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Optimization of Low-Calorific Coal Application at Different Loads in 600 MW Supercritical Thermal Power Plant with the PROMETHEE-GAIA Method

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Abstract − This study examined the 600 MW supercritical unit of a 1200 MW imported coal-fired thermal power plant in Çanakkale, Türkiye. Coal blends consisting of low-calorific domestic coal (4087 kcal/kg) and high-calorific imported coal (5954 kcal/kg) were combusted at the single mill and burner level to analyze unit parameters at different loads. Initially, input parameters, levels affecting unit parameters, and output parameters influenced by different coal types were identified and prioritized. Using criteria weights determined by the entropy method, the optimal load and domestic-imported coal blend ratio were determined using the Preference Ranking Organization Method for Enrichment Evaluation-Geometrical Analysis for Interactive Aid (PROMETHEE-GAIA) multicriteria decision-making method. The optimization study concluded that a 450 MW load with a 14.6% domestic coal feed rate is the most suitable alternative.

Keywords − *Domestic coal, entropy weighting method, PROMETHEE-GAIA, supercritical, thermal power plant*

1. Introduction

In today's constantly evolving energy landscape, the pursuit of eco-friendly and economical energy solutions has gained significance. Importing fuel-based (high-calorific) thermal power plants built with environmental responsibility has long played an important role in meeting the increasing energy demand caused by the rising population in our country and even worldwide. However, with the growing concerns over carbon emissions, resource depletion, and especially economic stability, exploring and utilizing low-cost domestic coal alternatives in such plants has become important.

Using low-calorific domestic coal provides advantages in reducing dependence on foreign markets and mitigating risks associated with supply interruptions. Promoting domestic coal mining in our country can revitalize local economies by creating employment opportunities in coal-rich regions and encouraging economic growth. Additionally, revenues from domestic coal production can be invested in infrastructure development and social welfare programs, thus contributing to national economic prosperity. Domestic coal can reduce carbon emissions and environmental impacts when mined and burned more responsibly than imported coal alternatives. By adhering to strict environmental regulations and investing in clean coal technologies, our country can reduce the ecological footprint of energy production and establish a reliable

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energy supply. Thus, countries utilizing local resources can strengthen their energy security and insulate themselves from foreign political tensions [1].

Transitioning from imported coal to lower-calorific domestic coal in our country's imported coal-fired thermal power plants requires a multi-faceted approach addressing technological, economic, and environmental issues. Investing in research and development to overcome technological barriers associated with domestic coal use is essential. Innovations in clean coal technologies, such as carbon capture and storage, coal enrichment, and efficient combustion processes, are key to enhancing the environmental performance of domestic coal use. Additionally, using domestic coal provides an opportunity to balance energy security, economic development, and environmental sustainability. Countries like ours can diversify energy sources, reduce dependence on imported fuels, and revitalize regional economies by utilizing local resources. However, realizing the full potential of domestic coal use requires addressing technological challenges through comprehensive regulatory approaches and committed efforts to encourage its use.

According to the 2022 data from the General Directorate of Mining and Petroleum Affairs (MAPEG) and Enerdata, global total coal production was 817 billion tons, while consumption was 786 billion tons. Our country's total coal production was 10537 million tons, and consumption was 11980 million tons in the same period. Of this consumption, 60.2% was hard coal, and 83.5% was lignite and asphaltite used in thermal power plants. The remaining amounts were used in heating, iron-steel, and other industrial branches [2].

When examining electricity generation sources in Türkiye as of February 2024, it is observed that 11.5% of total production was by natural gas and Liquefied natural gas (LNG) power plants. Dams provided 22.0% of the total production, while run-of-river hydroelectric plants contributed 6.1%. Imported coal power plants accounted for 23.7% of the total production in February, while domestic coal power plants contributed 14.2%. Renewable, wind, geothermal, and solar energy plants contributed 10.4% and 9.1% of the total production, respectively. Other thermal power plants had a 3.1% share in production [3]. These data indicate that Türkiye has a diverse range of sources in electricity production and an energy portfolio that includes a variety of sources. However, this diversity also presents significant challenges and opportunities regarding energy security and sustainability. Intensely using externally dependent sources such as imported coal and natural gas may increase energy imports and exposure to foreign policy risks. Therefore, prioritizing production methods based on local sources such as domestic coal and renewable energy can enhance energy security by reducing dependency. However, these sources can also bring environmental and social impacts, requiring a balanced approach. The further adoption of renewable energy sources and the development of efficient technologies can play a critical role in overcoming these challenges. Additionally, the effective implementation of energy policies and management is crucial. This can help the energy sector achieve its goals of sustainability, security, and economic development.

In order to support these considerations, Hendri and Lubis aimed to determine the optimum blending ratio of medium-grade and low-grade coal for use in energy plants. They evaluated the blending ratios of medium- and low-calorific coal in various combinations (0%, 20%, 40%, and 50%) across different analysis types [4]. Unlike Hendri and Lubis's study, this study investigates the use of mixtures of low-calorific domestic coal and high-calorific imported coal at different percentages (0%, 2%, 14.2%, 15.4%, and 14.6%) and under various load conditions (450MW, 560MW, and 605MW). In a system designed to burn high-calorific imported coal, a controlled and gradual feed of a mixture of high-calorific imported coal and low-calorific domestic coal was introduced and burned using a single mill and burner. Based on the results, criteria such as total unit coal consumption, coal cost, efficiency, SO_2, NOx, Dust, CO, and the real-time total energy consumption of fans and mills were selected to determine the optimal coal blending ratio and corresponding unit load. To determine the optimal feeding ratio and corresponding unit load from nine different decision alternatives formed according to load and coal feeding ratio, the Preference Ranking Organization Method for Enrichment Evaluation- Geometrical Analysis for Interactive Aid (PROMETHEE-GAIA) method was used as the multicriteria decision-making method, and the Entropy method was used to calculate the importance (weight) of the criteria. A literature review reveals that no studies utilize multicriteria optimization methods to determine the appropriate coal blend for burning different coal mixtures in such thermal plants. Therefore, this study will be a pioneering effort in this direction.

This study examines the potential of using domestic coal instead of imported coal in thermal plants. It seeks to explain the transformative potential of adopting domestic resources by comprehensively analyzing the advantages and disadvantages of adopting local resources and their impact on energy security, economic development, and environmental sustainability. This study represents an example of the application of PROMETHEE-GAIA, one of the multicriteria decision-making methods, using real-time data from an actual plant in the academic field. It will also serve as an example in the industrial field for using low-calorific coal as a mixture in such plants.

2. Materials and Methods

2.1. System Description and Design Parameters

The plant, located in Çanakkale, has an installed capacity of 2x610 MWe, operating with supercritical steam pressure and temperature. Supercritical thermal power plants operate above the critical point of water (Critical water – T_c=374.14 °C – P_c=22.09 MPa) at 610 °C – 250/285 bar [5]. Table 1 presents some system parameters at maximum load (600 MW). These parameters are design parameters. The plant's turbine consists of one High-Pressure (HP), one Intermediate-Pressure (IP), and two Low-Pressure (LP) turbines. The steam turbine driving the generator, capable of producing 600 MWe (607.91 MW), operates at supercritical pressure. It consists of a single-stage reheater, one HP, one IP, and two LPA LPB turbines. The fresh steam pressure of the turbine is 24.2 MPa (242 bar), and the fresh steam temperature is 566 °C. The heat consumption of the turbine operating at 3,000 rpm is 7,600 kJ/kWh. HP, IP, and LP steam turbine outlets have intermediate steam extraction lines for use in HP and LP heaters and IP steam outlets in the deaerator. The steam turbine directly connects to a 50 Hz, 22 kV, three-phase alternating current generator. Emergency shutdown valves, turbine control valves, and intermediate extraction lines are located on the steam turbine.

Table 1. Design specifications of the system

Definition	Value	Unit
Power plant	600	MWe
Boiler steam production capacity	1827	ton/h
Generator rated voltage	22	kV
Main steam pressure	24.2	Mpa
Main steam temperature	566	°C
Boiler feed water inlet pressure	29.3	Mpa
Boiler feed water inlet temperature	275	°C
Condenser vacuum pressure	-96	kPa
Turbine speed	3000	rpm
Designed coal consumption (At full load)	200 – 220	Ton/h
Condenser water outlet flow rate	1537	Ton/h
Mill coal conveying air temperature	80	°C

The imported (high-calorific) coal used in the units arrives at the facility's port through the sea. Coal is unloaded and loaded at the plant's port using the unloading and loading system and stored in the stockyard via belt conveyors. Again, using belt conveyors, coal taken from the stockyard is passed through crushers and screens to reach appropriate particle sizes and then transferred to coal bunkers. Pulverized coal is sent to burners in the boiler with mill transport air after being ground in mills. The analysis values of high-calorific Colombian and low-calorific domestic coal types used in the study are presented in Table 2. All analyses in the study were conducted in the plant laboratory.

Table 2. Analysis values of coal types used in the study

Coal Origin	Humidity (%)	Carbon (%)	Volatile (%)	Dust (%)	Sulfur (%)	Upper Cal. Value (kcal/kg)	Lower Cal. Value (kcal/kg)
Colombia	12.4	45.71	34.65	7.24	0.7	6241	5954
Local Coal	20.57	32.22	31.83	15.38	1.05	4368	4087

Pulverized coal combustion in thermal power plants is a critical process where finely ground coal is burned to generate energy [6]. In pulverized coal combustion systems, pulverized coal is sprayed into the combustion chamber using combustion air and suitable burners, similar to gas and liquid fuels. The coal particle remains suspended in the combustion air for a moment in the combustion chamber, dries quickly due to the created turbulence, vaporizes, ignites rapidly, and completes its combustion. The particle size of the coal is of great importance at this point. If the pulverized coal particle size is too small, ignition is risky during transport.

Conversely, if the particle size is large, combustion does not occur at the desired section within the boiler but towards the boiler outlet, resulting in suboptimal fuel efficiency. The sample analysis values for coal particle size per 100 grams taken from the plant after the mills are as follows: for large particles, i.e., above 200 microns, 6.97%; between 200-150 microns, 10.97%; for medium-sized and desired proportions, between 150-106 microns, 11.05%; and between 106-90 microns, 20.91%. For small particles, between 90-63 microns, 21.23%; between 63-40 microns, 17.95%; and for the smallest particles, below 40 microns, 10.92%. These values have been calculated by averaging ten different measurements.

By creating a suitable burner arrangement and operating conditions, the flame fills the combustion chamber as turbulently as possible, avoiding licking the walls and aiming for stable combustion conditions. The heat generated from coal combustion in the combustion chamber is transferred to the water pipes located on the sides of the combustion chamber through convection and radiation heat distribution [7]. The combustion gases ascending within the boiler pass through the superheater at the upper part of the boiler and subsequently through the economizer, where the incoming water is heated, transferring its heat to the steam in the packages and being released to the atmosphere at around 115 °C. The superheated steam, heated by the heat transferred from the combustion gases, is delivered to the turbine.

As seen in Figure 1, the boiler burners in the system total 24. They are positioned in three tiers, with eight burners on each tier facing each other. Pulverized coal entering with air from the burners forms a vortex in the center of the boiler. It burns, transferring its heat to the superheater packages located at the upper part and separating as flue gas. Figure 1 shows the positioning of the boiler superheater packages and burner tiers.

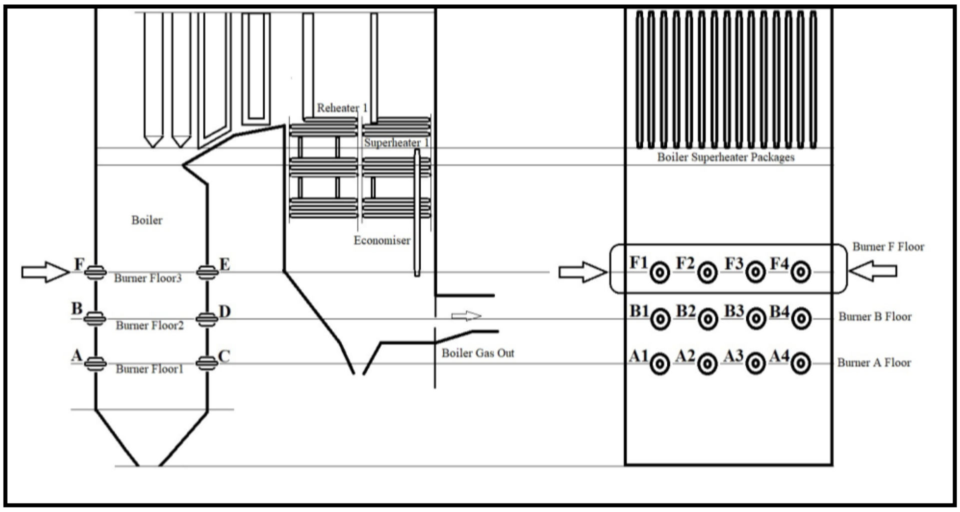


Figure 1. Boiler design and burner layout

The plant's DCS system is controlled by Nexus OnCore Control System software on computers with a Windows operating system. Nexus OnCore control systems are modern systems with a compact structure designed specifically for smaller industrial plants. These systems have been developed to replace programmable logic controllers (PLC) by bringing large plants' advanced diagnostic and operational capabilities to a small form factor. Nexus OnCore Compact Control System can be applied across a wide range of industries, facilitating both the integration of new machinery and the renewal of existing systems. The system consolidates operator information from various equipment and adapts to constantly changing operational needs, enabling more effective plant management [8]. Figure 2 presents the control system view of the turbine section of the thermal power plant where the study was conducted. As seen in the figure, all equipment in the system and real-time system tracking are controlled through the Nexus OnCore program.

All system tracking and data of determined parameters during the study were recorded with this program. Data were taken from the system at five-minute intervals and arranged as hourly averages. The reason for selecting short time intervals was to achieve more accurate data and filter out deviation data.

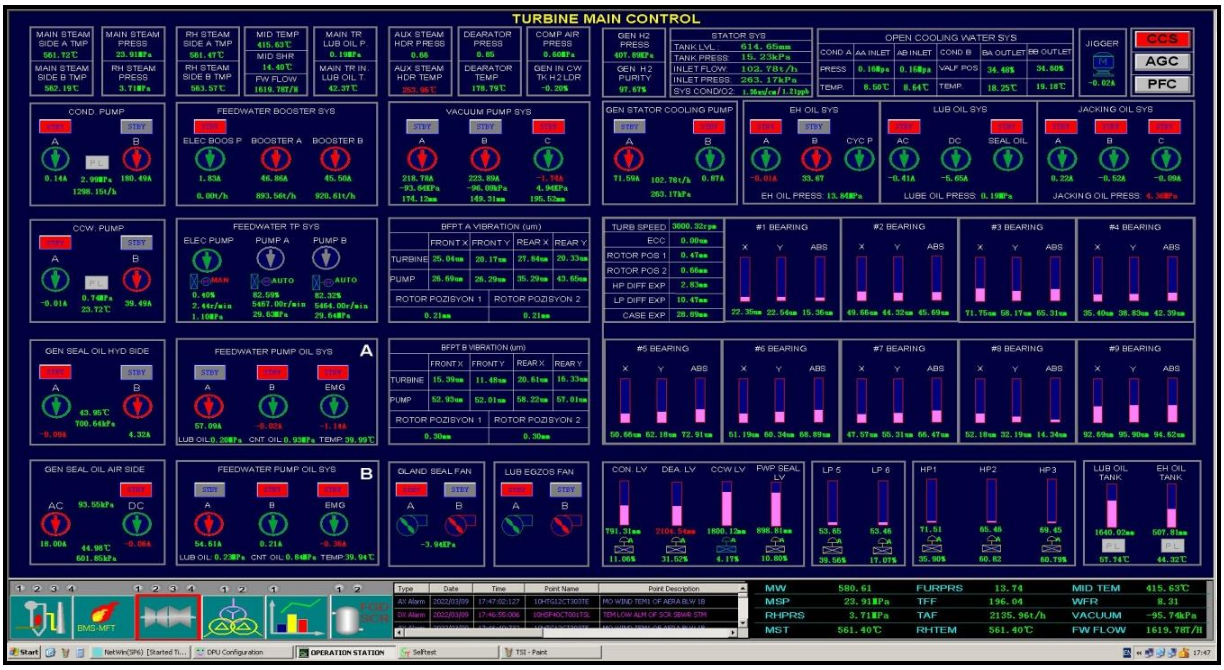


Figure 2. Distributed Control System (DCS)

During the study, feeding two different types of coal blends to the boiler was closely monitored and recorded. These data were first calculated as hourly averages and then as daily averages. The prepared coal blend was transferred to the coal bunkers, ground in the mill, and directed to the F-tier burners in the boiler, which are the highest. Burning at this tier was to minimize slag deposition on the boiler walls and reduce temperature differences in different regions (especially lower tiers) of the boiler, thus maintaining a homogeneous temperature distribution within the boiler.

This study determined the optimal blend ratio of coal mixtures fed at different loads in a 600 MW supercritical plant by following the steps shown in Figure 3. First, two different calorific coal types were mixed in the specified ratio and sent to the bunker of the mill (Mill F) to be ground. In the second stage, the prepared blend was ground in the mill to reach the appropriate particle size and then sent to the boiler for combustion. In the third stage, the criteria most affected by the combustion of different coal types were determined and monitored before the study, and data were recorded. In the final stage, the data obtained from the combustion and the importance weights of the criteria were calculated using the entropy method, and the optimal coal blend ratio and corresponding unit load were determined using the multicriteria decision-making method PROMETHEE-GAIA (Academic Version).

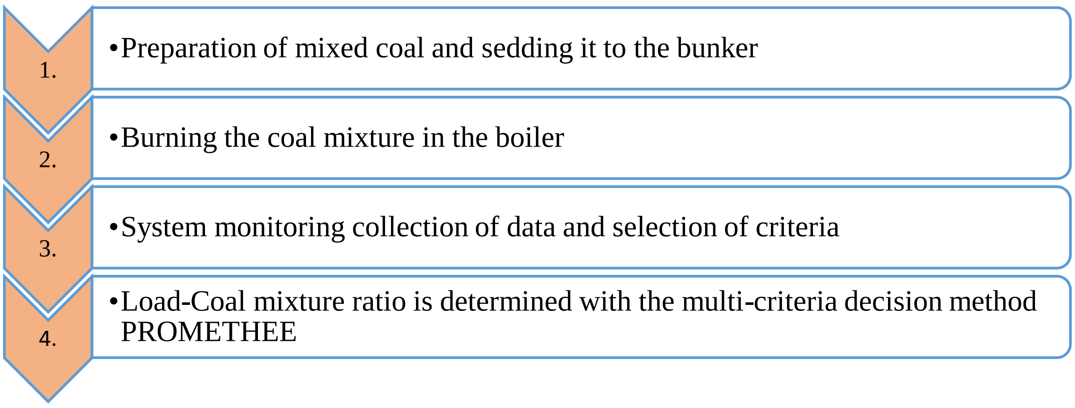


Figure 3. Stage of the study

2.2. System Outputs (Criteria)

The primary criteria identified after the combustion of the blended coal were unit load, total coal consumption, coal cost, overall system efficiency, instantaneous total energy consumption of fans and mills, and flue gas emissions of SO_2, NOx, dust, and CO, totaling nine.

Unit load: The unit load is the mode of operation of the unit according to the day-ahead schedule, with a maximum load of 600 MW and a minimum load of 350 MW. This value may change according to the load demand from the energy grid at that moment. During this study, since the plant was in commercial operation, it adhered to the instructions of the energy grid managers. During the time covered in the study, the unit load changed according to instructions, and stable operation at the desired load and time was not possible. Nevertheless, data were collected when the unit was stable.

Total coal consumption: Total coal consumption is the hourly total coal consumption fed to the unit. Total coal consumption varies depending on the unit's load at that moment. At the maximum operating load of the unit, total coal consumption is 200-220 tons/hour. It may vary depending on the quality of the coal and the unit's operating load. The domestic coal ratio fed to the unit is included in this value.

Coal cost: Coal cost is calculated based on imported and domestic prices during the study period. As is known, coal prices are determined by international standards and may vary seasonally. The coal prices for the period were determined according to the 2022 hard coal sector report. Imported coal was calculated at $341/ton, and domestic coal at $235/ton [9]. Coal cost is an important parameter in thermal power plants. Generally, imported coal is more expensive than domestic coal, but when considered a calorific ally, high-calorific imported coal can be more advantageous for companies. However, imported coal impacts the current account deficit of the country where the plant is located, making the use and promotion of domestic coal more advantageous overall [10].

Unit efficiency: The unit's efficiency is calculated as the ratio of gross energy produced to total energy supplied to the system. Efficiency is important for the unit. The most critical factors affecting efficiency are coal quality and combustion quality. The most significant outputs of combustion quality are flue gas emissions and the unburned carbon ratio in the flue gas ash [11]. The lower the percentage of unburned carbon, the better the combustion. The low proportion of unburned carbon within the boiler signifies efficient combustion. This indicates that the quality of the coal and the quantity and quality of air during combustion are optimal. The power plant manufacturer specifies that this ratio should be less than 4%. This ratio may vary depending on the types of power plants. This ratio can be higher in plants with low coal quality and suboptimal combustion efficiency.

Total energy consumption of fans and mills: The total energy consumption of fans and mills is the equipment most affected by changes in coal quality. Fans must load more than usual to ensure optimal combustion within the boiler with changes in coal quality, drawing more current and consequently more energy. Similarly, with low-quality coal feeding, the unit requires more coal to maintain its existing load, increasing the mill load and drawing more current and energy. These values change simultaneously, so they are calculated as total current. These are calculated based on the total current drawn by two Inducer Draft Fan (IDF), two Forced Draft Fan (FDF), two Primer Air Fan (PAF), one Booster Fan, and six mill motors (6 kV).

SO_2, NOx, dust, and CO emissions: SO_2, NOx, dust, and CO emissions result from flue gas combustion in the boiler. These are parameters directly affected by coal changes. The company is meticulous about the filtration of flue gas emissions from both units. Each unit has one Electrostatic Precipitator (ESP) for dust emission, one Selective Catalytic Reduction (SCR) for NOx reduction emission, and one Flue Gas Desulphurization (FGD) system for flue gas sulfur emission filtration. Legal limits were observed when applying low-calorific and different types of coal to the system. The limit values set by the Ministry of Environment and Forestry are presented in Table 3 [12].

Table 3. Flue gas emission limit values (2010) [12]

Description	Value	Unit
SO_2	200	Mg/Nm^3
$NO – NO_2$	200	Mg/Nm^3
CO	200	Mg/Nm^3
Dust	30	Mg/Nm^3

2.3. Decision Alternatives

Nine decision alternatives were created by changing the unit load and feed rates against the nine criteria identified in the study during the combustion of the blended coal (Table 4). Table 4 lists the unit’s working load against the ratio of domestic coal fed to the unit. This table shows domestic coal was fed to the unit at different rates under different load conditions. Compared with decision alternatives, the unit’s operation with only imported coal, without any domestic coal feed, is 0%. In the 0% scenario, only imported coal is fed into the unit. When selecting the coal feeding rates in Table 4, the health of the unit’s equipment and operational performance were considered. It was closely monitored to avoid situations that could endanger the system, and the proportions of domestic coal fed were continuously changed. In such large power plants, it is necessary to proceed in a controlled and balanced manner regarding workload and operating methods. Therefore, a single domestic coal feeding rate was not maintained for a long period (more than eight hours). In addition, when selecting the unit’s operating load, the instructions of the energy grid managers were adhered to.

Table 4. Decision alternatives

No	Load MW	Domestic Coal Rate (%)
1	605	2
2	605	14.2
3	605	15.4
4	450	15.4
5	560	15.4
6	560	14.6
7	450	14.6
8	450	0
9	605	0

The study aims to determine the optimal working mode according to the criteria of these nine decision alternatives. In such multicriteria decision-making situations, the most commonly used methods include Analytic Hierarchy Process (AHP), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), Elimination and Choice Translating Reality (ELECTRE), PROMETHEE-GAIA (Preference Ranking Organization Method), and VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR). These methods are preferred according to different levels of complexity and problem types [13].

The PROMETHEE-GAIA, a multicriteria decision-making method, was used to identify the best choice in this study's multicriteria decision-making (optimization) problem. The optimization application was carried out in the Visual PROMETHEE (Academic Version) program. Developed by J.P. Brans, the PROMETHEE method determines the ranking among criteria in multicriteria decision-making [14]. This method is known for its simplicity but performs well in such multicriteria problems. It evaluates and ranks alternatives based on different criteria. This ranking helps decision-makers determine the most appropriate alternative. The preference method of PROMETHEE is based on pairwise comparisons. Each alternative is compared with another within itself and presents the most suitable alternative to the decision-maker [15]. PROMETHEE I and PROMETHEE II provide a complete ranking of decision alternatives. PROMETHEE I is used to obtain partial ranking, while PROMETHEE II is used for complete ranking [14, 16]. Different versions of PROMETHEE (III, IV, V, VI, etc.) have been developed today [17].

The Entropy method was used to determine the importance (weights) of the criteria within the method. The entropy method is a weighting method used to determine the importance of criteria in a ranking problem. Major methods used to assess the importance of criteria in multicriteria decision-making problems include a heuristic method, principal component analysis, Taguchi Method-Signal/Noise Ratio, and entropy method. Compared to these subjective weighting models, the biggest advantage of the entropy method is that it prevents human factors from interfering in weighting indicators, thereby increasing the objectivity of comprehensive evaluation results [17]. For this reason, the entropy weighting method (EWM) has been widely used in decision-making mechanisms in recent years.

3. Results and Discussion

Optimizing coal feed ratios in thermal power plants is crucial for balancing operational efficiency with environmental impact [17]. Table 5 presents a comprehensive dataset evaluating system performance under different loads according to domestic coal feed ratios. Based on these data, meaningful conclusions can be drawn regarding operational scenarios' efficiency and environmental impacts.

As seen in Table 5, total coal consumption (t/h) varies at different loads. For instance, the highest coal consumption was recorded at 605 MW load with a 15.4% domestic coal feed ratio at 214.390 t/h. The efficiency of the power plant generally increases at higher loads. For example, at a 605 MW load with a 15.4% domestic coal feed ratio, the efficiency is 0.413627, while at the same feed ratio, the efficiency drops to 0.409574 at a 450 MW load. This indicates that higher loads can be more efficient but demand more coal.

Environmental emissions are a critical factor in evaluating the performance of thermal power plants. SO_2 emissions, in particular, are associated with high coal consumption and low efficiency [18]. For example, at 605 MW and a 2% domestic coal feed ratio, SO_2 emissions are 335.348 mg/m³, while at the same load with a 0% domestic coal feed ratio, this value drops to 275.898 mg/m³. This suggests that lower domestic coal ratios can reduce SO_2 emissions. NOx emissions show a similar trend. At a 605 MW load with a 0% domestic coal feed ratio, NOx emissions are 89.547 mg/m³, while at a 15.4% domestic coal feed ratio, this value is 77.281 mg/m³. This indicates that higher domestic coal ratios can reduce NOx emissions. Dust and CO emissions vary according to coal feed ratios and load levels. For example, at a 605 MW load with a 0% domestic coal feed ratio, dust emissions are 3.4002 mg/m³, while at a 15.4% ratio, this value drops to 2.9037 mg/m³. Similarly, CO emissions decrease with increasing domestic coal ratios. For instance, at a 605 MW load with a 15.4% domestic coal feed ratio, CO emissions are 41.049 mg/m³; at a 0% ratio, this value is 20.563 mg/m³.

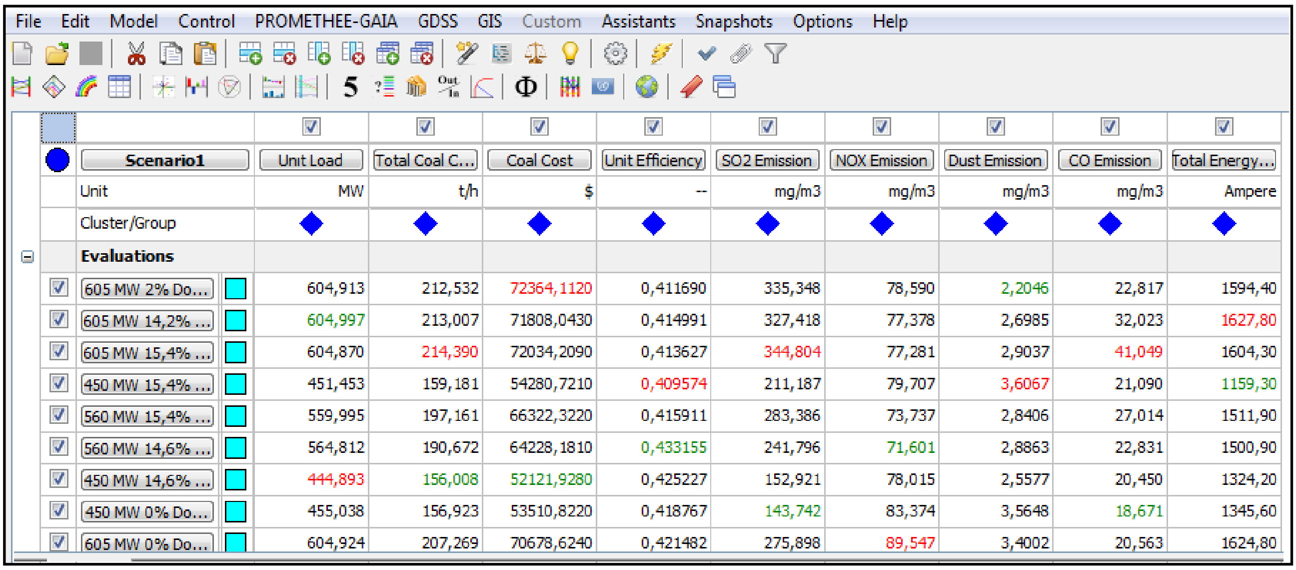
Energy consumption varies at different loads and domestic coal feed ratios. The highest energy consumption is recorded at a 605 MW load with a 14.2% domestic coal feed ratio of 1.627.8 amperes. This value is recorded as 1.624.8 amperes at the same load with a 0% domestic coal feed ratio. These differences in energy consumption indicate the impact of coal feed ratios on energy efficiency.

These data reveal the critical role of domestic coal feed ratios at different loads on operational efficiency and environmental impact in thermal power plants. While higher loads achieve higher efficiency, they can result in higher coal consumption and emissions. Optimizing domestic coal ratios can contribute to more sustainable energy production by reducing environmental emissions [18, 19].

Table 5. Result values of domestic coal feed rates of the system at different loads (Decision matrix for entropy method)

Coal Ratio According to Unit Load	Unit Load (MW/h)	Total Coal Consumption (t/h)	Coal Cost ($)	Efficiency	SO_2 Emission mg/m^3	NOx Emission mg/m^3	Dust Emission mg/m^3	CO Emission mg/m^3	Energy Consumption Ampere
605 MW 2% Domestic Coal	604.913	212.532	72.364,112	0.411690	335.348	78.590	2.2046	22.817	1.594.4
605 MW 14.2% Domestic Coal	604.997	213.007	71.808,043	0.414991	327.418	77.378	2.6985	32.022	1.627.8
605 MW 15.4% Domestic Coal	604.870	214.390	72.034,209	0.413627	344.804	77.281	2.9037	41.049	1.604.3
450 MW 15.4% Domestic Coal	451.453	159.181	54.280,721	0.409574	211.187	79.707	2.6067	21.089	1.159.3
560 MW 15.4% Dom. Coal	559.995	197.161	66.322,322	0.415911	283.386	73.737	2.8406	27.014	1.511.9
560 MW 14.6% Dom. Coal	564.812	190.672	64.228,181	0.433155	241.796	71.601	2.8863	22.831	1.500.9
450 MW 14.6% Dom. Coal	449.893	156.008	52.121,928	0.425227	152.921	78.015	2.5577	20.450	1.324.2
450 MW 0% Domestic Coal	455.038	156.923	53.510,822	0.418767	143.742	83.374	3.5648	18.671	1.345.6
605 MW 0% Domestic Coal	604.924	207.269	70.678,624	0.421482	275.898	89.547	3.4002	20.563	1.624.8

Figure 4 presents the interface visual of the Visual PROMETHEE program used as the multicriteria decision-making method in this study. The measurement values of the criteria in Table 5. were entered using the interface shown in Figure 4. As seen in Figure 4, a decision matrix consisting of nine different criteria and nine different alternatives was obtained.



Scenario1	Unit Load	Total Coal C...	Coal Cost	Unit Efficiency	SO2 Emission	NOX Emission	Dust Emission	CO Emission	Total Energy...
Unit	MW	t/h	$	--	mg/m3	mg/m3	mg/m3	mg/m3	Ampere
Cluster/Group									
Evaluations									
605 MW 2% Do...	604,913	212,532	72364,1120	0,411690	335,348	78,590	2,2046	22,817	1594,40
605 MW 14,2% ...	604,997	213,007	71808,0430	0,414991	327,418	77,378	2,6985	32,023	1627,80
605 MW 15,4% ...	604,870	214,390	72034,2090	0,413627	344,804	77,281	2,9037	41,049	1604,30
450 MW 15,4% ...	451,453	159,181	54280,7210	0,409574	211,187	79,707	3,6067	21,090	1159,30
560 MW 15,4% ...	559,995	197,161	66322,3220	0,415911	283,386	73,737	2,8406	27,014	1511,90
560 MW 14,6% ...	564,812	190,672	64228,1810	0,433155	241,796	71,601	2,8863	22,831	1500,90
450 MW 14,6% ...	444,893	156,008	52121,9280	0,425227	152,921	78,015	2,5577	20,450	1324,20
450 MW 0% Do...	455,038	156,923	53510,8220	0,418767	143,742	83,374	3,5648	18,671	1345,60
605 MW 0% Do...	604,924	207,269	70678,6240	0,421482	275,898	89,547	3,4002	20,563	1624,80

Figure 4. Visual PROMETHEE

3.1. Determining Weights Using the Entropy Method

The entropy method is a powerful tool to ensure objectivity, especially in scientific and technical evaluations. Determining the importance of the criteria weights with this method is performed in five steps. These are, respectively [20]:

- Creating the decision matrix
- Normalization
- Calculation of the entropy value
- Determination of the degree of divergence
- Calculation of weights

The criteria weights were determined following these five steps in the entropy method. In the first step, a 9x9 decision matrix was created with the study's results (Table 5) and expressed in (3.1) and Figure 4.

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \dots & x_{2n} \\ \vdots & \vdots & \dots & \vdots \\ x_{1} & x_{m2} & \dots & x_{mn} \end{bmatrix}, \quad i \in \{1,2,\cdots,m\} \text{ and } j \in \{1,2,\cdots,n\} \tag{3.1}$$

In the second step, normalization was performed by calculating the ratio of each criterion value corresponding to a decision alternative to the total value of that criterion using (3.2). The results of the normalization process (Table 6) and the obtained normalization matrix are presented in Table 7.

$$P_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}} \tag{3.2}$$

Table 6. The sum of the criteria for each decision alternative

Unit Load (MW)	Total Coal Consumption (t/h)	Coal Cost ($)	Efficiency	SO_2 Emission mg/m^3	NOx Emission mg/m^3	Dust Emission mg/m^3	CO Emission mg/m^3	Energy Consumption Ampere
4900.895058	1707.141974	577348.962	3.764422848	2316.50	709.23	26.66	226.51	13293.19

Table 7. Normalization matrix

Unit Load (MW)	Total Coal Consumption (t/h)	Coal Cost ($)	Efficiency	SO_2 Emission mg/m^3	NOx Emission mg/m^3	Dust Emission mg/m^3	CO Emission mg/m^3	Energy Consumption Ampere
0.123429024	0.12449575	0.12533860	0.109363423	0.14476446	0.110810195	0.082684402	0.100734638	0.119941203
0.123446226	0.12477385	0.12437546	0.110240205	0.141341265	0.109100866	0.10120617	0.141373738	0.122450209
0.123420266	0.12558389	0.12476719	0.109877817	0.148846605	0.108964965	0.108903378	0.181226987	0.120684817
0.092116405	0.09324414	0.09401718	0.108801331	0.091166233	0.112384781	0.135268528	0.093105701	0.087210458
0.114263838	0.11549199	0.11487389	0.110484662	0.122333516	0.103967455	0.10653767	0.119263949	0.113733425
0.115246687	0.11169057	0.11124672	0.115065327	0.10437964	0.100956425	0.108249202	0.100796447	0.112907924
0.09179813	0.09138548	0.09027803	0.112959414	0.066016273	0.109999565	0.095926889	0.090284584	0.099614942
0.092848016	0.09192160	0.09268367	0.111243296	0.062051048	0.117555646	0.133700044	0.082430487	0.101226722
0.123431409	0.12141268	0.12241924	0.111964524	0.11910096	0.126260102	0.127523717	0.090783467	0.122230299

The entropy value was calculated using (3.3) in the third step. For this, first, the product of the logarithm of each criterion value in the normalization matrix (Table 7) was taken (Table 8). Then, the k value was calculated by dividing one by the logarithm of the number of decision alternatives (see (3.4)). In (3.4), m represents the total number of decision alternatives. As previously mentioned, the total number of decision alternatives in this study is nine. The entropy value for each criterion was calculated by multiplying the total of each criterion's logarithm values by the k value (Table 9).

$$e_j = -k\sum_{i=1}^{m} P_{ij}\cdot \ln\left(P_{ij}\right) \tag{3.3}$$

and

$$\mathrm{k} = 1/\ln(\mathrm{m}) \tag{3.4}$$

Table 8. $P_{ij}\cdot \ln\left(P_{ij}\right)$ matrix

Unit Load (MW)	Total Coal Consumption (t/h)	Coal Cost ($)	Efficiency	SO_2 Emission mg/m^3	NOx Emission mg/m^3	Dust Emission mg/m^3	CO Emission mg/m^3	Energy Consumption Ampere
-0.2582245	-0.2593848	-0.2602952	-0.2420298	-0.2797786	-0.2437753	-0.2061094	-0.2312127	-0.2543657
-0.2582432	-0.2596858	-0.2592544	-0.2430899	-0.2765452	-0.2417110	-0.2318224	-0.2765762	-0.2571516
-0.2582149	-0.2605591	-0.2596786	-0.2426526	-0.2835288	-0.2415457	-0.2414708	-0.3095365	-0.2551968
-0.2196701	-0.221224	-0.2222827	-0.2413465	-0.2183495	-0.2456536	-0.2706037	-0.2210347	-0.2127438
-0.2478662	-0.2492957	-0.2485779	-0.2433842	-0.2570232	-0.2353487	-0.2385651	-0.2536047	-0.2472448
-0.2490112	-0.2448283	-0.2442983	-0.2488006	-0.2358688	-0.2314997	-0.2406725	-0.2312927	-0.2462728
-0.2192289	-0.2186551	-0.2171061	-0.2463336	-0.1794225	-0.2427997	-0.2248688	-0.2171153	-0.2297561
-0.2206803	-0.2194002	-0.2204539	-0.2442942	-0.1724893	-0.2516682	-0.2690254	-0.2057300	-0.2318489
-0.2582271	-0.2560059	-0.2571175	-0.2451545	-0.2534210	-0.2612840	-0.2626290	-0.2178147	-0.2569095

Table 9. Entropy values of the criteria

Unit Load (MW)	Total Coal Consumption (t/h)	Coal Cost ($)	Efficiency	SO_2 Emission mg/m^3	NOx Emission mg/m^3	Dust Emission mg/m^3	CO Emission mg/m^3	Energy Consumption Ampere
0.996423793	0.996275104	0.99628645	0.999937088	0.981432382	0.999117926	0.994785662	0.984841565	0.984841565

In the fourth step, the degree of divergence for each criterion was calculated using (3.5) (Table 10). The degree of divergence is calculated by subtracting the entropy value from one.

$$d_j = 1 - e_j \tag{3.5}$$

Table 10. Difference degrees of the criteria

Unit Load (MW)	Total Coal Consumption (t/h)	Coal Cost ($)	Efficiency	SO_2 Emission mg/m^3	NOx Emission mg/m^3	Dust Emission mg/m^3	CO Emission mg/m^3	Energy Consumption Ampere
0.003576206	0.003724895	0.003713549	0.000062912	0.018567618	0.000882074	0.005214337	0.015158435	0.002609700

In the final step, the importance weight for each criterion was determined by dividing a criterion's d_j value by the total d_j values of all criteria (see (3.6)). The importance weights (weights) calculated for each criterion using (3.6) are presented in Table 11, and the percentage weights in Table 12.

$$w_j = d_j / \sum_{j=1}^{n} d_j \tag{3.6}$$

Table 11. Importance degrees (weights) of the criteria w_j

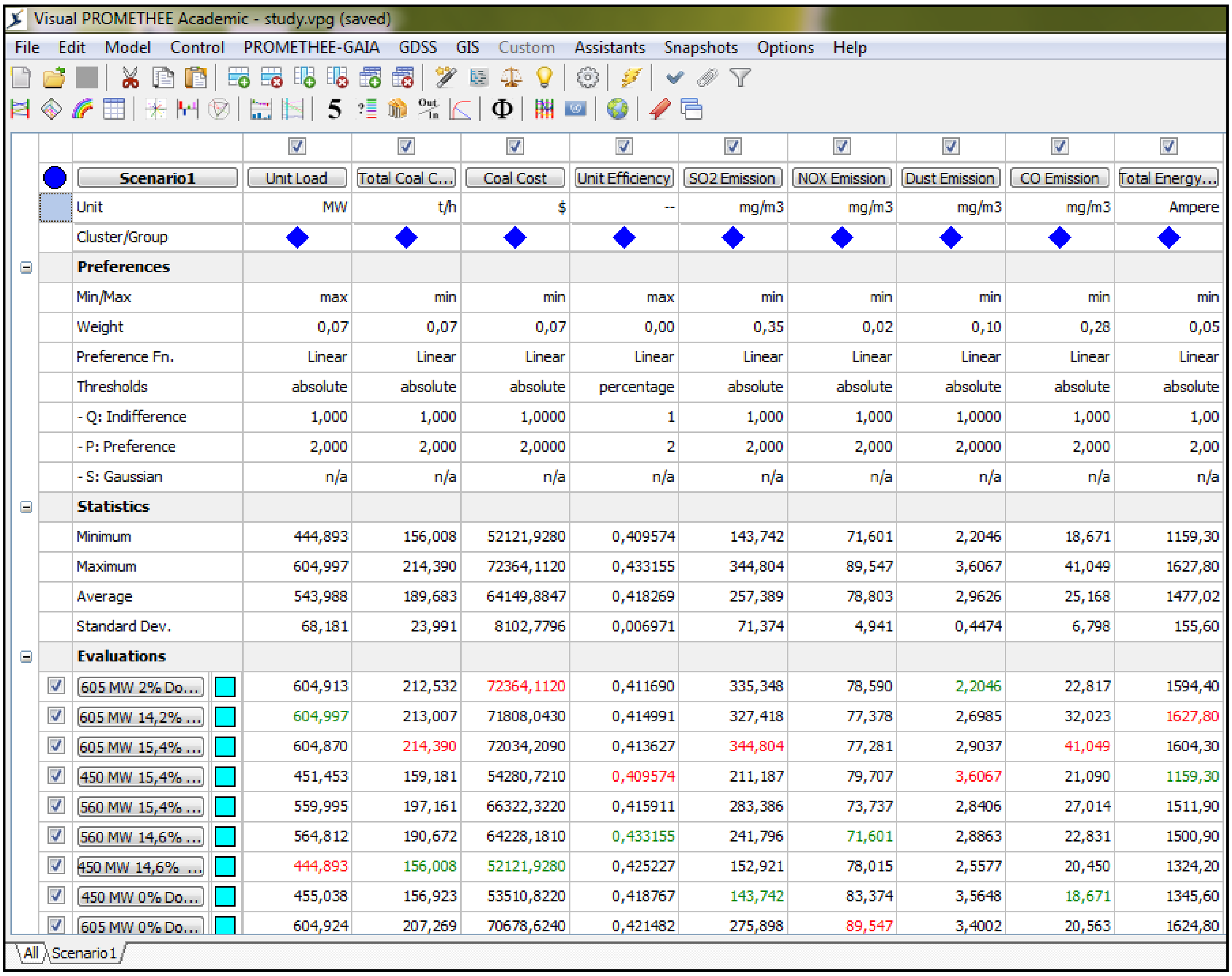
Unit Load (MW/h)	Total Coal Consumption (t/h)	Coal Cost ($)	Efficiency	SO_2 Emission mg/m^3	NOx Emission mg/m^3	Dust Emission mg/m^3	CO Emission mg/m^3	Energy Consumption Ampere
0.06683283	0.069611556	0.069399518	0.001175714	0.346995169	0.016484375	0.097446536	0.283283715	0.048770586

Table 12. Percentage ratios of the importance degrees of the criteria

Unit Load (MW/h)	Total Coal Consumption (t/h)	Coal Cost ($)	Efficiency	SO_2 Emission mg/m^3	NOx Emission mg/m^3	Dust Emission mg/m^3	CO Emission mg/m^3	Energy Consumption Ampere
6.68%	6.96%	6.94%	0.12%	34.70%	1.65%	9.74%	28.33%	4.88%

As seen in Table 12, the highest weights among the criteria were 34.70% for SO_2 from flue gas emissions and 28.33% for CO. Flue gas emission values are the most important parameters in the operating values of solid-fuel thermal power plants. SO_2 and CO are among the parameters most affected by coal changes. The high importance of these criteria relative to others was an expected result. Thus, the weight values of the criteria were calculated in five steps, and the computed weight values for each criterion were entered into the Visual PROMETHEE program (Figure 5).

When applying the PROMETHEE method, it is necessary to determine the preference functions. The PROMETHEE preference function is used to identify deviation among alternatives for each criterion [21]. For this study, the types of preference functions were determined by the preference function selection assistant as a feature provided by the application. Since one of the criteria, unit efficiency, is calculated as a percentage, the threshold value was selected as a percentage.



Scenario1	Unit Load	Total Coal C...	Coal Cost	Unit Efficiency	SO2 Emission	NOX Emission	Dust Emission	CO Emission	Total Energy...
Unit	MW	t/h	$	--	mg/m3	mg/m3	mg/m3	mg/m3	Ampere
Cluster/Group									
Preferences									
Min/Max	max	min	min	max	min	min	min	min	min
Weight	0,07	0,07	0,07	0,00	0,35	0,02	0,10	0,28	0,05
Preference Fn.	Linear	Linear	Linear	Linear	Linear	Linear	Linear	Linear	Linear
Thresholds	absolute	absolute	absolute	percentage	absolute	absolute	absolute	absolute	absolute
- Q: Indifference	1,000	1,000	1,0000	1	1,000	1,000	1,0000	1,000	1,00
- P: Preference	2,000	2,000	2,0000	2	2,000	2,000	2,0000	2,000	2,00
- S: Gaussian	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Statistics									
Minimum	444,893	156,008	52121,9280	0,409574	143,742	71,601	2,2046	18,671	1159,30
Maximum	604,997	214,390	72364,1120	0,433155	344,804	89,547	3,6067	41,049	1627,80
Average	543,988	189,683	64149,8847	0,418269	257,389	78,803	2,9626	25,168	1477,02
Standard Dev.	68,181	23,991	8102,7796	0,006971	71,374	4,941	0,4474	6,798	155,60
Evaluations									
605 MW 2% Do...	604,913	212,532	72364,1120	0,411690	335,348	78,590	2,2046	22,817	1594,40
605 MW 14,2% ...	604,997	213,007	71808,0430	0,414991	327,418	77,378	2,6985	32,023	1627,80
605 MW 15,4% ...	604,870	214,390	72034,2090	0,413627	344,804	77,281	2,9037	41,049	1604,30
450 MW 15,4% ...	451,453	159,181	54280,7210	0,409574	211,187	79,707	3,6067	21,090	1159,30
560 MW 15,4% ...	559,995	197,161	66322,3220	0,415911	283,386	73,737	2,8406	27,014	1511,90
560 MW 14,6% ...	564,812	190,672	64228,1810	0,433155	241,796	71,601	2,8863	22,831	1500,90
450 MW 14,6% ...	444,893	156,008	52121,9280	0,425227	152,921	78,015	2,5577	20,450	1324,20
450 MW 0% Do...	455,038	156,923	53510,8220	0,418767	143,742	83,374	3,5648	18,671	1345,60
605 MW 0% Do...	604,924	207,269	70678,6240	0,421482	275,898	89,547	3,4002	20,563	1624,80

Figure 5. Input matrix using nine criteria and nine alternatives for the PROMETHEE method of multicriteria optimization

Figure 6 presents the PROMETHEE flow chart created based on the Visual PROMETHEE full-ranking result of the decision alternatives in the study. As seen in Figure 6, according to the program's calculations, the best choice was feeding 0% of domestic coal at a 450 MW load (first row in the PROMETHEE flow table). However, since the study aimed to find the domestic coal feed ratio, the best working mode among the decision alternatives in the table selected was feeding 14.6% of domestic coal at a 450 MW load (second row in PROMETHEE flow table). The figure shows that the domestic coal feed ratio should be reduced as the load increases—the system's adverse reaction to domestic coal increases in high-load operating conditions. The worst working mode is feeding 15.4% of domestic coal at a 605 MW load.

The PROMETHEE flow chart in Figure 6 shows the Phi, Phi+, and Phi- scores. Positive flow (Phi+) indicates the positive superiority of an alternative over others, while negative flow (Phi-) indicates its negative superiority over others [22, 23]. The working mode with a net superiority value of 0.7004 at a 450 MW load with 0% domestic coal feed was the first choice while feeding 15.4% of domestic coal at a 605 MW load with -0.3672 was the last choice. According to this multicriteria optimization result, the preferred working modes in order are 450 MW load with 14.6% domestic coal feed, 450 MW load with 15.4% domestic coal feed, 560

MW load with 14.6% domestic coal feed, and 605 MW load with 0% domestic coal feed, as their net superiority values are positive.

PROMETHEE Flow Table

	action	Phi	Phi+	Phi-
1	450 MW 0% Dom. Coal	0,7004	0,7931	0,0927
2	450 MW 14,6% Dom.	0,5104	0,6587	0,1484
3	450 MW 15,4% Dom.	0,3507	0,5828	0,2321
4	560 MW 14,6% Dom.	0,1272	0,4922	0,3651
5	605 MW 0% Dom. Coal	0,0929	0,4488	0,3559
6	560 MW 15,4% Dom.	-0,2291	0,3363	0,5654
7	605 MW 2% Dom. Coal	-0,3587	0,2332	0,5919
8	605 MW 14,2% Dom.	-0,4717	0,1920	0,6637
9	605 MW 15,4% Dom.	-0,7220	0,0707	0,7927

Figure 6. Visual PROMETHEE flow table

The PROMETHEE GAIA plane in Figure 7 is a representation used in Multicriteria Decision Making (MCDM) processes. It helps decision-makers determine the criteria weights and make choices among alternatives objectively and systematically. This plane is designed to minimize subjective influences from decision-makers [23, 24]. It is designed as a two- and three-dimensional plane showing the alignment of alternatives and criteria. This plane allows decision-makers to see which criteria move in the same or opposite direction with which alternatives. This information helps make healthier and more informed decisions. The GAIA plane also guides decision-makers in selecting among preferences and helps determine the most appropriate alternative. The thick line close to the horizontal axis in the plane indicates the most suitable alternative for decision-makers [25].

The 2D GAIA plane analysis in Figure 7 shows that the “NOx” criterion has the greatest length. Criteria representing conflicting preferences are represented by axes directed in opposite directions, as seen in the case of “Load” and “Energy Consumption.” The position of the criteria indicates their similarity or conflict. The smaller the angle, the more similar the two criteria are. The small angle between “Cost” and “Total Coal Consumption” indicates their similarity. Because the more total coal consumption there is, the higher the cost. Alternatives close to each other show similar performances, such as “450 MW at 14.6% domestic coal” and “450 MW at 15.4% domestic coal.” In the 2D GAIA analysis presented in Figure 7, a multicriteria decision-making process is considered reliable when the quality level is above 70%, which, with a result of 93.6%, indicates that the multicriteria optimization process in this study was successful [26].

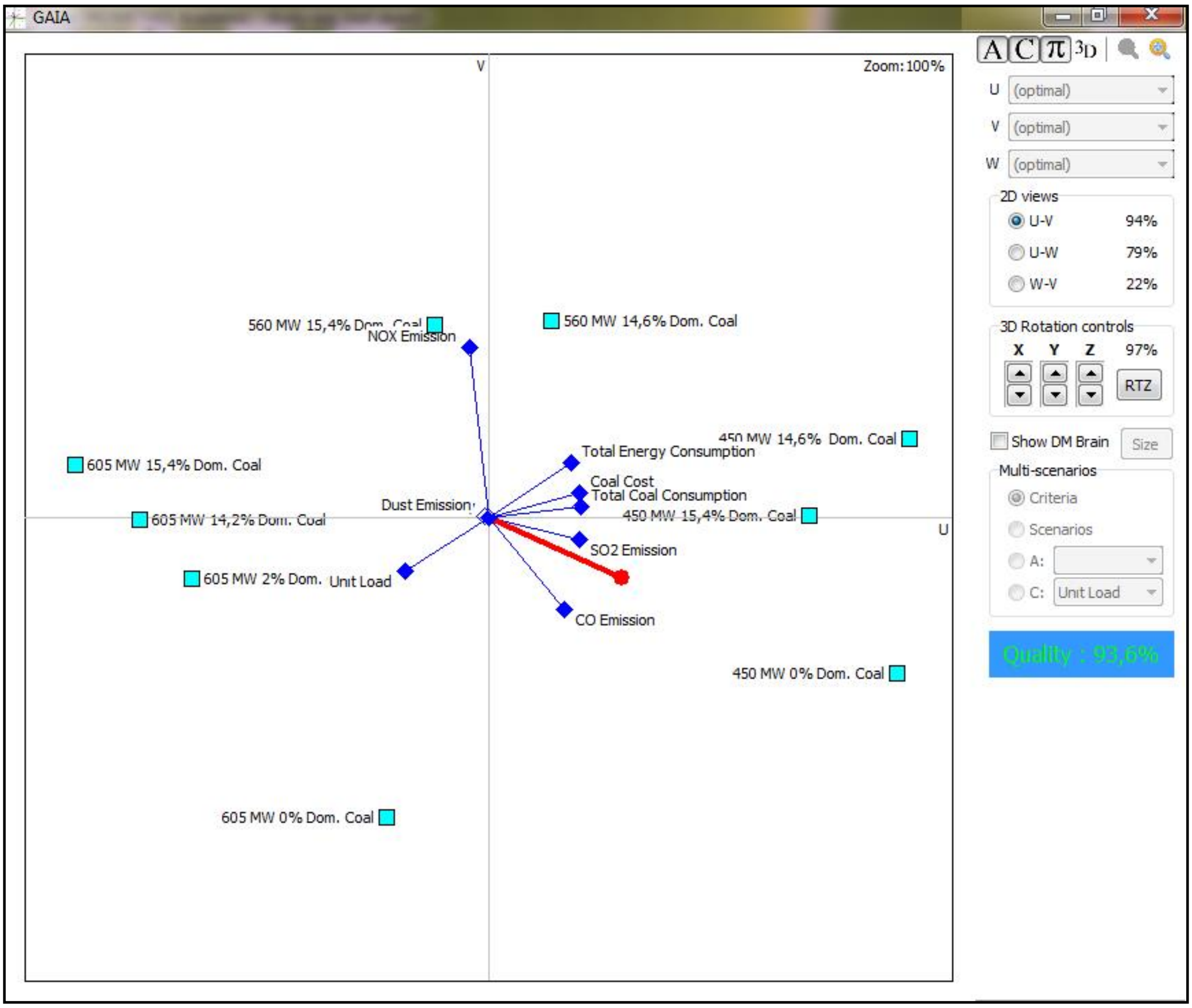


Figure 7. The arrangement of alternatives and criteria on the GAIA plane

4. Conclusion

This study examines domestic and imported coal blends in a 600 MW unit of a supercritical thermal power plant and its various output parameters. The study evaluated the effects of different load and coal blend ratios on plant performance. A controlled and gradual blend of high-calorific imported and low-calorific domestic coal was fed and burned with a single mill and burner in a system designed for high-calorific imported coal combustion. Various criteria were used to determine the optimal coal blend ratio and corresponding unit load based on the system and measurement data obtained. These criteria included total coal consumption, coal cost, efficiency, SO_2, NOx, dust, CO, and instantaneous total energy consumption of fans and mills. The unit was tested at different domestic coal feed ratios at 605 MW, 560 MW, and 450 MW loads. The analysis and multicriteria decision-making studies concluded:

▪ According to the calculated criteria weights, the optimal coal blend ratio and corresponding unit load were determined to be 14.6% domestic coal feed at a 450 MW load.

▪ Physical observations indicated that exceeding the calculated domestic coal tonnage resulted in system instability, equipment malfunctions, and increased slag deposition within the boiler.

▪ Since a significant portion of the study criteria consisted of flue gas emission values, the most important factor affecting these items is the coal analysis values. Therefore, attention should be paid to the analysis values of coal used in similar future studies. Using domestic coal with worse analysis values may result in significantly different outcomes.

- Based on system observations, analyses, and the experience of this study, burning in the opposite burners on the upper tiers of the boiler may yield better results in similar future studies.

- This study is a short-term study. The long-term consequences of operating such power plants with out-of-design coal types in an uncontrolled manner may be much more severe. It may cause permanent damage to the boiler superheater packages or slag accumulation on the boiler walls, leading to issues requiring long and costly remediation. Therefore, the system should be closely monitored, and the boiler should be inspected at short intervals in similar future studies.

As a result, this study is a pioneering work evaluating the effects of low-calorific domestic and high-calorific imported coal blends on the performance of a 600 MW supercritical thermal power plant under different load conditions and determining the optimal load-blend ratio. This study will be an example of using different coal blends in similar plants. As a continuation of this study, the optimal operating mode under various load conditions can be determined when using the design coal of the system in similar plants. Similarly, the system's optimal operating temperature can be determined by observing changes in air temperature at the outlet parameters of such a plant.

Author Contributions

The first author directed the project and supervised this study's findings. The second author devised the main conceptual ideas and developed the theoretical framework. The first and second authors performed the experiment and statistical analyses. The first author wrote the manuscript with support from the second author. The third author reviewed the paper. All authors read and approved the final version of the paper. This paper is derived from the first author's master's thesis, supervised by the third author.

Conflicts of Interest

All the authors declare no conflict of interest.

Ethical Review and Approval

No approval from the Board of Ethics is required.

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