TECHNICAL FRAMEWORK HANDBOOK

B&V PROJECT NO. 410348

PREPARED FOR

Climate Investment Funds

16 DECEMBER 2022

Special Notice

In conducting our analysis and in forming an opinion of the projection of future operations summarized in this report, Black & Veatch has made certain assumptions with respect to conditions, events, and circumstances that may occur in the future. This methodology utilized by Black & Veatch in performing the analysis follows generally accepted practices for such projections. Such assumptions and methodologies are summarized in this report and are reasonable and appropriate for the purpose for which they are used; however, actual results may differ materially from those projected, as influenced by the conditions, events, and circumstances that actually occur. Such factors may include, but are not limited to, the ability to execute the capital improvement program as scheduled and within budget, regional climate and weather conditions affecting demand and supply, and adverse legislative and regulatory actions, or legal decisions (including but not limited to environmental law and regulations) affecting the ability of Black & Veatch's client to operate its system. Readers of this report are advised that any projected or forecasted financial, operating, performance, or strategy merely reflects the reasonable judgment of Black & Veatch at the time of the preparation of such information and is based on a number of factors and circumstances beyond Black & Veatch's control. Accordingly, no assurances are made that the projections or forecasts will be consistent with actual results or performances. Use of this report will constitute agreement by the user that (i) there is no warranty, express or implied, in this report, (ii) the user accepts the sole risk of any such use, and (iii) the user waives any claim for damages of any kind against Black & Veatch

Table of Contents

LIST OF TABLES

LIST OF FIGURES

Abbreviations

AHP	Analytical Hierarchy Process
BESS	Battery Energy Storage System
CCS	Carbon Capture and Storage
CFBC	Circulating Fluidized Bed Combustion
CIF	Climate Investment Funds
CO2	Carbon Dioxide
CPP	Coal Power Plants
CSL	Coal Supply Agreement
CSP	Concentrated Solar Power
CSR	Corporate Social Responsibility
g/kWh	gram per kilo Watt hour
GHG	Green House Gases
kWh	Kilowatt Hour
LCOE	Levelized Cost of Electricity
LCOS	Levelized Cost of Storage
MW	Megawatt
MWh	Mega Watt hour
MCDM	Multi-criteria Decision Making
PF	Pulverized Fuel
PLF	Plant Load Factor
PPA	Power Purchase Agreement
PV	Photo Voltaic

1.0 Introduction

The Climate Investment Funds (CIF), one of the world's largest and most ambitious climate finance mechanism has engaged Black & Veatch to develop an actionable technical framework for the following purpose:

1. Selection of Coal Power Plant (CPP) for repurposing

2. Selection of best suitable repurposing concepts

In order to rank CPPs for repurposing and identifying best available & suitable repurposing concept, Black & Veatch developed a three-stage framework. The first stage framework helps select the CPP most suitable for early retirement and is based on the Analytical Hierarchy Process (AHP). The second stage includes the identification of best suitable repurposing concept applicable for selected CPP and is based on Weighted Linear Combination (WLC), a common Multi-Criteria Decision Making (MCDM) method. Finally, the last stage of this exercise is to undertake pre-feasibility study to understand synergies between identified repurposing concept and selected coal power plant.

This handbook brings together the explanation of mathematical process such as AHP and WLC, which is used for ranking of CPP for repurposing and identification of best suitable repurposing concept. The handbook is intended for user to understand the process i.e., AHP and WLC, and its application for the above stated first and second stage technical framework.

2.0 Analytical Hierarchy Process

Analytical hierarchy process (AHP) is a multi-criteria decision making (MCDM) methodology that was developed by Thomas Saaty in the 1970s. AHP is one of the main mathematical models currently available to support decision theory in transparent manner. The application of AHP begins with the following hierarchy:

1. The problem is structured into a hierarchy with the goal on the top.
2. The criteria in the middle and the coal power plants in the lowest rung.

This creates two levels of analysis, as displayed in Figure 2-1.

Level 1: The criteria in middle focusing on the apportionment of weightages

Level 2: The lower rung of hierarchy, which involves developing a ranking of the Coal Power Plants (CPP) for each criterion. The rankings developed are then weighted using the weightages of criteria obtained in Level 1 analysis, to obtain the aggregate ranking of the CPP.

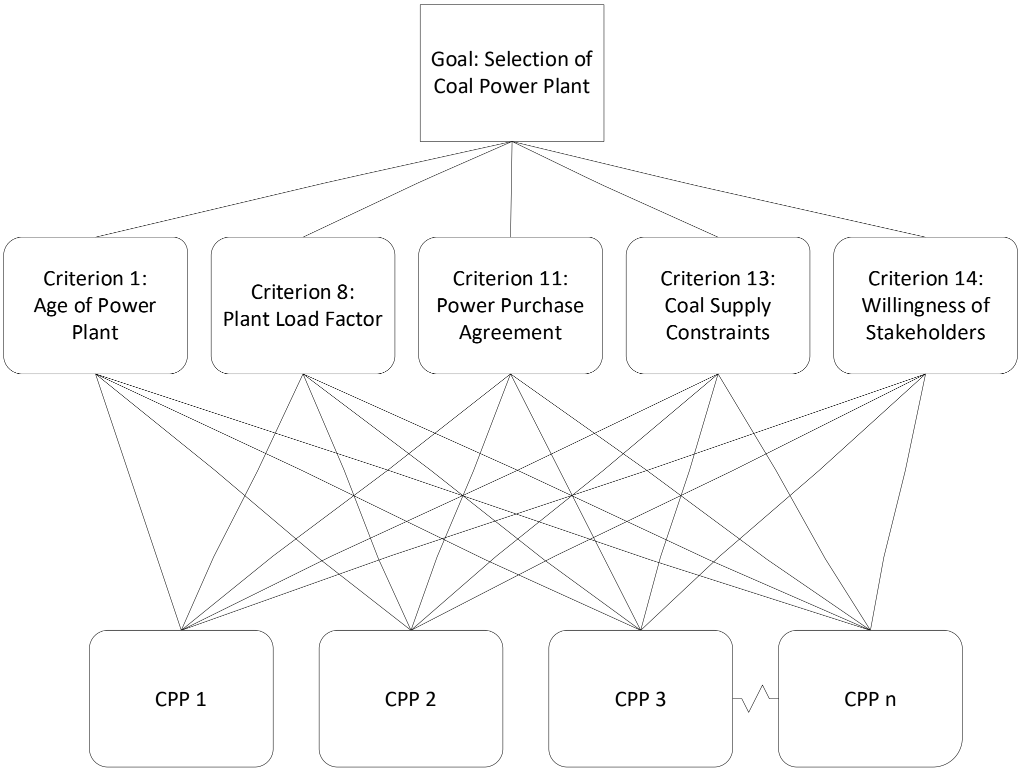

Figure 2-1 Representative AHP Diagram for this Exercise

By providing a transparent and mathematically rigorous framework, AHP allows the decision-makers to clearly understand the process by which preferences are translated to ranking. The methodology has been used to structure solutions to multiple problems in the context of energy planning. A review study published in 2004 found that AHP has been used to study energy resource allocation, utilization of solar energy technologies, sustainable mobility, evaluation of generation capacity bids and electric utility planning [1]. Recent research reaffirms the preeminent position of AHP in studying issues relating to sustainable development such as renewable energy sources, evaluation of power plants, and green public procurement implementation [2].

In this exercise, AHP has been used to rank coal power plants in order of their suitability for being repurposed. Eighteen criteria spanning techno-commercial, regulatory and contractual, environmental, and social aspects have been used in the analysis. The following two-level analysis has to be performed in this process:

Level 1 Analysis:

The criterial in middle of hierarchy are compared pairwise to obtain the criteria comparison matrix and determine the weightages for each criterion. The pairwise comparison of criteria is purely subjective.

Level 2 Analysis:

For each criterion, shortlisted coal power plants are compared pairwise, and the criterion-specific alternative comparison matrices are obtained. The comparison here is based on the differences in values the parameter (or a corresponding index, for qualitative criteria) takes for the shortlisted coal power plants. The goal of this analysis is to determine criteria specific ranking of CPP and subsequently the aggregate ranking.

3.0 AHP Methodology

The following three-step procedure is used at each level of analysis in the AHP methodology. While typically there are two levels of analysis as explained in the previous chapter, there may be more depending on whether any sub-criteria have been considered.

Step 1: Development of the comparison matrix

- The comparison matrix $A = [a_{ij}]$ is a square matrix of dimensions $n \times n$ where n is the number of criteria (for Level 1) or alternatives (for Level 2) being compared.
- The rows (top to bottom) and the columns (left to right) correspond to the criteria/alternatives in a given order. While the order does not matter, the same order must be used for rows and columns.
- Pairwise comparisons are undertaken within the set of criteria/alternatives and the matrix is filled depending on the strength and order of preference using the Saaty scale given below.
- For instance, if Item 3 is **very strongly preferred** to Item 5, then a_{35} (i.e., the element in the third row and fifth column) is 7. Further, if Item 6 were **strongly preferred** to Item 2, then a_{26} (i.e., the element in the second row and sixth column) is 1/5. It is recommended that intermediate strength of preference, denoted by even numbers in the Saaty scale, are not used unless necessary.
- Since each item would be equally preferred to itself, all elements on the principal diagonal (i.e., $a_{ii}\ \forall\ i$) would be 1. The reflection of any element across the principal diagonal is its inverse, i.e., $a_{ji} = a_{ij}^{-1}$.

Table 3-1 Saaty Scale

Strength of Preference	Row Element (Item i) Preferred	Column Element (Item j) Preferred
Extremely preferred	9	1/9
Very strongly to extremely preferred	8	1/8
Very strongly preferred	7	1/7
Strongly to very strongly preferred	6	1/6
Strongly preferred	5	1/5
Moderately to strongly preferred	4	1/4
Moderately preferred	3	1/3
Equally to moderately preferred	2	1/2
Equally preferred	1	1

Step 2: Calculation of the ranking vector

- The ranking vector is simply the principal eigenvector of the comparison matrix, normalized such that its elements sum to 1. One possible approximation of the principal eigenvector can be calculated as below [3].
- The column sum for each column is obtained by summing all elements in the column.

- Each matrix element is divided by the corresponding column sum to give the normalized comparison matrix.
- In each row, the elements of the normalized comparison matrix are averaged. The vector thus obtained is the ranking vector for the analysis. Mathematically, it can be represented as:

$$r_i = \frac{1}{n}\sum_{j=1}^{n}\frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}}$$

- It can be verified that the sum of the elements in the ranking vector is always 1.
- For Level 1 analysis, the ranking vector provides the relative weightages of the criteria. For Level 2 analysis, the ranking vector gives the relative preference of the alternatives for the corresponding criterion.
- The Level 2 ranking vectors for all criteria are summed up with the weightages for the criteria provided by the Level 1 ranking vector. The vector thus obtained provides the final ranking vector for the alternatives.

Step 3: Verifying the consistency of the comparison matrix

- Ideally, the preferences indicated in the comparison matrix would be cardinally consistent, i.e., $a_{ij} \times a_{jk} = a_{ik} \forall\ i, j, k$. This, in turn, implies that all the rows are multiples of each other.
- However, since the matrix elements are usually obtained from comparisons made by humans, some degree of inconsistency is expected and, indeed, preferred [4].
- The degree of inconsistency can be quantified using the principal eigenvalue of the matrix, λ_{max}. The principal eigenvalue of the matrix is approximated as the sum of the pairwise products of the column sum of the comparison matrix and the corresponding ranking vector value.
- The consistency index (CI) is calculated as $CI = \frac{\lambda_{max} - n}{n-1}$.
- The consistency index is compared against a benchmark random index (RI) which is the average of CIs obtained from randomly created (i.e., typically inconsistent) comparison matrices and depends on the size of the comparison set. The consistency rate (CR) is calculated as $CR = \frac{CI}{RI_n}$.
- A CR of not more than 0.1 is deemed acceptable. If the CR exceeds this value, it is suggested that the comparison matrix is reviewed for inconsistencies.

4.0 Criteria for Selection of Coal Power Plant

The selection criteria considered in the framework have been divided into three categories – techno-commercial, regulatory and contractual, and social and environmental criteria. While this section briefly discusses these categories and enumerates the criteria therein, can be referred for a more involved discussion of the criteria and the approach towards developing the Saaty scale associated with the Level 2 analysis for each criterion.

4.1 Techno-Commercial Criteria

Techno-commercial criteria relate to the design and performance of the coal power plant. The broad idea is to prioritize the retirement of power plants that have low efficiencies by design, perform much below their rated characteristics, are increasingly unreliable, or do not offer ancillary services that could have justified their continued operation. The criteria considered in this category are as follows:

1. **Age of power plant**

   Globally, coal power plants are retired at an average lifetime of 38 years [5] but have the ability to operate for longer. However, typically, older plants are less efficient, highly polluting and may be tied up in expensive PPAs, making it uneconomical to comply with stringent environmental regulations or compete with alternative technologies. According to a study by the International Energy Agency, the efficiency of new subcritical plants may be 38 percent on a LHV basis, while that of an older subcritical plant may be 20 percent to 25 percent [6]. Thus, the age of the power plant is an important factor in selecting coal power plants to be retired early.

   For Level 2 analysis, the age differences corresponding to different strengths of preference (corresponding to the Saaty scale) are given below. In a pairwise comparison, the plant of the higher age is more preferred.

Table 4-1 Saaty Scale for Pairwise Comparison on the Criterion of Age of Power Plant

Magnitude of Difference	Strength of Preference
Greater than 30 years	Extremely preferred
Greater than 20 years but less than or equal to 30 years	Very strongly preferred
Greater than 10 years but less than or equal to 20 years	Strongly preferred
Greater than 0 years but less than or equal to 10 years	Moderately preferred
Equal to 0 years	Equally preferred

2. **Rated capacity**

   The rated capacity refers to the MW capacity of a coal power plant. Coal power plants of higher capacity would have larger land parcels and well-developed infrastructure associated with them, making them more suitable for repurposing. Further, repurposing large power plants may also provide economies of scale. Thus, while smaller power plants may be opted to be repurposed as demonstration projects, the framework considers size of the power plant to be directly correlated with the suitability of repurposing.

For Level 2 analysis, the differences in rated capacity corresponding to different strengths of preference (corresponding to the Saaty scale) are given below. In a pairwise comparison, the plant of the higher capacity is more preferred.

Table 4-2 Saaty Scale for Pairwise Comparison on the Criterion of Rated Capacity

Magnitude of Difference	Strength of Preference
Greater than 500 MW	Extremely preferred
Greater than 300 MW but less than or equal to 500 MW	Very strongly preferred
Greater than 100 MW but less than or equal to 300 MW	Strongly preferred
Greater than 0 MW but less than or equal to 100 MW	Moderately preferred
Equal to 0 MW	Equally preferred

3. Type of power plant

Boilers in coal power plants are typically classified into Atmospheric Fluidized Bed Combustion (AFBC), Circulating Fluidized Bed Combustion (CFBC), and Pulverized Fuel (PF). The latter is further subdivided into sub-critical, supercritical, and ultra-supercritical. Modern technologies such as supercritical and ultra-supercritical boilers are more efficient and flexible as compared to the technologies like AFBC and CFBC boilers. The AFBC and CFBC require minimal modification to manage SOx emissions, which offsets its slightly lower efficiency as compared to PF boilers. However, the introduction of stringent emission regulations which go beyond the levels achievable with in-furnace desulphurization could necessitate additional modification for AFBC and CFBC and negate this advantage. Hence, the CFBC and AFBC boilers, along with subcritical PF, make a stronger case for repurposing.

As this is a categorical variable, the five boiler types have been assigned indices as follows: Subcritical AFB – 9, Subcritical CFB – 7, Subcritical PF – 5, Supercritical – 3, Ultra supercritical – 1. Further, the differences in ratings corresponding to different strengths of preference (corresponding to the Saaty scale) are given below. In a pairwise comparison, the plant with the higher index is more preferred.

Table 4-3 Saaty Scale for Pairwise Comparison on the Criterion of Type of Power Plant

Magnitude of Difference	Strength of Preference
8	Extremely preferred
6	Very strongly preferred
4	Strongly preferred
2	Moderately preferred
0	Equally preferred

4. Average heat rate deviation

The efficiency of a coal power plant is assessed through its heat rate which depends on the boiler, the turbine-generator and other auxiliary systems. While the design efficiency is captured in the previous criterion, here the deviation of the actual efficiency from it is considered. As per a study by the Central Electricity Authority (CEA), the gross heat rate deviations are in the range of 13.6 percent to 24.1 percent for plant units sized between 100 MW and 500 MW [7]. The average heat rate deviation for the power plant can be calculated as the difference between the design heat rate averaged for all the units (weighted by their capacities) and the actual heat rate, expressed as a percentage of the former. A significant deviation from the design heat rate makes the plant better suited for repurposing.

For Level 2 analysis, the differences in average heat rate deviations corresponding to different strengths of preference (corresponding to the Saaty scale) are given below. In a pairwise comparison, the plant with the higher deviation is more preferred.

Table 4-4 Saaty Scale for Pairwise Comparison on the Criterion of Average Heat Rate Deviation

Magnitude of Difference	Strength of Preference
Greater than 15 percent	Extremely preferred
Greater than 10 percent but less than or equal to 15 percent	Very strongly preferred
Greater than 5 percent but less than or equal to 10 percent	Strongly preferred
Greater than 0 percent but less than or equal to 5 percent	Moderately preferred
Equal to 0 percent	Equally preferred

5. **Ramp rate**

Coal-fired plants have typically been operated as baseload power plants. In the era of proliferating renewable energy deployments, however, it is necessary to have flexible sources in the generation mix. These sources should be able to be ramped up or down to mitigate the issues of variability and intermittency arising from renewables. The ability of thermal power plants to provide such support has been studied by the CEA [8]. One metric of the flexibility of generation source is the ramp rate, expressed as the ratio of ramping gradient (in MW/minute) to the capacity of the power plant (in MW). A lower ramp rate may indicate its unsuitability to support the grid, hence making a case for suitable candidate for repurposing.

For Level 2 analysis, the differences in ramp rates corresponding to different strengths of preference (corresponding to the Saaty scale) are given below. In a pairwise comparison, unlike most other criteria, the plant with the lower ramp rate is more preferred.

Table 4-5 Saaty Scale for Pairwise Comparison on the Criterion of Ramp Rate

Magnitude of Difference	Strength of Preference
Greater than 3 percent	Extremely preferred

Magnitude of Difference	Strength of Preference
Greater than 2 percent but less than or equal to 3 percent	Very strongly preferred
Greater than 1 percent but less than or equal to 2 percent	Strongly preferred
Greater than 0 percent but less than or equal to 1 percent	Moderately preferred
Equal to 0 percent	Equally preferred

6. **Forced outage rate**

Data from the CEA indicates that the loss in generation due to forced outages has increased from 12 percent in 2012-13 to 19 percent in 2017-18 [9]. Unreliable generation fleet leads to increased operation and maintenance costs that eventually get passed down to the consumer. For a power plant, the most important indicator of reliability is the equivalent forced outage rate which gives the probability that the plant will not be available to deliver its full capacity. It is calculated by taking the sum of each unit's capacity-weighted forced outage hours and derated hours divided by the sum of the total equivalent service hours, outage hours, and derate hours. The most unreliable plants should be prioritized for repurposing.

For Level 2 analysis, the differences in forced outage rates corresponding to different strengths of preference (corresponding to the Saaty scale) are given below. In a pairwise comparison, the plant with the higher forced outage rate is more preferred.

Table 4-6 Saaty Scale for Pairwise Comparison on the Criterion of Forced Outage Rate

Magnitude of Difference	Strength of Preference
Greater than 9 percent	Extremely preferred
Greater than 6 percent but less than or equal to 9 percent	Very strongly preferred
Greater than 3 percent but less than or equal to 6 percent	Strongly preferred
Greater than 0 percent but less than or equal to 3 percent	Moderately preferred
Equal to 0 percent	Equally preferred

7. **Load serving location**

The primary region or location served by the coal power plant can be categorized as either power surplus or power deficit. Being load surplus may be a result of growing generation capacity in the region, declining loads due to economic reasons, or both. The surplus represents both challenges and opportunities. In the case of repurposing thermal power plants, it represents an opportunity to retire coal power plants in a region where the impact on the frequency of the grid is likely to be less severe. Thus, power plants located in power surplus areas can be prioritized for repurposing.

As this is a categorical variable, the two categories of locations have been assigned indices as follows: Power surplus – 2, and Power deficit – 1. Further, the differences in ratings corresponding to different strengths of preference (corresponding to the Saaty scale) are given below. In a pairwise comparison, the plant with the higher index is more preferred.

Table 4-7 Saaty Scale for Pairwise Comparison on the Criterion of Load-Serving Location

Magnitude of Difference	Strength of Preference
1	Extremely preferred
0	Equally preferred

8. **Plant load factor (PLF)**

The plant load factor (PLF) is the ratio of actual generation by the power plant to the maximum generation if it were operating at rated capacity. It is generally considered as a measure of the capacity utilization of a power plant. The average PLF of coal power plants in India has decreased from 73.3 percent in 2011-12 to 56.0 percent in 2019-20 [10]. A lower PLF of a coal power plant indicates that the plant is operating at a sub-optimal level with operating parameters worse than design limits. Thus, a reduced PLF would make the coal power plant a preferred candidate for repurposing.

For Level 2 analysis, the differences in plant load factors, as expressed in percentages, corresponding to different strengths of preference (corresponding to the Saaty scale) are given below. In a pairwise comparison, unlike most other criteria, the plant with the lower plant load factor is more preferred.

Table 4-8 Saaty Scale for Pairwise Comparison on the Criterion of Plant Load Factor

Magnitude of Difference	Strength of Preference
Greater than 30 percent	Extremely preferred
Greater than 20 percent but less than or equal to 30 percent	Very strongly preferred
Greater than 10 percent but less than or equal to 20 percent	Strongly preferred
Greater than 0 percent but less than or equal to 10 percent	Moderately preferred
Equal to 0 percent	Equally preferred

9. **Levelized cost of electricity (LCOE)**

The Levelized Cost of Electricity (LCOE) captures the capital expenditure, fuel costs, O&M costs, financing costs, as well as any regulatory costs incurred in the generation of electricity. Repurposing of coal power plants provides an opportunity to retire higher LCOE plants that result in a financial burden on the consumers or are subsidized by the taxpayer. Analysis by IEA has estimated the LCOE of coal power plants, without a coal tax or carbon capture and storage (CCS), to be between 47.84 to 99.79 USD/MWh [11]. However, it is to be noted that the economic value of a generator's reliability and flexibility to meet grid requirement, is not considered in LCOE but captured in other criteria.

For Level 2 analysis, the differences in LCOE, expressed in USD/MWh, corresponding to different strengths of preference (corresponding to the Saaty scale) are given below. In a pairwise comparison, the plant with the higher LCOE is more preferred.

Table 4-9 Saaty Scale for Pairwise Comparison on the Criterion of LCOE

Magnitude of Difference	Strength of Preference
Greater than 30 USD/MWh	Extremely preferred
Greater than 15 USD/MWh but less than or equal to 30 USD/MWh	Very strongly preferred
Greater than 5 USD/MWh but less than or equal to 15 USD/MWh	Strongly preferred
Greater than 0 USD/MWh but less than or equal to 5 USD/MWh	Moderately preferred
Equal to 0 USD/MWh	Equally preferred

4.2 Regulatory and Contractual Criteria

Regulatory and contractual criteria refer to the power plant company's statutory and contractual obligations. The broad idea for these criteria is to prioritize the repurposing of power plants whose track record of compliance is poor, cost of compliance is high, or cost of exiting these obligations is low. The criteria considered in this category are:

1. **Local emission track record**

   Coal power plants are sources of local air pollutants like sulfur dioxide (SO_2), nitrogen oxides (NO_x) and particulate matter. However, the impact of the emissions may differ based on the stack height, environmental characteristics and demographics of the area the coal power plant is located in. Therefore, the approach adopted is to understand the regulatory limits on emissions and compare the plants on the basis of the frequency and severity of their transgressions. Plants with more frequent transgressions would be regarded as more suitable for repurposing based on this criterion.

   As this is a categorical variable, power plants with track records above and below the median incidence rate have been assigned indices as follows: High incidence of transgressions – 2, and Low incidence of transgressions – 1. Further, the differences in ratings corresponding to different strengths of preference (corresponding to the Saaty scale) are given below. In a pairwise comparison, the plant with the higher index is more preferred.

Table 4-10 Saaty Scale for Pairwise Comparison on the Criterion of Local Emission Track Record

Magnitude of Difference	Strength of Preference
1	Extremely preferred
0	Equally preferred

2. **Power Purchase Agreement (PPA)**

The Power Purchase Agreement (PPA) or Power Sales Agreement (PSA) is the primary contract between the generation company and public utility or private party for the purchase or sale of power from generating station. The PPA or PSA generally guarantees a secure revenue stream and includes other contractual details like risk allocation and structure, exit clauses, expiration of contract, etc. The absence or imminent expiry of the Agreement provides an attractive opportunity to retire and repurpose a coal power plant, as compared to plants having significant remaining term under the PPA.

Depending upon the length of the residual term of the PPA, the parameter takes on the following values: no active PPA – 9, less than five years – 7, less than ten years but not less than five years – 5, less than fifteen years but not less than ten years – 3, not less than fifteen years – 1. Further, the differences in the value of the parameter corresponding to different strengths of preference (corresponding to the Saaty scale) are given below. In a pairwise comparison, the plant with the higher value is more preferred.

Table 4-11 Saaty Scale for Pairwise Comparison on the Criterion of PPA

Magnitude of Difference	Strength of Preference
8	Extremely preferred
6	Very strongly preferred
4	Strongly preferred
2	Moderately preferred
0	Equally preferred

3. Coal Supply Agreement (CSA)

The Coal Supply Agreement (CSA) with the coal supplier provides a steady supply of coal to operate coal power plant. Like a PPA, a CSA also has its risk allocation and structure, supply price, exit clauses and expiration of contract. The framework focuses on the origin of the coal being supplied i.e., whether it is imported, sourced domestically, or is a mixture of both. Use of domestic coal provides additional economic benefits to a country such as energy security and employment generation along the entire value chain. Imported coal, on the other hand, increases the country's import bill and risk exposure of the power system. Thus, coal power plants utilizing imported coal are considered more favorable for repurposing under this criterion. It should be noted that the possible benefits of using imported coal, such as increased efficiency and reliability, would be accounted for in other criteria.

For Level 2 analysis, the power plants using imported, blended, and domestic coal would be assigned the values 3, 2, and 1 respectively for this parameter. Further, the differences in the value of the parameter corresponding to different strengths of preference (corresponding to the Saaty scale) are given below. In a pairwise comparison, the plant with the higher value is more preferred.

Table 4-12 Saaty Scale for Pairwise Comparison on the Criterion of CSA

Magnitude of Difference	Strength of Preference
2	Extremely preferred
1	Moderately preferred

0	Equally preferred

4. Coal supply constraints

Recently, coal supply constraints in many countries have placed coal power plants at the risk of shutdown, reiterating the importance of this factor in the current and long-term scenarios. Here, this criterion considers the ability of coal power plants to maintain average coal inventories in the longer run. As per industry practice, coal power plants generally have coal inventories to operate for 15 days in case of pit head plants and can go up to 30 - 45 days as the distance of plant from coal mines increases. Since the requirements vary with, among other factors, location, type, and geography of the plant, applying a single yardstick in terms of quantity of reserves may not be appropriate. The approach adopted in the framework is that plants unable to maintain the statutorily prescribed amount of reserve may be considered as favorable options for repurposing.

As this is a categorical variable, power plants able and unable to maintain the statutorily prescribed amount of reserve have been assigned indices as follows: Unable to maintain reserve – 2, and Able to maintain reserve – 1. Further, the differences in ratings corresponding to different strengths of preference (corresponding to the Saaty scale) are given below. In a pairwise comparison, the plant with the higher index is more preferred.

Table 4-13 Saaty Scale for Pairwise Comparison on the Criterion of Coal Supply Constraints

Magnitude of Difference	Strength of Preference
1	Extremely preferred
0	Equally preferred

4.3 Social and Environmental Criteria

While statutory requirements regulate the social and environmental impacts of the power plant, they may not necessarily cover all aspects. Further, it may be important to distinguish between the power plants if there is a significant difference even though they both lie within the compliance limits. Thus, the following criteria recognize the positive and negative impacts of coal power plants on the society and the environment, including air pollution, water pollution, and local employment. The criteria considered in this category are:

1. Willingness of stakeholders

Identification and engagement of stakeholders affected by decommissioning of the coal power plant is a crucial step, as they may wield significant influence on the process of repurposing the coal power plant. Thus, obtaining the buy-in of key stakeholders is important for undertaking the repurposing successfully. These key stakeholders are the owners of the coal power plant, the lenders, the workforce employed at the power plant, and the government. Although willingness is a subjective measure, it can be gauged broadly through extensive engagement in the form of surveys and interviews.

Depending upon the results of the interviews, for the Level 2 analysis, the degree of support from stakeholders can be broadly classified into two categories and assigned indices as follows: Willing to agree to the repurposing – 2 and Less willing to agree to the repurposing – 1. Further, the differences in indices corresponding to different strengths of preference (corresponding to the Saaty scale) are given below. In a pairwise comparison, the plant with the higher index is more preferred.

Table 4-14 Saaty Scale for Pairwise Comparison on the Criterion of Willingness of Stakeholders

Magnitude of Difference	Strength of Preference
1	Extremely preferred
0	Equally preferred

2. **Carbon dioxide emissions**

CO_2 emissions is one of the key drivers for the accelerated retirement of coal power plants. Although the efficiency or the heat rate is an important determiner of CO_2 emissions, the latter also depends upon the characteristics of the fuel as well as the use of any carbon-capture technology. Thus, this has been considered as a separate criterion. Typically, the specific CO_2 emissions (i.e., CO_2 emissions per unit of electricity generated) ranges from 0.8 to 1.1 kg-CO_2/kWh [12, 13].

Since the exact range may be different for different geographies and does not account for CCS, the approach adopted here is a relativistic one. The plants being considered in the analysis are arranged in decreasing order of the average specific CO_2 emissions produced over the past 12 months and partitioned into five groups (A – E) with equal number of power plants. Depending upon the group the candidate power plant belongs to, the parameter takes on the following values: Group A (highest CO_2 emissions) – 9, Group B (high CO_2 emissions) – 7, Group C (intermediate CO_2 emissions) – 5, Group D (low CO_2 emissions) – 3, Group E (lowest CO_2 emissions) – 1. Further, the differences in the value of the parameter corresponding to different strengths of preference (corresponding to the Saaty scale) are given below. In a pairwise comparison, the plant with the higher value is more preferred.

Table 4-15 Saaty Scale for Pairwise Comparison on the Criterion of Carbon Dioxide Emissions

Magnitude of Difference	Strength of Preference
8	Extremely preferred
6	Very strongly preferred
4	Strongly preferred
2	Moderately preferred
0	Equally preferred

3. **Impact on local economy**

A coal power plant is a significant economic presence in its neighborhood, especially in developing countries. Therefore, the corporation that owns the power plant engages with the community due to a mixture of regulatory (government-mandated CSR), economic (legitimacy theory for businesses) and ethical reasons. The decommissioning of the power plant may thus negatively impact the local economy of the community. The quantum of the impact depends upon the contribution of the corporation vis-à-vis the capacity of the administration to absorb the shock. Thus, the parameter chosen is the annual CSR expenditure by the corporation in the local area expressed as a fraction of the annual local budget for expenditure on public goods, where it would be preferable to prioritize the retirement of coal power plants with the lowest contribution to the local economy. Depending on the geography and civic administration, 'local' could refer to the municipality, district, or any other appropriate sub-division.

As the rules and customs may be different for different areas, the approach adopted here is a relativistic one. The plants being considered in the analysis are arranged in increasing order of the value of the parameter chosen above and partitioned into five groups (A – E) with equal number of power plants. Depending upon the group the candidate power plant belongs to, the parameter takes on the following values: Group A (lowest CSR fraction) – 9, Group B (low CSR fraction) – 7, Group C (intermediate CSR fraction) – 5, Group D (high CSR fraction) – 3, Group E (highest CSR fraction) – 1. Further, the differences in the value of the parameter corresponding to different strengths of preference (corresponding to the Saaty scale) are given below. In a pairwise comparison, the plant with the higher value is more preferred.

Table 4-16 Saaty Scale for Pairwise Comparison on the Criterion of Impact on Local Economy

Magnitude of Difference	Strength of Preference
8	Extremely preferred
6	Very strongly preferred
4	Strongly preferred
2	Moderately preferred
0	Equally preferred

4. Impact on local employment

In addition to being an overall contributor to the local economy as discussed above, a coal power plant is specifically a key source of employment in its area. The decommissioning of the power plant may thus lead to a significant number of job losses in the community. The quantum of the impact depends upon the number of jobs supported by the power plant vis-à-vis the total labor force in the community. Thus, the parameter chosen is the number of direct and indirect jobs supported by the power plant as a fraction of the labor force, where it would be preferable to prioritize the retirement of coal power plants with the lowest contribution to the local employment.

The approach adopted for comparing the candidate power plants is similar to that for the above criterion. The plants being considered in the analysis are arranged in increasing order of the value of the parameter chosen above and partitioned into five groups (A – E) with equal number of power plants. Depending upon the group the candidate power plant belongs to, the parameter takes on the following values: Group A (lowest employment fraction) – 9, Group B (low employment fraction) – 7, Group C (intermediate employment fraction) – 5, Group D (high employment fraction) – 3, Group E (highest employment fraction) – 1. Further, the differences in the value of the parameter corresponding to different strengths of preference (corresponding to the Saaty scale) are given below. In a pairwise comparison, the plant with the higher value is more preferred.

Table 4-17 Saaty Scale for Pairwise Comparison on the Criterion of Impact on Local Employment

Magnitude of Difference	Strength of Preference
8	Extremely preferred
6	Very strongly preferred
4	Strongly preferred
2	Moderately preferred
0	Equally preferred

5. Effluents and water pollution

Coal-fired thermal power generation impacts the water ecosystem in three significant ways. First, the slurry discharged or stored in coal ash ponds may mix with groundwater, lakes, ponds or other water bodies, contaminating them with toxic substances such as heavy metals. Second, in plants employing the once-through cooling system, the cooling water, after absorbing heat from the steam cycle, is discharged into a water body such as a river, lake, or sea. The discharged water can increase the overall temperature of the water body, thereby negatively impacting the aquatic biodiversity. Third, in plants using cooling towers, there is a higher consumption of water which can contribute to increased water stress in the region. In India, new freshwater-based coal power plants are required to achieve zero wastewater discharge and a specific consumption of less than 3 L/kWh [14]. In South Africa, in 2020-21, the average specific water use was 1.42 L/kWh [15].

The plants being considered in the analysis are categorized into five groups (A – E) as follows.

a. Group A (once-through cooling with freshwater) – 9

b. Group B (cooling tower with freshwater consuming more than 3 L/ kWh) – 7

c. Group C (cooling tower with freshwater consuming between 1.5 and 3 L/kWh) – 5

d. Group D (once-through cooling with seawater in an ecologically sensitive area) – 3

e. Group E (other) – 1

Further, the differences in the value of the parameter corresponding to different strengths of preference (corresponding to the Saaty scale) are given below. In a pairwise comparison, the plant with the higher value is more preferred.

Table 4-18 Saaty Scale for Pairwise Comparison on the Criterion of Effluents and Water Pollution

Magnitude of Difference	Strength of Preference
8	Extremely preferred
6	Very strongly preferred
4	Strongly preferred
2	Moderately preferred
0	Equally preferred

5.0 AHP Application for CPP Selection

5.1 Level 1 Analysis

Level 1 of the AHP methodology involves assigning weightages to the eighteen criteria that were enumerated in above section and listed below in Table 5-1.

Table 5-1 Criteria for the Selection of Coal Power Plants

Sr. No.	Criterion or Parameter	Unit of Value
A	Age of power plant	Years
B	Rated capacity	MW
C	Type of power plant	Index {1, 3, 5, 7, 9} *
D	Average heat rate deviation	Percentage (percent)
E	Ramp rate	Percentage per minute (percent/min)
F	Forced outage rate	Percentage (percent)
G	Load serving location	Index {1, 2} *
H	Plant load factor (PLF)	Percentage (percent)
I	Levelized cost of electricity (LCOE)	USD/MWh
J	Local emission track record	Index {1, 2} *
K	Power Purchase Agreement (PPA)	Index {1, 3, 5, 7, 9} *
L	Coal Supply Agreement (CSA)	Index {1, 2, 3} *
M	Coal supply constraints	Index {1, 2} *
N	Willingness of stakeholders	Index {1, 2} *
O	Carbon dioxide emissions	Index {1, 3, 5, 7, 9} *
P	Impact on local economy	Index {1, 3, 5, 7, 9} *
Q	Impact on local employment	Index {1, 3, 5, 7, 9} *
R	Effluents and water pollution	Index {1, 3, 5, 7, 9} *
*Please refer Section 4.0 for the reference Index given against the criteria.		

Based on discussions with subject matter experts and stakeholder consultations, pairwise comparisons among the above criteria are undertaken and converted using the Saaty scale (Table 5-2) to develop the comparison matrix. An example of a completed comparison matrix as shown in Table 5-3. Note that the entries in boldface indicate the corresponding criteria in Table 5-1 and the entries in the matrix indicate the importance of the row-number criterion vis-à-vis the column-number criterion.

In the excel based framework for better interface to user, the table for pairwise comparison is created as shown in Table 5-4. In Table 5-4, the “A/B” or “B/A” refers to “A as compared to B” or “B as compared A” and the ratings are given as per the Saaty scale as tabulated in Table 5-2. In this framework the Table 5-4 is automatically linked to Table 5-3, to populate the quantitative equivalent of ratings.

Table 5-2 Saaty Scale

Strength of Preference	Row Element Preferred	Column Element Preferred
Extremely preferred	9	1/9
Very strongly to extremely preferred	8	1/8
Very strongly preferred	7	1/7
Strongly to very strongly preferred	6	1/6
Strongly preferred	5	1/5
Moderately to strongly preferred	4	1/4
Moderately preferred	3	1/3
Equally to moderately preferred	2	1/2
Equally preferred	1	1

Table 5-3 AHP Level 1 Comparison Matrix

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
A	1	5	5	1	7	7	5	7	5	1	1	5	3	3	1	3	5	7
B	1/5	1	1	1/3	3	3	3	3	1	1/3	1/5	1	1/3	1/3	1/7	1/5	3	3
C	1/5	1	1	1/3	3	3	3	3	1	1/3	1/5	1	1/3	1/3	1/5	1/3	5	3
D	1	3	3	1	7	7	5	7	3	1	1/3	3	3	3	1/3	3	5	3
E	1/7	1/3	1/3	1/7	1	1	1	1	1/5	1/7	1/9	1/3	1/7	1/3	1/5	1/3	1/3	1/3
F	1/7	1/3	1/3	1/7	1	1	1	1	1/3	1/7	1/9	1	1/7	1/3	1/7	1/7	1	1
G	1/5	1/3	1/3	1/5	1	1	1	1	1/3	1/5	1/7	1	1/5	1/3	1/7	1/5	1	1
H	1/7	1/3	1/3	1/7	1	1	1	1	1/3	1/7	1/9	1/3	1/7	1/5	1/7	1/3	1	1
I	1/5	1	1	1/3	5	3	3	3	1	1/3	1/5	1	1/3	1	1/5	1	1/3	3
J	1	3	3	1	7	7	5	7	3	1	1	5	3	3	1/3	3	3	5
K	1	5	5	3	9	9	7	9	5	1	1	7	3	3	1	3	5	7
L	1/5	1	1	1/3	3	1	1	3	1	1/5	1/7	1	1/3	1/3	1/7	1	1/3	3
M	1/3	3	3	1/3	7	7	5	7	3	1/3	1/3	3	1	1	1/5	1	3	3
N	1/3	3	3	1/3	3	3	3	5	1	1/3	1/3	3	1	1	1/5	7	7	3
O	1	7	5	3	5	7	7	7	5	3	1	7	5	5	1	9	9	7
P	1/3	5	3	1/3	3	7	5	3	1	1/3	1/3	1	1	1/7	1/9	1	5	3
Q	1/5	1/3	1/5	1/5	3	1	1	1	3	1/3	1/5	3	1/3	1/7	1/9	1/5	1	1
R	1/7	1/3	1/3	1/3	3	1	1	1	1/3	1/5	1/7	1/3	1/3	1/3	1/7	1/3	1	1

Table 5-4 AHP Level 1 Comparison - Excel Based Framework Interface

	A	B		C		D		E		F		G	
		Compare	Rating	Compare	Rating	Compare	Rating	Compare	Rating	Compare	Rating	Compare	Rating
A		A/B	Strongly Prefered	A/C	Strongly Prefered	A/D	Equally Prefered	A/E	Very Strongly Prefered	A/F	Very Strongly Prefered	A/G	Strongly Prefered
B				B/C	Equally Prefered	D/B	Moderately Prefered	B/E	Moderately Prefered	B/F	Moderately Prefered	B/G	Moderately Prefered
C						D/C	Moderately Prefered	C/E	Moderately Prefered	C/F	Moderately Prefered	C/G	Moderately Prefered
D								D/E	Very Strongly Prefered	D/F	Very Strongly Prefered	D/G	Strongly Prefered
E										E/F	Equally Prefered	E/G	Equally Prefered
F												F/G	Equally Prefered
G													
H													
I													
J													
K													
L													
M													
N													
O													
P													
Q													
R													

	H		I		J		K		L		M	
	Compare	Rating	Compare	Rating	Compare	Rating	Compare	Rating	Compare	Rating	Compare	Rating
A	A/H	Very Strongly Prefered	A/I	Strongly Prefered	A/J	Equally Prefered	A/K	Equally Prefered	A/L	Strongly Prefered	A/M	Moderately Prefered
B	B/H	Moderately Prefered	B/I	Equally Prefered	J/B	Moderately Prefered	K/B	Strongly Prefered	B/L	Equally Prefered	M/B	Moderately Prefered
C	C/H	Moderately Prefered	C/I	Equally to Moderately	J/C	Moderately Prefered	K/C	Strongly Prefered	C/L	Equally Prefered	M/C	Moderately Prefered
D	D/H	Very Strongly Prefered	D/I	Moderately Prefered	D/J	Equally Prefered	K/D	Moderately Prefered	D/L	Moderately Prefered	D/M	Moderately Prefered
E	E/H	Equally Prefered	I/E	Strongly Prefered	J/E	Very Strongly Prefered	K/E	Extremely Prefered	L/E	Moderately Prefered	M/E	Very Strongly Prefered
F	F/H	Equally Prefered	I/F	Moderately Prefered	J/F	Very Strongly Prefered	K/F	Extremely Prefered	F/L	Equally Prefered	M/F	Very Strongly Prefered
G	G/H	Equally Prefered	I/G	Moderately Prefered	J/G	Strongly Prefered	K/G	Very Strongly Prefered	G/L	Equally Prefered	M/G	Strongly Prefered
H			I/H	Moderately Prefered	J/H	Very Strongly Prefered	K/H	Extremely Prefered	L/H	Moderately Prefered	M/H	Very Strongly Prefered
I					J/I	Moderately Prefered	K/I	Strongly Prefered	I/L	Equally Prefered	M/I	Moderately Prefered
J							J/K	Equally Prefered	J/L	Strongly Prefered	J/M	Moderately Prefered
K									K/L	Very Strongly Prefered	K/M	Moderately Prefered
L											M/L	Moderately Prefered
M												
N												
O												
P												
Q												
R												

	N		O		P		Q		R	
	Compare	Rating	Compare	Rating	Compare	Rating	Compare	Rating	Compare	Rating
A	A/N	Moderately Prefered	A/O	Equally Prefered	A/P	Moderately Prefered	A/Q	Strongly Prefered	A/R	Very Strongly Prefered
B	N/B	Moderately Prefered	O/B	Very Strongly Prefered	P/B	Strongly Prefered	B/Q	Moderately Prefered	B/R	Moderately Prefered
C	N/C	Strongly Prefered	O/C	Moderately Prefered	C/P	Strongly Prefered	C/Q	Strongly Prefered	C/R	Moderately Prefered
D	D/N	Moderately Prefered	O/D	Moderately Prefered	D/P	Moderately Prefered	D/Q	Strongly Prefered	D/R	Moderately Prefered
E	N/E	Moderately Prefered	O/E	Strongly Prefered	P/E	Moderately Prefered	Q/E	Moderately Prefered	R/E	Moderately Prefered
F	N/F	Moderately Prefered	O/F	Very Strongly Prefered	P/F	Very Strongly Prefered	F/Q	Equally Prefered	F/R	Equally Prefered
G	N/G	Moderately Prefered	O/G	Very Strongly Prefered	P/G	Strongly Prefered	G/Q	Equally Prefered	G/R	Equally Prefered
H	N/H	Strongly Prefered	O/H	Very Strongly Prefered	P/H	Moderately Prefered	H/Q	Equally Prefered	H/R	Equally Prefered
I	I/N	Equally Prefered	O/I	Strongly Prefered	I/P	Equally Prefered	Q/I	Moderately Prefered	I/R	Moderately Prefered
J	J/N	Moderately Prefered	O/J	Moderately Prefered	J/P	Moderately Prefered	J/Q	Moderately Prefered	J/R	Strongly Prefered
K	K/N	Moderately Prefered	K/O	Equally Prefered	K/P	Moderately Prefered	K/Q	Strongly Prefered	K/R	Very Strongly Prefered
L	N/L	Moderately Prefered	O/L	Very Strongly Prefered	L/P	Equally Prefered	Q/L	Moderately Prefered	L/R	Moderately Prefered
M	M/N	Equally Prefered	O/M	Strongly Prefered	M/P	Equally Prefered	M/Q	Moderately Prefered	M/R	Moderately Prefered
N			O/N	Strongly Prefered	N/P	Very Strongly Prefered	N/Q	Very Strongly Prefered	N/R	Moderately Prefered
O					O/P	Extremely Prefered	O/Q	Extremely Prefered	O/R	Very Strongly Prefered
P							P/Q	Strongly Prefered	P/R	Moderately Prefered
Q									Q/R	Equally Prefered
R										

The rows against Criteria A, K, and O have only integral values, implying that they are equally or more important than all other criteria and, thus, would be expected to have the highest weightages. Conversely, the columns against Criteria E, F, G, and H have only integral values indicating that they are equally or less important than all other criteria, and thus would have the lowest weightages. Since no two rows are identical, all criteria would have distinct weightages. The ranking vector in Table 5-5, developed following Step 2 of the AHP methodology as described above in Section 3.0, confirms these expectations.

Table 5-5 AHP Level 1 Ranking Vector or Weightages for the Comparison Criteria

Sr. No.	Criterion or Parameter	Weightage	Rank
A	Age of power plant	11.66 percent	3
B	Rated capacity	3.14 percent	11
C	Type of power plant	3.41 percent	9
D	Average heat rate deviation	8.91 percent	5
E	Ramp rate	1.27 percent	18
F	Forced outage rate	1.42 percent	16
G	Load serving location	1.56 percent	15
H	Plant load factor (PLF)	1.33 percent	17
I	Levelized cost of electricity (LCOE)	3.38 percent	10
J	Local emission track record	9.70 percent	4
K	Power Purchase Agreement (PPA)	13.46 percent	2
L	Coal Supply Agreement (CSA)	2.54 percent	12
M	Coal Supply Constraints	6.15 percent	7
N	Willingness of stakeholders	6.23 percent	6
O	Carbon dioxide emissions	16.54 percent	1
P	Impact on local economy	5.13 percent	8
Q	Impact on local employment	2.45 percent	13
R	Effluents and water pollution	1.71 percent	14

Further, the consistency of the pairwise comparisons can be verified using the Consistency Index. For the above matrix, the CI is 0.135, which results in a Consistency Rate (CR) of 0.083. This falls within the acceptable limit of 0.1. Thus, these weights can be considered for the Level 2 analysis. Note that these weights are only indicative and used mainly to demonstrate the framework.

5.2 Level 2 Analysis

As the number of coal power plants in the country could be quite large, a filtering exercise based on the preferred regulatory environment can be performed to focus the Level 2 analysis. Specifically, the filtering exercise could have the following criteria:

- **Region**: In addition to national policies, subnational authorities such as provincial and local governments and associated regulatory authorities can abet or hinder the process of repurposing the coal power plant.

- **Ownership**: Depending upon the prevailing regulatory environment, it may be preferable to target government-owned or private-owned power plants. For instance, divestment regulations may add to procedural complexities in repurposing of government-owned power plants. On the other hand, it may be easier to receive the buy-in of the government rather than private owners for repurposing projects with significant economic benefit beyond just financial value.

The coal power plants thus selected are passed along to the AHP framework. Having obtained the weightages for the criteria from the Level 1 analysis, these coal power plants are compared on each criterion in Level 2.

As an example, ten candidate coal power plants are considered with the details respective to each criterion depicted in Table 5-6. The values correspond to the units as mentioned in Table 5-1. Details on the assignment of values, especially the qualitative criteria (C3, C7, C10 – C18), are given in Section 4.0 along with the description of the criteria. It should be noted that, for all criteria, apart from C5 (Ramp rate) and C8 (Plant load factor), a higher value indicates a greater preference for the corresponding candidate coal power plant to be prioritized for accelerated decommissioning.

Table 5-6 Candidate Coal power Plants

Candidate Coal Power Plant	C1 - Age of Power Plant	C2 - Rated Capacity	C3 - Type of Power Plant	C4 - Average Heat Rate Deviation	C5 - Ramp Rate	C6 - Forced Outage Rate	C7 - Load Serving Location	C8 - Plant Load Factor (PLF)	C9 - Levelized Cost of Electricity (LCOE)	C10 - Local Emission Track Record	C11 - Power Purchase Agreement (PPA)	C12 - Coal Supply Agreement (CSA)	C13 - Coal Supply Constraints	C14 - Willingness of Stakeholders	C15 - Carbon Dioxide Emissions	C16 - Impact on Local Economy	C17 - Impact on Local Employment	C18 - Effluents and Water Pollution
1	10	100	1	5	5	10	2	65	32	2	1	3	1	2	7	1	3	5
2	10	180	3	7	3	8	2	55	30	2	1	2	1	2	5	7	7	7
3	5	330	5	12	3	6	2	70	27	1	1	2	2	2	9	1	3	7
4	25	660	7	10	2	3	2	75	28	1	7	2	2	1	1	5	3	1
5	25	800	9	4	1	2	1	80	26	1	7	2	1	2	5	3	1	3
6	40	250	5	14	4	7	1	65	30	1	9	1	1	1	1	7	5	1
7	50	150	3	15	5	8	1	75	42	2	9	1	1	1	7	5	7	5
8	18	30	1	11	8	15	2	65	45	2	5	2	2	1	3	7	5	3
9	26	450	5	9	5	6	1	52	38	1	7	2	2	1	7	9	9	5
10	22	130	3	8	6	12	2	54	30	2	5	2	1	2	5	3	1	5

As an example of Level 2 analysis, C1 (Age of the power plant) is considered for the ten candidate coal power plants with their ages reproduced in the below table.

Table 5-7 Age of Coal Power Plants

Sr. No.	Coal Power Plant (CPP)	Age (years)
1	Coal Power Plant 1	10
2	Coal Power Plant 2	10
3	Coal Power Plant 3	5
4	Coal Power Plant 4	25
5	Coal Power Plant 5	25
6	Coal Power Plant 6	40
7	Coal Power Plant 7	50
8	Coal Power Plant 8	18
9	Coal Power Plant 9	26
10	Coal Power Plant 10	22

By using the correspondence of each criterion to the Saaty scale given in Section 4.0, the comparison matrix for Level 2 analysis for each criterion is constructed. For example, in the first row the ages of each coal power plant would be subtracted from that of Coal Power Plant 1. Depending upon the magnitude of the difference, the corresponding strength of preference is chosen. Finally, if the difference is positive, the integer value corresponding to the preference is used; and if negative, the reciprocals are used. The process for the first row i.e., age of each coal power plant is summarized in the below table.

Table 5-8 Magnitude of Difference - Age

	CPP 1	CPP 2	CPP 3	CPP 4	CPP 5	CPP 6	CPP 7	CPP 8	CPP 9	CPP 10
Age (years)	10	10	5	25	25	40	50	18	26	22
Difference from CPP 1	0	0	5	-15	-15	-30	-40	-8	-16	-12
Row 1 of the matrix	1	1	3	1/5	1/5	1/7	1/9	1/3	1/5	1/5

The completed matrix is given below. Note that the first and second rows (and columns) are identical as Coal Power Plant 1 and Coal Power Plant 2 have the same age. Similarly, Coal Power Plant 4 and Coal Power Plant 5 have the same ages and, thus, the corresponding rows (and columns) are identical.

Table 5-9 CPP Comparison Matrix - Age as Criterion

	CPP 1	CPP 2	CPP 3	CPP 4	CPP 5	CPP 6	CPP 7	CPP 8	CPP 9	CPP 10
CPP 1	1	1	3	1/5	1/5	1/7	1/9	1/3	1/5	1/5
CPP 2	1	1	3	1/5	1/5	1/7	1/9	1/3	1/5	1/5
CPP 3	1/3	1/3	1	1/5	1/5	1/9	1/9	1/5	1/7	1/5
CPP 4	5	5	5	1	1	1/5	1/7	3	1/3	3
CPP 5	5	5	5	1	1	1/5	1/7	3	1/3	3
CPP 6	7	7	9	5	5	1	1/3	7	5	5
CPP 7	9	9	9	7	7	3	1	9	7	7
CPP 8	3	3	5	1/3	1/3	1/7	1/9	1	1/3	1/3
CPP 9	5	5	7	3	3	1/5	1/7	3	1	3
CPP 10	5	5	5	1/3	1/3	1/5	1/7	3	1/3	1

The ranking vector for the criterion is developed by following Step 2 of the AHP methodology described above in Section 3.0. This vector, along with the ages of the coal power plants, is given below. It can be observed that the order of priority corresponds well with the actual age.

Table 5-10 Ranking Vector for CPP for Age as Criterion

Sr. No.	Coal Power Plant (CPP)	Ranking Vector	Age (years)
1	Coal Power Plant 1	2.35 percent	10
2	Coal Power Plant 2	2.35 percent	10
3	Coal Power Plant 3	1.50 percent	5
4	Coal Power Plant 4	8.00 percent	25
5	Coal Power Plant 5	8.00 percent	25
6	Coal Power Plant 6	21.77 percent	40
7	Coal Power Plant 7	34.40 percent	50
8	Coal Power Plant 8	4.22 percent	18
9	Coal Power Plant 9	11.02 percent	26
10	Coal Power Plant 10	6.39 percent	22

A similar procedure was performed for the other criteria and the obtained ranking vectors are tabulated below each criterion in Table 5-11.

Table 5-11 AHP Level 2 Ranking Vectors for All Criteria (in percentages)

Candidate Coal Power Plant	C1 - Age of Power Plant	C2 - Rated Capacity	C3 - Type of Power Plant	C4 - Average Heat Rate Deviation	C5 - Ramp Rate	C6 - Forced Outage Rate	C7 - Load Serving Location	C8 - Plant Load Factor (PLF)	C9 - Levelized Cost of Electricity (LCOE)	C10 - Local Emission Track Record	C11 - Power Purchase Agreement (PPA)	C12 - Coal Supply Agreement (CSA)	C13 - Coal Supply Constraints	C14 - Willingness of Stakeholders	C15 - Carbon Dioxide Emissions	C16 - Impact on Local Economy	C17 - Impact on Local Employment	C18 - Effluents and Water Pollution
1	2	2	2	3	4	13	16	7	9	18	2	28	2	18	15	2	4	10
2	2	5	4	4	12	8	16	15	5	18	2	9	2	18	7	15	17	23
3	2	9	10	14	12	4	16	5	3	2	2	9	21	18	30	2	4	23
4	8	22	20	9	21	2	16	3	4	2	12	9	21	2	2	7	4	2
5	8	35	34	2	33	1	2	2	2	2	12	9	2	18	7	4	2	4
6	22	6	10	19	7	6	2	7	5	2	24	3	2	2	2	15	9	2
7	34	4	4	26	4	8	2	3	20	18	24	3	2	2	15	7	17	10
8	4	1	2	12	1	33	16	7	29	18	6	9	21	2	3	15	9	4
9	11	13	10	7	4	4	2	29	16	2	12	9	21	2	15	30	32	10
10	6	3	4	5	2	20	16	23	5	18	6	9	2	18	7	4	2	10
Note: The values in each column may not add up to 100 percent due to rounding.																		

It can be observed that the trend in the values of the parameter for a particular criterion is replicated in the corresponding vector for all criteria except C5 and C7. For these criteria, the trend is exactly reversed as a lower value indicates higher preference. The ranking vector from each consolidated output of the AHP is obtained by calculating the weighted sum of all vectors, where the weights are as obtained in the Level 1 analysis (Table 5-5). The consolidated output is presented in Table 5-12.

Table 5-12 AHP Consolidated Output

Sr. No.	Candidate Coal Power Plant	Consolidated Vector	Rank
1	Coal Power Plant 1	8.30 percent	7
2	Coal Power Plant 2	7.99 percent	10
3	Coal Power Plant 3	11.24 percent	3
4	Coal Power Plant 4	8.04 percent	8
5	Coal Power Plant 5	8.58 percent	6

Sr. No.	Candidate Coal Power Plant	Consolidated Vector	Rank
6	Coal Power Plant 6	10.34 percent	4
7	Coal Power Plant 7	16.19 percent	1
8	Coal Power Plant 8	9.28 percent	5
9	Coal Power Plant 9	12.01 percent	2
10	Coal Power Plant 10	8.03 percent	9

Thus, the decision-maker is presented with a ranked list of all alternatives, allowing them to prioritize the allocation of resources between the candidate coal power plants. It can be observed that Coal Power Plant 7, which has the highest priority for C1, C4, C10 and C11, also has the highest priority in the consolidated output as they have significant weightages. On the other hand, Coal Power Plant 5, despite having the highest priority in C2, C3, and C5, ranks sixth overall. This is because these criteria have low weightages. Thus, the AHP methodology allows the decision-maker to exactly understand the rationale behind the rankings. While the consolidated output of the AHP framework is cardinal in nature (i.e., an alternative with 16 percent is *twice* as good as an alternative with 8 percent), the decision-maker may choose to interpret it only ordinally especially if the resource allocation between the projects is fixed a priori.

Although this is an integrated framework, where the characteristics of the coal power plant are used as an input and the aggregate ranking is the final output, the AHP methodology can also be combined with more detailed analysis of individual or categories of criteria. These detailed analyses would partially or completely substitute the Level 2 analysis of this framework while the Level 1 analysis of the AHP would continue to be used to assign weightages to these criteria or categories of criteria. For instance, the Level 2 analyses for techno-commercial criteria (C1 – C9) can be substituted by a detailed model of the local and regional grid to understand the impact of early retirement of the coal power plants on the cost and stability of the power system. Similarly, the social and environmental criteria (C14 – C18) can be substituted by an environmental and social impact analysis (ESIA) to evaluate the impacts of early retirement of the coal power plants on the environment and society. However, undertaking such detailed analyses for each candidate coal power plant just for selection could be time and resource intensive. Thus, using the integrated AHP framework can aid in the efficient selection of the top power plants.

6.0 Selection of Repurposing Concept

6.1 Weighted Linear Combination

Once the candidate coal power plant that would be repurposed has been identified, the suitable repurposing concepts are identified using the Weighted Linear Combination (WLC), which is a commonly used MCDM methodology. In the WLC methodology, each alternative is scored using individual criteria as bases, one at a time. The weighted sum of the scores obtained by the alternative against each criterion is calculated where the weights denote the relative importance of the respective criterion. The sum thus obtained denotes the WLC score of the alternative.

Consider that the index i denotes an alternative and j denotes a criterion. Further, let w_j be the weight assigned to Criterion j, which corresponds to its importance relative to other criteria. Thus, if s_{ij} represents the score of Alternative i on the basis of Criterion j, then the WLC score of Alternative i is given by the following equation.

$$s_i^{WLC} = \sum_j w_j s_{ij}$$

If the weights truly represent the relative importance of the criteria and do not incorporate any scaling effects, then the scoring scales and units must be the same for all criteria. Further, since this is an additive model, it is imperative that the scales for all the criteria correspond in a similar manner to the preference with respect to the overall goal. Thus, for all criteria, a high score should correspond to a higher preference (i.e., the objective is score maximization) or a lower preference (i.e., the objective is score minimization). Finally, although it is not necessary that the weights are normalized, it is preferred that they sum up to 1 so that the WLC score is in the same scale as the individual criterion scores.

In this framework, given the large number of available repurposing concepts, preliminary steps before the actual application of the WLC methodology are applied. The overview of the complete algorithm for this framework is shown in Figure 6-1.

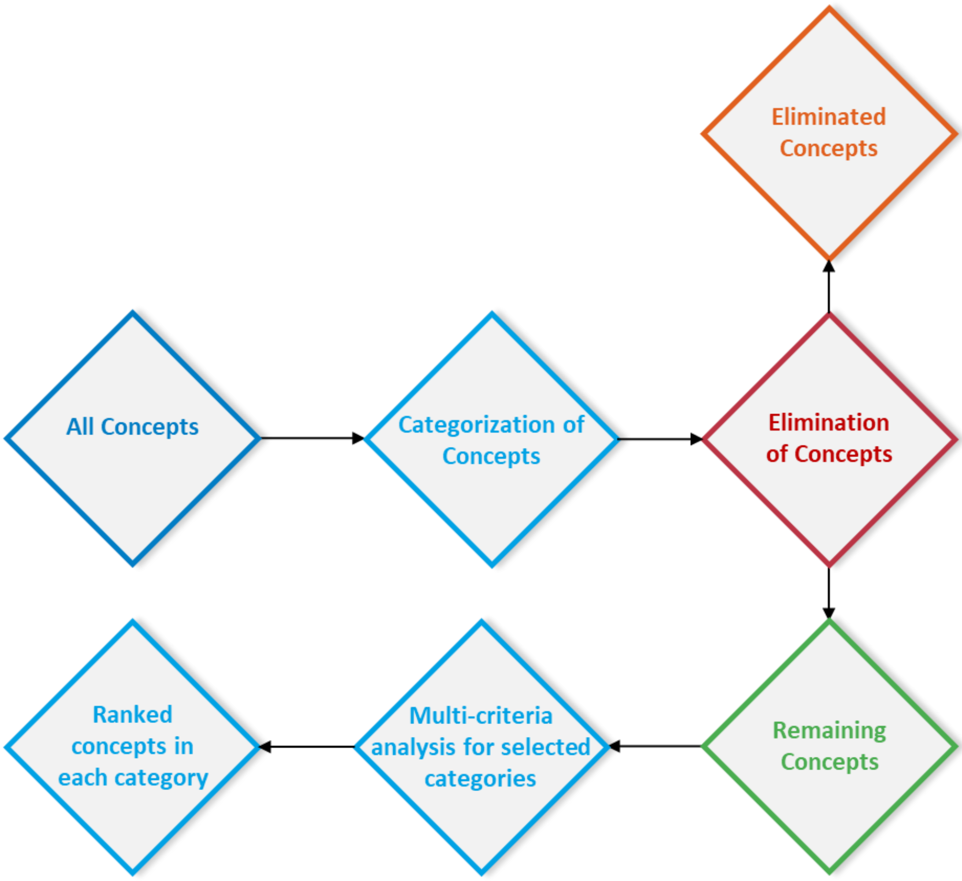

Figure 6-1 Algorithm for Selection of Repurposing Alternative

6.2 WLC Methodology for selection of repurposing concept

As discussed in Section 6.1, the scoring scale adopted for all criteria must be identical. Since the criteria considered here cover different aspects and cannot be converted to a common unit, a qualitative three-point scale is used to score the concepts. The concepts best suited for repurposing on the basis of a criterion are scored as 1, while the concepts most ill-suited for repurposing on the basis of a criterion are scored 0. Concepts showing intermediate characteristics are scored 0.5.

To illustrate the use of the framework, consider the result of the AHP methodology in Section 5.0, where Coal Power Plant 7 was chosen. With regard to its location, it is an inland power plant that receives moderately high solar irradiance and was serving a slightly power deficit community. Thus, the decision-maker would like to choose a repurposing concept that will generate electricity combined with an energy storage concept at the site of the coal power plant. Geothermal energy and offshore wind have been eliminated as they cannot be supported at the plant site. Further, repurposing concepts involving carbon capture and storage (CCS) have been eliminated owing to the lack of desired technological maturity. Due to nuclear energy being phased out in the country, the option of setting up a nuclear SMR has also been eliminated. Table 6-1 lists the concepts in the Electricity Generation and Energy Storage categories and highlights the eliminated concepts.

Table 6-1 WLC Methodology Example: Pre-Selection Elimination

Repurposing Concepts	Elimination Yardstick
Electricity Generation	
Biomass-fired boiler	-
Geothermal plant	Suitability of region's technical parameter
Municipal waste-fired boiler + CCS	Commercialization of concept on large scale
Natural gas-fired boiler + CCS	Commercialization of concept on large scale
Natural gas-fired combined cycle plant with CCS	Commercialization of concept on large scale
Nuclear Small Modular Reactor	Social Acceptance
Offshore wind	Tie-in with the government's stated policies
On-shore wind farm	-
Renewable natural gas (RNG)-fired boiler	-
Solar PV power plant	-
Energy Storage	
Li-ion BESS	-
Li-ion BESS + Synchronous Condenser	-
Molten salt thermal energy storage	-
Compressed air energy storage	-
Volcanic stone thermal energy storage	Commercialization of concept on large scale
Miscibility Gap Alloy (MGA) technology thermal storage	Commercialization of concept on large scale
Second-life use of EV batteries	Commercialization of concept on large scale
Redox flow BESS	Commercialization of concept on large scale
Metal-air BESS	Commercialization of concept on large scale
Gravity-based storage	Commercialization of concept on large scale
Flywheel	-

The remaining nine concepts are passed to the WLC framework. The guidelines for the three-point scale to score concepts in the Electricity Generation and Energy Storage categories are described in Table 6-2 and Table 6-3.

Table 6-2 Guidelines for Three-Point Scale for Electricity Generation

Criteria	Best	Average	Poor
Use of existing assets	Boiler-turbine-generator and associated auxiliaries	Switchyard, steam process, water and cooling system,	Boiler-turbine building, jetty, and switchyard
Water requirement	There is no significant water requirement.	There is a moderately significant water requirement.	There is a significant water requirement.
Logistical requirement	Means of transportation of goods and material is sufficient.	Some additional infrastructures would be required which would have a moderate cost impact.	Significant investment would be required to facilitate the repurposing concept.
Safety	Less operational safety concerns	Moderate operational safety concerns	High operational safety concerns
Specific electricity output	At least 50 percent of the electricity output of the existing coal power plant	Between 10 percent and 50 percent of the electricity output of the existing coal power plant	At least 50 percent of the electricity output of the existing coal power plant
Generation flexibility	Can be ramped up or down with low response time to meet the system requirement	Can be ramped up or down, but would require significant response time	Cannot be ramped up or down
Execution time	Less than 2 years	2 to 5 years	More than 5 years
Levelized cost of electricity (LCOE)	Highly competitive	Moderately competitive	Uncompetitive
Job creation potential	Many jobs	Medium jobs	Less jobs
Greenhouse gas emissions	Low	Moderate	High

Table 6-3 Guidelines for Three-Point Scale for Energy Storage

Criteria	Best	Average	Poor
Use of existing assets	Boiler-turbine-generator and associated auxiliaries	Switchyard, steam process, water and cooling system,	Boiler-turbine building, jetty, and switchyard
Water requirement	There is no significant water requirement.	There is a moderately significant water requirement.	There is a significant water requirement.

Criteria	Best	Average	Poor
Logistical requirement	Means of transportation of goods and material is sufficient.	Some additional infrastructures would be required which would have a moderate cost impact.	Significant investment would be required to facilitate the repurposing concept.
Safety	Less operational safety concerns	Moderate operational safety concerns	High operational safety concerns
Specific electricity output	High energy density	Moderate energy density	Low energy density
Specific power output	High power density	Moderate power density	Low power density
Execution time	Less than 2 years	2 to 5 years	More than 5 years
Levelized cost of storage (LCOS)	Highly competitive	Moderately competitive	Uncompetitive
Job creation potential	Many jobs	Medium jobs	Less jobs
Greenhouse gas emissions	Low	Moderate	High

Continuing the above example, based on the above guidelines, the nine repurposing concepts that were not eliminated in Table 6-1 have been scored against each criterion as provided in Table 6-4 and Table 6-5. However, the actual scoring for these criteria would depend on the region and features of the site. Further, all the concepts in the Energy Storage category have been scored as 'Average' for criteria where sufficient information was not available. As this is a linear methodology, this does not affect the rankings based on the other criteria.

Table 6-4 WLC Methodology Example: Scoring of Electricity Generation Concepts

Criteria	Biomass-Fired Boiler	On-Shore Wind Farm	RNG-Fired Boiler	Solar PV Power Plant
Use of existing assets	Best - 1	Poor - 0	Best - 1	Poor - 0
Water requirement	Poor - 0	Best - 1	Poor - 0	Best - 1
Logistical requirement	Average - 0.5	Best - 1	Average - 0.5	Best - 1
Safety	Average - 0.5	Best - 1	Average - 0.5	Best - 1
Specific electricity output	Best - 1	Poor - 0	Best - 1	Poor - 0
Generation flexibility	Average - 0.5	Poor - 0	Average - 0.5	Poor - 0
Execution time	Average - 0.5	Best - 1	Average - 0.5	Best - 1
Levelized cost of electricity (LCOE)	Average - 0.5	Best - 1	Poor - 0	Best - 1
Job creation potential	Best - 1	Average - 0.5	Best - 1	Average - 0.5
Greenhouse gas emissions	Average - 0.5	Best - 1	Average - 0.5	Best - 1

Table 6-5 WLC Methodology Example: Scoring of Energy Storage Generation Concepts

Criteria	Li-ion BESS	Li-ion BESS + Synchronous Condenser	Molten Salt Thermal Energy Storage	Compressed Air Energy Storage	Flywheel
Use of existing assets	Poor - 0	Average - 0.5	Average - 0.5	Poor - 0	Poor - 0
Water requirement	Average - 0.5	Average - 0.5	Average - 0.5	Average - 0.5	Average - 0.5
Logistical requirement	Average - 0.5	Average - 0.5	Average - 0.5	Average - 0.5	Average - 0.5
Safety	Poor - 0	Poor - 0	Average - 0.5	Average - 0.5	Average - 0.5
Specific electricity output	Best - 1	Best - 1	Best - 1	Poor - 0	Poor - 0
Specific power output	Best - 1	Best - 1	Poor - 0	Poor - 0	Average - 0.5
Execution time	Average - 0.5	Average - 0.5	Average - 0.5	Average - 0.5	Average - 0.5
Levelized cost of storage (LCOS)	Best - 1	Best - 1	Average - 0.5	Best - 1	Average - 0.5
Job creation potential	Average - 0.5	Average - 0.5	Average - 0.5	Average - 0.5	Average - 0.5
Greenhouse gas emissions	Best - 1	Best - 1	Best - 1	Poor - 0	Best - 1

The final step is to assign the weightages to the criteria. These weightages will depend on the priorities of the policymakers of the region. Based on internal discussions, the following indicative normalized weightages, as shown in Table 6-6, were developed for criteria in the Electricity Generation. The aggregate weightages for the three sets of the criteria are highlighted in the table.

Table 6-6 WLC Methodology Example: Weightages for Criteria for Electricity Generation

Criteria	Weightage
Technical criteria	**30.0 percent**
Use of existing assets	3.0 percent
Water requirement	1.5 percent
Logistical requirement	3.0 percent
Safety	6.0 percent
Specific electricity output	12.0 percent
Generation flexibility	4.5 percent
Commercial criteria	**50.0 percent**
Execution time	5.0 percent
Levelized cost of electricity (LCOE)	45.0 percent
Social and environmental criteria	**20.0 percent**
Job creation potential	8.0 percent
Greenhouse gas emissions	12.0 percent
Total	**100.0 percent**

Table 6-7 WLC Methodology Example: Weightages for Criteria for Energy Storage

Criteria	Weightage
Technical criteria	**40.0 percent**
Use of existing assets	4.0 percent
Water requirement	2.0 percent
Logistical requirement	4.0 percent
Safety	8.0 percent
Specific electricity output	12.0 percent
Specific power output	10.0 percent
Commercial criteria	**50.0 percent**
Execution time	5.0 percent
Levelized cost of storage (LCOS)	45.0 percent
Social and environmental criteria	**10.0 percent**
Job creation potential	4.0 percent
Greenhouse gas emissions	6.0 percent
Total	100.0 percent

For each concept, the WLC score is calculated as explained in Section 6.1 by summing the products of the criterion score and the corresponding weight. Since the weights are normalized, the WLC scores also lie between 0 and 1. It should be noted that the WLC scores are ordinal, and not cardinal as in the case of AHP. These scores are tabulated in Table 6-8.

Table 6-8 WLC Methodology Example: WLC Scores and Final Ranking

Repurposing Concepts	WLC Score	Rank
Electricity Generation		
Biomass-fired boiler	0.6325	3
On-shore wind farm	0.7400	2
Renewable natural gas (RNG)-fired boiler	0.4075	4
Solar PV power plant	0.7650	1
Energy Storage		
Li-ion BESS	0.8050	2
Li-ion BESS + Synchronous Condenser	0.8250	1
Molten salt thermal energy storage	0.5400	4
Compressed air energy storage	0.5650	3
Flywheel	0.4200	5

In this example, amongst the Electricity Generation concepts, solar PV is the most favorable repurposing concept, followed by on-shore wind, biomass-fired boiler, and RNG-fired boiler. Further, for the Energy Storage category, Li-ion BESS + Synchronous Condenser is the most favorable repurposing concept, followed by Li-ion BESS, molten salt thermal energy storage, compressed air energy storage, and flywheel. Thus, the decision-maker would choose to conduct a pre-feasibility study on repurposing Coal Power Plant 7, identified by the AHP framework, to co-locate a solar PV power plant and a Li-ion BESS + synchronous condenser.

7.0 References

[1] S. D. Pohekar and M. Ramachandran, "Application of multi-criteria decision making to sustainable energy planning — A review," *Renewable and Sustainable Energy Reviews,* pp. 365-381, 2004.

[2] P. H. dos Santos, S. M. Neves, D. O. Sant'Anna, C. H. de Oliveira and H. Duarte Carvalho, "The Analytic Hierarchy Process Supporting Decision Making For Sustainable Development: An Overview Of Applications," *Journal of Cleaner Production,* pp. 119-138, 2019.

[3] K. Teknomo, "Analytical Hierarchy Process AHP Tutorial," 2017. [Online]. Available: https://people.revoledu.com/kardi/tutorial/AHP/Priority%20Vector.htm. [Accessed 24 January 2022].

[4] T. L. Saaty, "Decision-making with the AHP: Why is the principal eigenvector necessary," *European Journal of Operational Research,* pp. 85-91, 2003.

[5] Global Energy Monitor, "Estimating carbon dioxide emissions from coal plants," 2020. [Online]. Available: https://www.gem.wiki/Estimating_carbon_dioxide_emissions_from_coal_plants. [Accessed 25 January 2022].

[6] IEA, "Technology Roadmap: High-Efficiency, Low-Emissions Coal-Fired Power Generation," OECD/IEA, Paris, 2012.

[7] CEA, India, "Mapping of 85 pulverized coal fired thermal power generating units in different states," April 2020. [Online]. Available: https://cea.nic.in/wp-content/uploads/2020/04/report_85_pul_coal.pdf. [Accessed 27 January 2022].

[8] CEA, India, "Flexibilisation of Thermal Power Plants," 27 October 2017. [Online]. Available: https://cea.nic.in/wp-content/uploads/2020/04/taskforce_report.pdf. [Accessed 27 January 2022].

[9] CEA, India, "REVIEW OF PERFORMANCE OF THERMAL POWER STATION 2017-18," April 2020. [Online]. Available: https://cea.nic.in/wp-content/uploads/opm_grid_operation/2020/07/thermal_review-2018%20(1).pdf. [Accessed 27 January 2022].

[10] Ministry of Power, "Power Sector at a Glance ALL INDIA," 2022. [Online]. Available: https://powermin.gov.in/en/content/power-sector-glance-all-india. [Accessed 31 January 2022].

[11] IEA, "Levelised Cost of Electricity Calculator," 2020. [Online]. Available: https://www.iea.org/articles/levelised-cost-of-electricity-calculator. [Accessed 27 January 2022].

[12] CEA, India, "CO2 Baseline Database for the Indian Power Sector," December 2018. [Online]. Available: https://cea.nic.in/wp-content/uploads/baseline/2020/07/user_guide_ver14.pdf.

[13] Volker Quaschning, "Specific Carbon Dioxide Emissions of Various Fuels," May 2021. [Online]. Available: https://www.volker-quaschning.de/datserv/CO2-spez/index_e.php.

[14] N. Kumar Yadav and S. Arora, "Water-Inefficient Power: Implementing Water Norms and Zero Discharge in India’s Coal-Power Fleet," Centre for Science and Environment, New Delhi, 2021.

[15] Eskom, "Sustainability Report 2021," Eskom, 2021.