A Sustainability Approach in the Development of Coal Blend Model for Subcritical Pulverized Coal Fired Power Plants in the Philippines

Marvin I. Noroña and Annabelle R. Laureta
School of Industrial Engineering and Engineering Management
Mapua University
Philippines
minorona@mapua.edu.ph, aratuiste@gmail.com

ABSTRACT

Coal remains the largest source of fuel for electricity generation with 38% contribution to the total electricity produced worldwide in 2018. Coal fired power plants (CFPPs) are designed based on the characteristics of the coal to be used. Design coal availability is not guaranteed at all times, coal quality varies as the coal reserves depletes thus CFPPs are left with no choice but to utilize what is available. In response to these, the process of coal blending has been commonly practiced throughout the power plant industry. The current study focused on developing a coal blend model for subcritical pulverized coal fired power plant in the Philippines in terms of sustainability. The factors significant for blend consideration were determined using ANOVA and multiple regression analysis and were found to be coal moisture, ash, volatile matter, calorific value and cost. To develop a coal blend model, goal programming was utilized with the aim of meeting design coal quality to attain target efficiency, minimize coal cost and minimize solid waste production in the form of fly ash and bottom ash. The model developed will result to optimal performance in terms of sustainability – cost efficient, environmentally friendly and socially responsible.

Keywords
Coal Blending, Sustainability, Goal Programming, Power Plant

1. Introduction

Coal remains the largest source of fuel for electricity generation with 38% contribution to the total electricity produced worldwide in 2018. In the same year, global coal consumption increased by 1.4%, with the growth being driven by Asia Pacific region particularly by India (BP Statistical Review, 2019). In the Philippines, coal fired power plants (CFPPs) generated 51.9 million MWh in 2018, representing 52.1% of the country's power generation mix according to the 2018 Power Statistics released by the Department of Energy.

CFPPs are designed based on the characteristics of the coal to be used. According to Cole and Frank (2004), burning design specification coal will ensure that the plant will consistently meet generation demands through better plant reliability, capability and efficiency (as cited in Nalbandian, 2011). Design coal availability is not guaranteed at all times, coal quality varies as the coal reserves depletes thus coal fired power plants are left with no choice but to utilize what is available. Other alternative coal sources may have different characteristics than the design coals which could have unfavorable effects on the plant (Sloss, 2014).

In Malaysia, the quality of coal being used in a power plant studied by Zaid et al (2019) has greatly deteriorated over the years. The total moisture and ash content of their coal have increased while the gross calorific value decreased. As a consequence, the amount of primary air needed to remove moisture in the coal increased, the plant's auxiliary power consumption also increased and the boiler efficiency is reduced.

In China and Korea, CFPPs use coals that are significantly different from the design coal due to tight supply situation, uneven distribution of resources, transportation difficulties and rising price of coals (Wang, et al 2011, Jin, et al 2017, Ji, et al 2011, Sloss, 2014) In India, the coal production is unable to match the rapidly increasing demand of coal (Raaj, et al 2016). According to the International Energy Agency (IEA), in the year 2030 the use of coal is expected to increase by 60% as the global energy demand continues to increase at a growth rate of 1.5% (as cited in Santoso, et al 2016). In response to these challenges, the process of coal blending has been commonly practiced throughout the power plant industry (Zaid, et al 2019, Sloss, 2014).

Blending allows plants to consistently meet their design capacities and reduce operating costs while preventing the occurrence of fouling, slagging, corrosion and emission exceedances. Coal blending involves combining different types of coals to produce a combination that will meet plant requirements. It gives better cost options to end users, strengthen supply security, meet plant specification and ensure compliance to environmental regulations (Sloss, 2014).

It is well known that coal fired power plants are the major contributor of greenhouse gas emissions. In order to attain sustainable development and save the environment, several measures and technologies have been developed to reduce greenhouse gas emissions. This includes the high efficiency, low emissions (HELE) technologies which is composed of supercritical (SC), ultra-supercritical (USC) and advanced ultra-supercritical technologies (AUSC). Carbon capture sequestration (CCS) technologies which has the ability to dramatically reduce carbon dioxide emissions are also being introduced to coal plants. However, adopting these technologies would mean additional costs for power plant operators (Pitso, 2019, Widder et al, 2011).

Using coal blend, power plants are given more flexibility in choosing which coal to use in a more cost-efficient way. Optimizing coal blend will help improve plant efficiency and lead to reduction of greenhouse gases in the flue gas (Zaid, et al 2019). Coal blending also gives companies the option to use poor quality less expensive coals and blend it with higher quality expensive ones without sacrificing their plant. Blending also strengthen the security of supply because it enables power plant to utilize different types of coal from different sources. Meeting plant specification and compliance to environmental regulations can also be addressed by coal blending. Plants have the advantage of adjusting the coal blend depending on the need that arises (Sloss, 2014).

Published studies on coal blending models were mainly conducted in China where coal demand is increasing and coal quality is becoming a concern (Sloss, 2014). These studies have focused on the improvement of plant efficiency and reduction of operating cost through optimization of coal blend based on coal properties and combustion characteristics (Wang, et al 2011, Jin, et al 2017, Zaid et al 2019, Santoso, et al 2016, Shetty, et al 2015) and pulverizer-coal combination and distribution of pulverizer output (Ji, et al 2011). However, no written studies have been found on coal blending optimization model that focused on sustainable power plant operation.

Interestingly, since majority of the power plants in the Philippines are coal fired, coal blending is practiced. It is in this light that this study seeks an answer to the following question: What is the ideal blend ratio of Philippine based power plant to attain optimal performance in terms of sustainability?

The objectives of this study are as follows:

- To determine the factors that are significant for blend consideration
- To formulate a coal blend model based on performance optimization
- To recommend coal blend proportions corresponding to desired CFPPs performance results

Sustainability approach in coal blending performance optimization can help existing coal fired power plant achieve sustainable operation through improved efficiency and availability, reduced operating cost, waste minimization and lessen environmental impact. Finding the optimum coal blend will maximize the utilization of coal as more energy will be produced at minimum cost without detrimental effects on plant performance and the environment. The model that will be developed in this study could be used by power plants to find the optimum coal blend for new types of coal available in the market.

Sustainability approach in this study is limited only on improved plant efficiency measured by the net plant heat rate of the plant, reduced operating cost based on cost of fuel alone and solid waste minimization pertaining to fly ash collection. The study will also be limited to a typical subcritical pulverized coal fired power plant in the Philippines using two types of subbituminous imported coals.

2. Literature Review

Coal blending practice helps extend the limited supply of high-quality coal by getting enough coal for the boiler with correct quality and extend the range of acceptable coals. This would ensure sustainable coal plant operation in the years to come (Zaid, et al 2019). Optimizing coal blend could increase plant efficiency and reduce operating costs while reducing the probability of fouling, slagging, corrosion and emission exceedances. Coal characteristics that are regarded important in plant operation are calorific value and those determined by proximate and ultimate analysis like moisture, volatile matter, fixed carbon, ash and elemental composition of the coal. Grindability, granularity, free swelling index and ash fusion temperature are also the other important parameters in power plant operation (Sloss, 2014).

In a study done by Wang, et al (2011) on coal properties and combustion characteristics of blended coals in Northwestern China, it was found that proximate, ultimate and calorific analyses of blended coals can be calculated by mass-weighted average of individual coals. For the grindability of blended coals, it was observed that HGIs of individual coals and mixture ratio could not be used to predict the HGI of the blended coal. Aside from grindability, results also show the non-additive performance of ash composition and ash fusion temperatures which was due to the intense interaction of various mineral matters in blended coals.

Aside from coal properties, the method of blending also affects the effectivity of coal blending. Cited in the study of Ji (2011), there are three methods for coal blending. The first one is the blending of coal in a coal preparation plant according to the requirements of the power plant and delivering it to their stockpile. It is like producing a new single coal from two different types of coal and using it in the power plant. The second method of coal blending is blending outside the furnace where in the coal is blended in the coal yard or conveyor belt of a power plant. Lastly, blending inside the furnace and also known as mixed by pulverizers or blended by burners. In this method of blending, the different types of coal are pulverized in different mills, delivered to different layers of burners and finally blended in the furnace. The first two methods of blending could be disadvantageous to the operation of the power plant because it could create problems in the pulverizer and combustion system of the plant due to differences in coal quality like grindability and ignitability.

Most power plant adopts the blending inside the furnace method in coal blending as this method gives them more flexibility in adjusting the setting of the pulverizers and burners in accordance to the quality of coal. According to Ji (2011), there are three main problems that should be address to implement blending coal by pulverizer. First is the determination of optimum coal blending formula. Second is the selection of pulverizer-coal combination which involves selecting a combination of pulverizers and one for each individual coal under a blending scheme. Third, distribution of pulverizer output by allocating the output for each pulverizer based on a certain combination.

Several mathematical models have been developed to optimize coal blend. Y A Jin et al (2017) developed a multi-objective decision-making model based on fuzzy mathematics to determine the optimum coal blend ratio for a 350MW China based supercritical combustion power plant whose design coal is a lignite coal. The power plant uses three types of lignite coals and one type of bituminous coal whose properties deviate from the design coal. Based on the evaluation of the properties of the coal being used in the plant, the lignite coal should be blended to the bituminous coal to meet the boiler operation requirements. The power plant is equipped with six coal mills where in five mills will be on service and one on standby during normal operation. The method of coal blending being utilized in the plant is the in-furnace blending method wherein the different types of coals are burned together inside the furnace but were fed separately from different burners and different mills due to different grinding coefficients. The evaluation index considered in the study are volatile coal content or the ignition characteristics of coal, the low calorific value of coal, the comprehensive slagging index of mixed coal and mixed coal prices. Four coal blending schemes utilizing the five available mills were developed for each type of lignite coal blended with bituminous coal. Using the multi-objective decision making method in fuzzy mathematics, the optimum blend for each type of lignite coal was determined.

Another study utilized the Finite Impulse Response Neural Network (FIR-NN), Principle Component Analysis (PCA) and Partial Least Square (PLS) to optimize coal blending and achieve reduced production cost and increase energy efficiency. The study involved determining the best composition of low and high rank coal that would give the lowest total production cost. The relationship between net plant heat rate (NPHR), coal mass and percent low rank was determined using PCA and PLS. It was found that the net plant heat rate is proportional to the coal mass and has an inverse relation with the percentage of low rank coal. To predict the correlation between the variables, neural network was used. Results of the study showed that the 80:20 coal blend between low rank coal and high rank coal would result to lower production costs (Santoso, et al 2016).

The study conducted by Xia Ji, et al (2011) dealt on the combinatorial optimization of pulverizers for blended coal fired power plant. The study looked at optimization in a different perspective. Instead of focusing on the optimum coal blending formula, it focused on the selection of pulverizer coal combination and distribution of pulverizer output. It takes into consideration the effect of different pulverizer-coal combination to the distribution of coal inside the furnace during blending which could affect the ignition and burnout of the pulverized coal and flame distribution in the burner zone. The main optimization objectives that were considered in the study are to maintain a high level of combustion efficiency of all the coals, slagging prevention in the boiler burner zone, stable combustion at low load and reduction of pollutant emission. To solve the multi-objective problems, exhaustive algorithm method was applied for the pulverizer-coal combination optimization. While for the output combination optimization, the Non-dominated Sorting Genetic Algorithm II (NSGA-II) was used. The system was then applied in the Guangdong Red Bay Power Plant where it was able significantly increased the boiler's efficiency while maintaining the pollutant emissions in a good range. It was concluded that the indexes developed in the study can be used as guidance in determining the superiority and inferiority of different combinations and can serve as quantitative indicators for optimization program.

Aside from combustion characteristics of coal blend, fuel cost optimization model using Microsoft Visual Basic software have also been studied. A cost optimization flow chart shown in Figure 1 was used in the study of cost optimization for seven different types of imported coal. Coal suitability, cost of fuel, efficiencies and heat rate, and blending ratio were taken into consideration during the cost optimization analysis. It was concluded in the study that the use of imported coal, variation in blending ratios and improving operational efficiencies has an impact on the optimization of fuel cost. It was also concluded that overall optimization of the plant can be achieved by cost optimization due to reduced energy consumption, auxiliary power and emissions (Shetty, et al 2015).

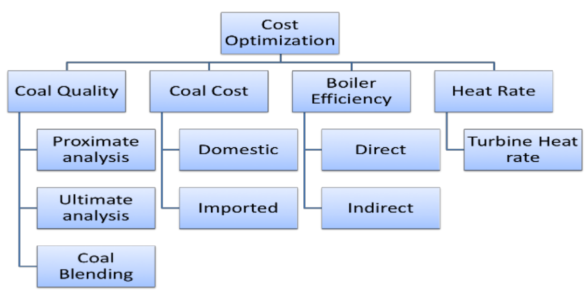

Figure 1. Cost Optimization Flow Chart (Shetty, et al 2015)

The need for coal blending due to unavailability of design coal, cost and degradation of coal quality has been apparent in the power plant industry. Studies conducted on coal blending involved determination of optimal blend based on the different coal qualities and their behavior when blended with other coals, coal suitability, cost of fuel, efficiency and heat rate. Aside from coal quality, studies also take into consideration process related constraints like the pulverizer-coal combination and pulverizer output that influences the performance of coal blend. Based on the reviewed literatures on coal blend optimization, the theoretical framework shown in Figure 2 has been developed.

Figure 2. Theoretical Framework (Ji, et al 2011, Jin, et al 2017, Santoso, et al 2016, Shetty, et al 2015, Sloss, 2014, Wang, et al 2011)

3. Methodology

3.1 Conceptual Framework

With coal blending as a focal concern of the power plant industry, equally important is a sustainability approach in optimizing coal blend performance for typical subcritical pulverized CFPPs in the Philippines a conceptual framework of which is presented below:

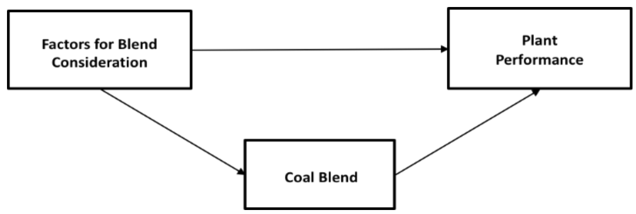

Figure 3. Conceptual Framework

Based on reviewed literatures, the factors that are significant for blend consideration are cost of coal and its qualities specifically moisture, calorific value, volatile matter and ash. The cost of the coal is a significant factor to consider because coal is the major fuel of a CFPP and the operating cost of the plant greatly depends on it. The quality of the coal is also a significant factor to consider because coal is the fuel that provides heat to produce steam in a CFPP. Its degradation due to depletion of coal reserves and coal handling and storage will affect plant performance.

A typical subcritical pulverized CFPP in the Philippines uses the inside the furnace method of coal blending which involves the use of different pulverizers for different types of coal. The power plant that was used in the study has five pulverizing systems, each corresponding to a row of burners and four sets will run at full load, one on standby.

For the performance parameters, the variables that was used as basis for the optimum blend are meeting design coal property to meet target efficiency, minimized operating cost and minimize solid waste.

3.2 Operational Framework

In order to create a coal blend model, significant relationship needs to be established between the factors for blend consideration and plant performance. To be able to do that, the following hypothesis testing will be performed as illustrated below:

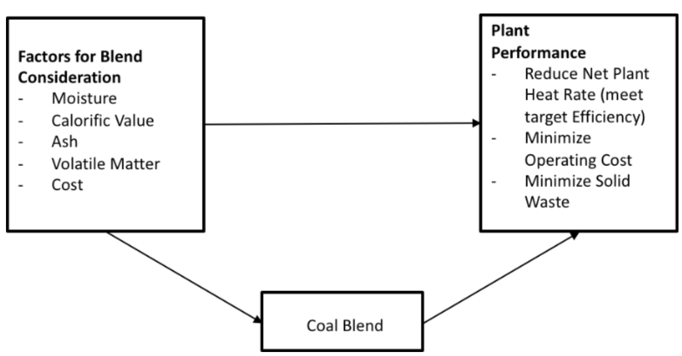

Figure 4. Operational Framework

H_{1o}: There is no significant relationship between the factors for blend consideration and plant performance
H_{1a}: There is a significant relationship between the factors for blend consideration and plant performance
H_{2o}: There is no significant relationship between coal blend and plant performance
H_{2a}: There is significant relationship between coal blend and plant performance

The data used in this research was collected from 2019 historical data of a typical subcritical pulverized coal fired power plant operating in the Philippines using two types of imported coal. The documents used in the study include certificate of analysis of coal shipments provided by the supplier, report of coal analysis from laboratory, daily operation log sheet and monthly report submitted to the Department of Energy.

Multiple regression was utilized to determine relationship between the factors for blend consideration and plant performance. On the other hand, a mathematical model using a combination of linear and goal programming was used for coal blend optimization.

3.3 Results and Discussion

3.3.1 Determination of Factors for Blend Consideration

The International Energy Agency (IEA) Clean Coal Centre generated a report on blending of coals to meet power station requirements based on survey and analysis of published literature. IEA Clean Coal Centre is an organization set up under the auspices of the International Energy Agency which was itself founded in 1974 by member countries of the Organization for Economic Co-operation and Development (OECD). According to the report, the major coal characteristics regarded as important to plant operation includes those that are determined by proximate analysis which includes moisture, volatile matter and ash, ultimate analysis for the elemental composition of the coal and other parameters like calorific value, grindability, granularity, free swelling index and ash fusion temperature. Coal characteristics determined by proximate analyses provides information on how the coal will behave when burned while those determined by ultimate analysis are used for a more thorough scientific investigation of coal. Moisture affects coal handling and decreases the heat content of coal, volatile matter determines reactivity of coal while ash affects handling cost and combustion and boiler efficiency due to slagging and fouling. Another important characteristic is the calorific value which is the amount of heat released by the complete combustion of a specified quantity of coal that is used to transform water into steam (Sloss, 2014, Energy Information Administration, 1995). Based on the foregoing, the study used moisture, volatile matter (VM), ash and calorific value (CV) as factors for blend consideration.

These five factors were used in the evaluation of coal fired power plant performance in terms of net plant heat rate (NPHR), operating cost and solid waste. ANOVA and multiple regression analysis using Minitab 18 were used to determine the relationship between each of the five factors and the plant performance parameters, with the following results as shown in Table 1-3.

Table 1. ANOVA and Model Summary of NPHR vs Moisture, CV, VM, Ash, Cost

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	5	24725173	4945035	19.99	0.000
Moisture	1	1658006	1658006	6.70	0.010
CV	1	424231	424231	1.71	0.191
VM	1	2958242	2958242	11.96	0.001
Ash	1	1484817	1484817	6.00	0.015
Cost	1	73577	73577	0.30	0.586
Error	300	74210341	247368		
Total	305	98935514			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
497.361	24.99%	23.74%	20.68%

Table 2. ANOVA and Model Summary of Solid Waste vs Moisture, CV, VM, Ash, Cost

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	5	66488	13297.6	18.43	0.000
Moisture	1	3124	3124.2	4.33	0.038
CV	1	805	805.1	1.12	0.292
VM	1	4359	4358.6	6.04	0.015
Ash	1	35858	35858.3	49.71	0.000
Cost	1	1053	1052.7	1.46	0.228
Error	300	216413	721.4		
Total	305	282900			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
26.8584	23.50%	22.23%	19.60%

Table 3. ANOVA and Model Summary of Operating Cost vs Moisture, CV, VM, Ash, Cost

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	5	1.28627E+15	2.57254E+14	17.29	0.000
Moisture	1	7.06679E+12	7.06679E+12	0.47	0.491
CV	1	3.91679E+13	3.91679E+13	2.63	0.106
VM	1	1.08532E+14	1.08532E+14	7.29	0.007
Ash	1	7.69395E+13	7.69395E+13	5.17	0.024
Cost	1	3.25455E+14	3.25455E+14	21.87	0.000
Error	300	4.46361E+15	1.48787E+13		
Total	305	5.74988E+15			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
3857292	22.37%	21.08%	18.24%

Results of ANOVA shows that the factors are statistically significant in predicting the three plant performance parameters with p- value < 0.05. The following regression model equations were determined using multiple regression:

NPHR = 15316 – 258.0 VM + 139.8 Ash + 53.2 Moisture + 0.656 CV – 0.098 Cost **(3.1)**

Solid Waste = -318 + 21.73 Ash + 9.90 VM + 2.31 Moisture – 0.0286 CV + 0.01175 Cost **(3.2)**

Operating Cost = -32992950 – 1006437 Ash + 1562712 VM + 109887 Moisture + 6533 Cost - 6299 CV **(3.3)**

Based on equation (3.1), the independent variables that have significant effect on NPHR are VM, ash and moisture. It can be seen from the equation that VM has a negative impact on NPHR. VM is the property of coal that dictates its combustibility. Coals with higher volatile matter are easier to ignite, have better flame stability and improved carbon burnout which would result to lower NPHR and higher efficiency. On the other hand, ash and moisture have a positive impact on NPHR which is due to boiler efficiency losses resulting from sensible heat loss due to ash and presence of moisture. Portion of the heat coming from coal combustion that is intended to elevate feedwater temperature is being absorbed by ash and moisture resulting to lower efficiency and higher NPHR.

On the other hand, the independent variables that have a significant positive effect on solid waste are ash and VM according to equation (3.2). Solid waste in CFPPs mainly comes from combustion by products which is why solid waste is directly proportional to the ash content of coal. VM also has a direct effect on solid waste because it affects the combustibility of coal. For the operating cost, all the factors have significant effect on operating cost based on equation (3.3). Better quality coals have higher prices which would result to higher operating costs.

In this regard, the null hypothesis H_{1o} which states that there is no significant relationship between factors for blend consideration and plant performance is rejected.

ANOVA was also performed to determine the relationship of coal blend to the three performance parameters, with the following results as shown in Table 4-6.

Table 4. ANOVA and Model Summary of NPHR vs Coal Proportion

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	1	21095946	21095946	82.39	0.000
Coal 1	1	21095946	21095946	82.39	0.000
Error	304	77839568	256051		
Lack-of-Fit	295	75037968	254366	0.82	0.720
Pure Error	9	2801600	311289		
Total	305	98935514			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
506.015	21.32%	21.06%	20.10%

Table 5. ANOVA and Model Summary of Operating Cost vs Coal Proportion

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	1	5.33895E+14	5.33895E+14	31.12	0.000
Coal 1	1	5.33895E+14	5.33895E+14	31.12	0.000
Error	304	5.21598E+15	1.71578E+13		
Lack-of-Fit	295	5.11244E+15	1.73303E+13	1.51	0.259
Pure Error	9	1.03540E+14	1.15045E+13		
Total	305	5.74988E+15			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
4142203	9.29%	8.99%	7.97%

Table 6. ANOVA and Model Summary of Solid Waste vs Coal Proportion

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	1	24535	24535.0	28.87	0.000
Coal 1	1	24535	24535.0	28.87	0.000
Error	304	258365	849.9		
Lack-of-Fit	295	257306	872.2	7.41	0.001
Pure Error	9	1059	117.7		
Total	305	282900			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
29.1528	8.67%	8.37%	7.13%

Results show that the proportion of coal is statistically significant to NPHR, solid waste and operating cost with p- value < 0.05. Thus, the null hypothesis H_{2o} which states that there is no significant relationship between coal blend and plant performance is rejected.

Based on the results of the hypothesis testing, it can be concluded that the factors for blend consideration that is statistically significant to plant performance are moisture, calorific value, volatile matter, ash and coal cost.

3.3.2 Coal Blend Model Formulation for Performance Optimization

The second objective of this research is to formulate a coal blend model to optimize plant performance in terms of three parameters. In this regard, goal programming, which is a variation of linear programming is more appropriate in view of multiple goals as follows:

- To meet design coal quality for target efficiency
- To minimize coal cost
- To minimize solid waste production in the form of fly ash and bottom ash.

The following table shows the parameters considered in goal programming:

Table 7. Parameters used in LP and GP

	Parameter				
	Moisture	**Gross Calorific Value**	**Volatile Matter**	**Ash**	**Cost**
Basis	as received basis				per ton
Unit	%	kcal/kg	%	%	Php
Design Coal	24	5200	35	1.2	-
Coal 1	28.36	4890	36.12	1.84	3882
Coal 2	16.73	5649	37.43	4.44	5341

Coal 1 in Table 7 is the original coal intended for plant operation whose quality no longer meets the quality of the design coal. Coal 2 is the more expensive coal used for blending. The primary objective of coal blending is to meet design coal quality therefore it should be considered a system (hard) constraint which must be satisfied or there is no feasible solution. While minimizing coal cost and solid waste production was considered as goal constraints.

To establish a specific numeric goal for coal cost and solid waste production, a linear program for minimization of coal cost and solid waste was first formulated.

3.3.2.1 Coal Cost Minimization

The objective function in equation (3.4) minimizes cost of blended coal (Z_C). It is subjected to four constraints in equations (3.5) to (3.8) whose variables are calorific value of individual coal (h_i), moisture of individual coal (m_i), volatile matter of individual coal (v_i), calorific value of design coal (H), moisture of design coal (M) and volatile matter of design coal (V).

Objective Function: Min $Z_C = \sum_{i=1}^{R} c_i X_i$ **(3.4)**

Subject to:

1. Calorific Value Constraint - $\sum_{i=1}^{R} h_i X_i \geq H$ **(3.5)**
2. Moisture Constraint - $\sum_{i=1}^{R} m_i X_i \leq M$ **(3.6)**
3. Volatile Matter Constraint - $\sum_{i=1}^{R} v_i X_i \leq V$ **(3.7)**
4. Percentage Constraint - $\sum_{i=1}^{R} X_i = 1$ **(3.8)**

Decision Variables:

X_i = percentage of individual coal $i = 1 \ldots R$

c_i = cost per ton of individual coal

Using Excel solver and the data in Table 2, the optimum blend to minimize coal cost was found to be 77% Coal 1 and 23% Coal 2. The minimum cost of blended coal is Php 4225 per ton.

3.3.2.2 Solid Waste Minimization

The objective function in equation (3.9) minimizes ash of blended coal (Z_A). It is also subjected to the four constraints in equations (3.5) to (3.8).

Objective Function: Min $Z_A = \sum_{i=1}^{R} a_i X_i$ **(3.9)**
Where: a_i = ash content of individual coal

Using Excel Solver and the data in Table 7, the optimum blend to minimize solid waste was found to be 77% Coal 1 and 23% of Coal 2. The minimum ash of the coal blend is 2.42%.

3.3.2.3 Goal Programming Model

The objective of the goal programming model in equation (3.10) is to minimize overachievement of blended coal cost target (*C*) and overachievement of blended coal ash target (*A*). It is subjected to goal constraints in equations (3.11) to (3.12) and system constraints in equations (3.5) to (3.8).

Objective: Minimize total deviation = $d_1^+ + d_2^+$ **(3.10)**
Goal Constraints:

1. Minimize coal cost - $\sum_{i=1}^{R} c_i X_i + d_1^+ - d_1^- = C$ **(3.11)**
2. Minimize ash - $\sum_{i=1}^{R} a_i X_i + d_2^+ - d_2^- = A$ **(3.12)**

Using Excel solver, the blend that would satisfy both the minimization of coal cost and solid waste is 60% Coal 1 and 40% Coal 2 for the given coal quality in Table 7.

Results of the GP lead to an optimum blend of 60:40 in meeting the three objectives.

3.3.2.4 Evaluation of the Optimal Coal Blend Proportion

The third objective of this research is to recommend coal blend proportions corresponding to desired CFPPs performance results. Using the developed model, the coal blend proportion that would meet design coal quality, minimize coal cost and solid waste is 60% Coal 1 and 40% Coal 2 for the given coal quality in Table 7. Summarized in Table 8 are the different proportions of Coal 1 and Coal 2 and their corresponding qualities.

Table 8. Summarized Coal Blend Quality for Different Proportions

	Moisture	Calorific Value	Volatile Matter	Ash	Cost
Basis	As received basis				per ton
Unit	%	Kcal/kg	%	%	Php
Design Coal	24.00	5200	35.00		
Blend Proportion (Coal 1: Coal 2)					
100:0	28.36	4890	36.12	1.84	3882
75:25	25.45	5080	36.45	2.49	4247
68:32	**24.64**	**5133**	**36.54**	**2.67**	**4349**
60:40	**23.71**	**5194**	**36.64**	**2.88**	**4466**
50:50	22.55	5270	36.78	3.14	4612
25:75	19.64	5459	37.10	3.79	4976
0:100	16.73	5649	37.43	4.44	5341

The 60:40 blend is the blend that has the lowest ash and cost among the blends that meets design coal specification. 75:25 and 100:0 have lower ash and cost but does not meet design coal specifications which could result to lower efficiency. While, 50:50, 25:75 and 0:100 meets design coal specification but has higher ash and cost. The 2019 average blend used by the plant was 68% Coal 1 and 32% Coal 2 which is comparable with the optimal blend obtained in the GP model showing its robustness.

4. Conclusion

ANOVA and multiple regression analysis was utilized to achieve the first objective of the study which is to determine the factors significant for blend consideration. Results showed that coal moisture, calorific value, volatile matter, ash and cost are statistically significant to plant performance parameters specifically net plant heat rate, operating cost and solid waste.

After determining the factors significant for blend consideration, the second objective which is to formulate a coal blend model was developed using a combination of goal programming and linear programming. Linear programming was used to obtain a specific numeric goal for cost and solid waste minimization. Results of the linear programming model was used as goal constraints in the goal programming model. On the other hand, the quality of the coal specifically moisture, calorific value and volatile matter were used as system constraint as the blend must meet design coal specifications to attain target efficiency.

Achieving the objectives of this study lead to answering the research question: What is the ideal blend ratio of Philippine based power plant to attain optimal performance in terms of sustainability? Using the developed model, the ideal blend ratio of a Philippine based power plant to achieve sustainable operation is 60% Coal 1 and 40% Coal 2 based on the average quality of coal received for the year 2019 which is found to be robust.

This study focused on achieving sustainable operation through coal blend optimization. Sustainable operation entails the pursuit of social, economic and environmental objectives. For this study, economic objective was focused on operating cost minimization, meeting target plant efficiency and security of supply. Operating cost minimization was achieved by reducing coal cost and solid waste. Coal blend optimization allows plants to use poor quality less expensive coals by blending it with higher quality more expensive coals without sacrificing overall plant operation. Lesser solid waste could also reduce plant operating cost because it would reduce costs incurred for solid waste management. The model developed in this study was also able to meet design coal qualities that is necessary for meeting target plant efficiency. It also addresses security of supply as it allows the use of other coals available in the market. Social objective concentrated on ensuring uninterrupted supply of electricity to customers and having a more competitive generation charge through reduction of operating cost and security of coal supply. While environmental objective is directed towards reduction of solid waste produced by coal fired power plants.

In conclusion, the model developed is robust and results to optimal performance in terms of sustainability – cost efficient, environmentally friendly and socially responsible.

5. Recommendation

The Goal Programming model developed in this study could be used by CFPPs in determining ideal blends for their plant operation depending on the quality of coal available in the market. Objective and constraints of the model could be adjusted based on plant requirement. The developed model is limited to meeting design coal quality to meet target efficiency, minimize operating cost based on cost of fuel alone and solid waste production. Further study on other factors that might affect coal blend performance is recommended. Other plant performance parameters like minimization of carbon dioxide emission could also be explored.

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Biographies

Marvin I. Norona is an Industrial Engineering professor at the Mapua University, School of Industrial engineering & Engineering Mangement and in the School of Graduate Studies. He earned his BS Industrial Engineering and MBA degrees from University of the Philippines and is a Doctor in Business Administration candidate finishing his thesis in lean and green Manufacturing. His research interests are in the areas of sustainability, supply chain management, production & operations management, lean manufacturing, quality management and smart manufacturing.

Annabelle R. Laureta is a Master of Science in Engineering Management student at Mapua University. She earned her Bachelor of Science degree in Chemistry from University of the Philippines-Diliman. She is currently employed as a chemist in a coal fired power plant in the Philippines. Her research interests are in the area of coal quality, optimization and sustainability.