Determining the comparative weight of factors between alternatives based on economic feasibility criteria

Table 17. Normalization of Factor Comparison Matrix Between Alternatives Based on Economic Feasibility Criteria

Alternatives	Weight
Rein-in	0,160
Buy-out	0,054
Crowd-out	0,786

In Table 17 each alternative gets weighting values based on Economic Feasibility. The Rein-in scenario gets a weight value of 0.160 or 16%, the Buy-out scenario gets a weight value of 0.054 or 5.4%, the Crowd-out scenario gets a weight value of 0.786 or 78.6%. If all these weights are added or added together you will get 0.100 or 100%.

2) Determining the comparison weight of factors between alternatives based on social acceptability criteria.

Table 18. Normalization of Factor Comparison Matrix Between Alternatives Based on Social Acceptability Criteria

Alternatives	Weight
Rein-in	0,199
Buy-out	0,107
Crowd-out	0,694

In Table 18, each alternative gets weighting values based on Social Acceptability. The Rein-in scenario gets a weight value of 0.199 or 19.9%, the Buy-out scenario gets a weight value of 0.107 or 10.7%, the Crowd-out scenario gets a weight value of 0.694 or 69.4%. If all these weights are added or added together you will get 0.100 or 100%.

3) Determining the comparison weight of factors between alternatives based on regulatory compatibility criteria.

Table 19. Normalization of Factor Comparison Matrix Between Alternatives Based on Regulatory Compatibility Criteria

Alternatives	Weight
Rein-in	0,461
Buy-out	0,345
Crowd-out	0,194

In Table 19 each alternative gets weighting values based on Regulatory Compatibility. The Rein-in scenario gets a weight value of 0.461 or 46.1%, the Buy-out scenario gets a weight value of 0.345 or 34.5%, the Crowd-out scenario gets a weight value of 0.194 or 19.4%. If all these weights are added or added together you will get 0.100 or 100%.

4) Determining the comparison weight of factors between alternatives based on environmental impact criteria

Table 20. Normalization of Factor Comparison Matrix Between Alternatives Based on Environmental Impact

Alternatives	Weight
Rein-in	0,536
Buy-out	0,123
Crowd-out	0,341

In Table 20, each alternative gets weighting values based on Environmental Impact. The Rein-in scenario gets a weight value of 0.536 or 53.6%, the Buy-out scenario gets a weight value of 0.123 or 12.3%, the Crowd-out scenario gets a weight value of 0.341 or 34.1%. If all these weights are added or added together you will get 0.100 or 100%.

4.4. Calculation of AHP (Analytic Hierarchy Process) Data Processing Results

After getting the respective values from each pairwise comparison weighting between criteria and each factor comparison between alternatives based on the criteria. The final step that must be taken to select risk mitigation scenarios for stranded assets at PT. XYZ is calculating the Aggregate for each risk mitigation scenario that is used as an alternative. The Aggregate value is obtained by multiplying the weighted value of pairwise comparisons between criteria and each factor comparison between alternatives based on the risk mitigation scenario selection criteria with the same criteria.

Table 21. Weighting of Pairwise Comparisons Between Criteria and Factor Comparisons Between Alternatives

Criteria	Pairwise comparison weights between criteria	Factor comparison weights between alternatives		
		Rein-in	Buy-out	Crowd-out
Economic Feasibility	0,322	0,160	0,054	0,786
Social Acceptability	0,057	0,199	0,107	0,694
Regulatory Compatibility	0,508	0,461	0,345	0,194
Environmental Impact	0,113	0,536	0,123	0,341

In Table 21, pairwise comparisons between criteria and factor comparisons between alternatives will be multiplied by each weighting of pairwise comparisons between criteria and factor comparisons between alternatives for selecting risk mitigation scenarios according to the criteria.

Table 22. Synthesis With Respect Results

Alternatives	Weight
Rein-in	0,387
Buy-out	0,244
Crowd-out	0,369

In Table 22 is the result of the overall AHP (Analytic Hierarchy Process) calculation for selecting risk mitigation scenarios for stranded assets using the Expert Choice 11 application in graphic form. This summation result is the final result of selecting risk mitigation scenarios for stranded assets. Rein-in scenario gets a score of 38.7%, Buy-out scenario gets a score of 24.4%, Crowd-out scenario gets a score of 36.9%. The results of this calculation also show that the Rein-in Scenario better meets the criteria that have been determined in selecting risk mitigation scenarios for stranded assets.

5. Conclusion

The results of the overall AHP (Analytic Hierarchy Process) calculation for selecting risk mitigation scenarios for stranded assets using the Expert Choice 11 application show that the Rein-in Scenario better meets the criteria that have been determined in selecting risk mitigation scenarios for stranded assets at PT. XYZ. Rein-in strategies involve more stringent enforcement of environmental and climate regulations that have a direct impact on the functioning of coal-fired power generation facilities. The government can implement a carbon pricing mechanism such as a cap-and-trade system or pricing mechanism to implement strict emission limits on pollutants such as sulfur dioxide, nitrogen oxide, and so on. Implementation of these measures could make the ongoing operation of a coal facility uneconomic or legally problematic, forcing the closure or substantial modification of the facility to bring it into compliance with the new standards.

Several limitation of this study are, the study's geographic concentration on Indonesia may limit its application to other locations with diverse economic and regulatory situations, lowering its generalizability. The study's dependence on expert judgments via the Analytical Hierarchy Process (AHP) may introduce biases depending on the chosen experts' backgrounds, thereby skewing the conclusions. Furthermore, this research does not thoroughly quantify the stranded asset risks, which may impair the precision and dependability of the advice provided. The actual problems of adopting the proposed techniques, such as political opposition and budgetary limits, are not adequately investigated, which may impact their practicality in real-world contexts.

In terms of implications of the study, the study provides useful insights that may impact policymaking by underlining the importance of including economic and environmental issues into coal plant retirement. This might result in the creation of more balanced and robust energy policy. For investors, the study emphasizes the need of accounting for stranded asset risks, which may push investments toward more sustainable and renewable energy sources. Energy businesses may find the insights beneficial in changing their business strategy to focus on sustainability and compliance with decarbonization standards, hence reducing possible financial losses. The findings might also help with worldwide decarbonization efforts, supporting the goals of international agreements like the Paris Accord. Finally, this study paves the way for future research in other geographic locations and energy conditions, laying the groundwork for investigating the universal applicability of the proposed tactics or finding essential adjustments.

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