INFLUENCE OF DIFFERENT PARAMETERS ON THE COST FUNCTION OF LAKVIJAYA POWER STATION

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Degree of Master of Science

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Thesis submitted in partial fulfillment of the requirements for the degree Master of Science in Electrical Engineering

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DECLARATION

I declare that this is my own work and this thesis does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

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ABSTRACT

Every power plant has its own cost function that describes how its cost varies with the power output. This data is used to find the incremental cost of each unit generated – hence the order in which the plant is dispatched in the merit list prepared by System Control Centre (SCC) of Ceylon Electricity Board (CEB). Lakvijaya Power Station (LVPS) is in operation for more than six years now, but its cost function has not been defined yet. Main target of this research is to define the cost function of LVPS and to determine the independent parameters affecting the function.

There are many parameters that affect the efficiency of the power plant. One is the temperature of inlet air which is used to convey pulverized coal to the furnace and to supply air required for combustion. Another key parameter is the cooling water temperature which is used as the coolant of the condenser. Next one is excess oxygen content in flue gas. Furthermore, mill temperature, power output, main steam pressure and main steam temperature were considered.

By using load levels, cost data and quadratic regression, the cost function was derived. Then the most influencing factors were identified using Pearson correlation analysis. As the second step, it was studied how the selected parameters affect the cost function. Multiple regression was used for those calculations. SPSS package was the selected tool for this analysis.

Validation for the final output was done for many cases and that proved realistic behavior of the derived function. This relationship can be used to identify the parameters affecting the efficiency and to which extent it influences the cost function. This function is recommended to be used for decision making and for the efficiency calculation of Lakvijaya Power Station.

Key words: cost function, incremental cost, plant dispatch, quadratic regression, multiple regression, efficiency

DEDICATION

I dedicate this thesis to my beloved parents, who have guided me from the very beginning of my life with endless love. And also to my two sisters who have been with me and helped me in difficult times in my whole life. And my ever loving wife Chiranji, who never lost faith in me even in very tense and difficult times and loved me unconditionally.

ACKNOWLEDGEMENTS

First I pay my sincere gratitude to Prof. H.Y.R. Perera who encouraged and guided me to develop this relationship and on preparation of final thesis.

I take this opportunity to extend my sincere thanks to all the operation engineers of Lakvijya Power Station and engineers of System Control Centre of Ceylon Electricity Board who supported and facilitated with necessary data and information.

It is a great pleasure to remember all my lecturers of University of Moratuwa and all friends in the post graduate program, for backing me from beginning to end of this course.

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LIST OF ABBREVIATIONS

Abbreviation	Description
CEB	Ceylon Electricity Board
LVPS	Lakvijaya Power Station
SCC	System Control Centre
SPSS	Statistical Package for Social Sciences
MST	Main Steam Temperature
MSP	Main Steam Pressure
CCS	Carbon Capture and Storage
HP	High Pressure
IP	Intermediate Pressure
LP	Low Pressure
FGD	Flue Gas Desulfurization
ESP	Electrostatic Precipitator
SCR	Selective Catalytic Reduction
PASW	Predictive Analytic Software

Chapter 1

INTRODUCTION - COAL POWER GENERATION

1.1 World Context

Even though coal power generation is very new to Sri Lanka, world context regarding coal power generation is totally different. Coal is the world's most abundant and widely distributed fossil fuel with reserves for all types of coal estimated to be about 990 billion tones, enough for 150 years at current consumption. Coal fuels 42% of global electricity production, and is likely to remain a key component of the fuel mix for power generation to meet electricity demand, especially the growing demand in developing countries.

To maximize the utility of coal use in power generation, plant efficiency is an important performance parameter. Efficiency improvements have several benefits,

- prolonging the life of coal reserves and resources by reducing consumption
- reducing emissions of carbon dioxide (CO2) and conventional pollutants
- increasing the power output from a given size of unit
- Potentially reducing operating costs.

Electricity generation from coal based power plants have been increased rapidly during last three decades. Figure 1.1 and figure 1.2 show the increment as a percentage. Total new coal generation capacity commissioned in the world in 2010 to 2014 is 200MW/day [IEA]. In 1990 world total coal power generation was 37.11% and it was 41.01% on 2013. Coal, the second source of primary energy (roughly 30%), is mostly used for power generation (over 40% of worldwide electricity is produced from coal). In addition, coal is used to produce virtually all non-recycled iron. Coal is abundant, affordable, easy to transport, store and use, plus free of geopolitical tensions. All these attributes made it very popular. On the other hand, pulverized coal plants are the most carbon-intensive source of power generation and this is a real issue as CO_2 emissions need to be dramatically and urgently reduced. Below figure 1.2 shows the world electricity generation based on the source used. Highest percentage which is 39% of electricity generation is from coal.

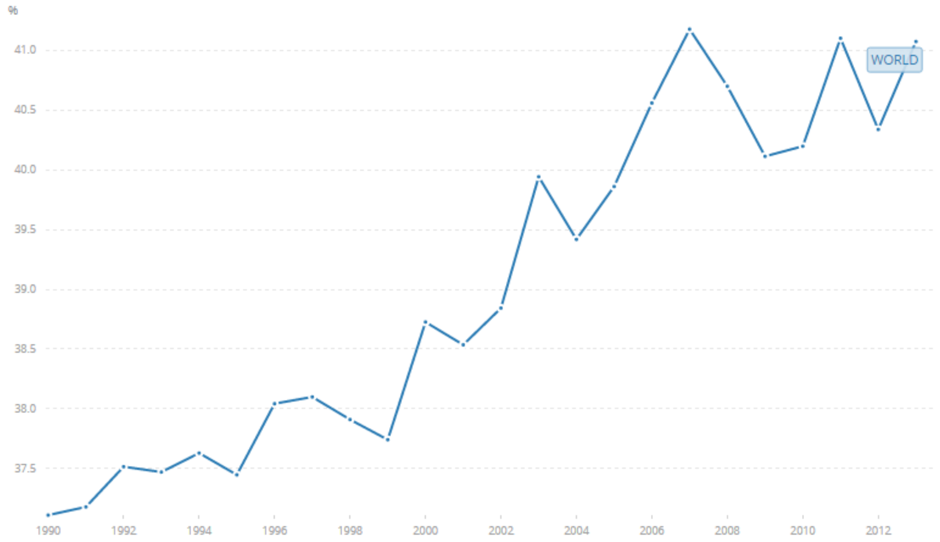


Figure 1.1 World coal power generations 1990-2013

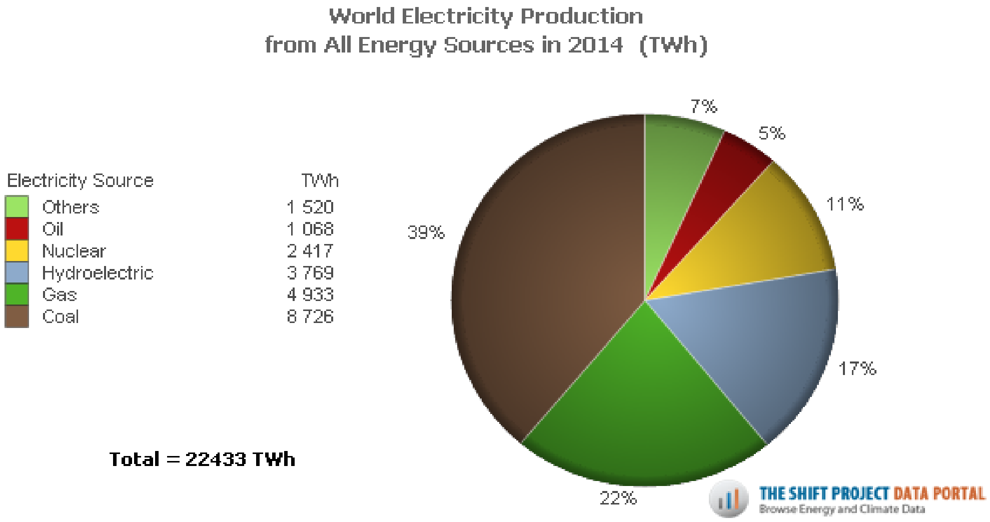


Figure 1.2 World coal power generation in 2014

Source: International Energy Agency

Whereas more efficient coal plants are built across the world, the transition from subcritical to supercritical (and ultra-supercritical) technology is very slow. And even worse news is that the dramatic reduction of CO_2 emissions that our climate targets require is possible only through development of carbon capture and storage (CCS) technologies. Progress on CCS is very disappointing.

Figure 1.3 shows the process flow of power generation from coal. Pulverized coal from coal mill is being provided to the boiler combustion. This energy absorbs by the water tubes and water inside the boiler which helps to generate steam. Generated steam superheated and feed to the High Pressure (HP) turbine. Exhaust called cold reheater again go through the boiler and it is called hot reheated steam. This steam enters to the Intermediate Pressure (IP) turbine and exhaust directly feeds to the Low Pressure (LP) turbine. This rotor couples to the rotor of the generator which is finally generating electricity.

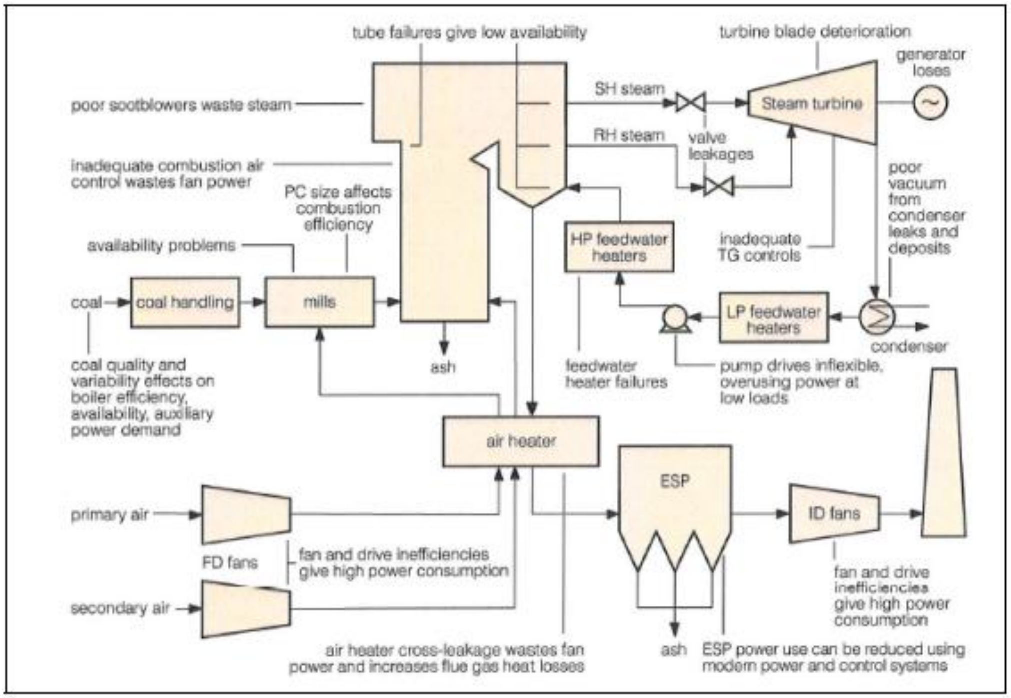


Figure 1.3 Process flow of Coal Power Plant

The calculation of coal-fired power plant efficiency is not as simple as it may seem. Plant efficiency values from different plants in different regions are often calculated and expressed on different bases and using different assumptions. There is no definitive methodology.

1.2 Power Generation of Sri Lanka

Energy data of Sri Lanka in 2015

- Installed capacity – 3,200 MW (approx)
- Capacity Mix – Hydro 40% Thermal 60%
- Energy Mix – Renew 49% Thermal 51%
- Peak Demand – 2,393 MW (2016)
- Energy Generation (net) – 13,090 GWh
- Energy Sales - 11,786 GWh
- Trans. & Dist. Losses – 9.96 %
- Electrification level – 98.5 % (estimated)
- Per capita consumption – 562 kWh

From installed capacity, 900MW from Lakvijaya power station. Total thermal generation of 1875MW can be divided as follows.

- Coal - 825 MW (CEB) –Net generation
- Oil Fired - 1050 MW (CEB 550 : IPP 500 MW)

First unit of Lakvijaya power station was commissioned on 2011, unit 2 and 3 were commissioned on 2014 and 2015 respectively. Figure 1.4 and figure 1.5 show the power generation mix of Sri Lanka from 2010 to 2015

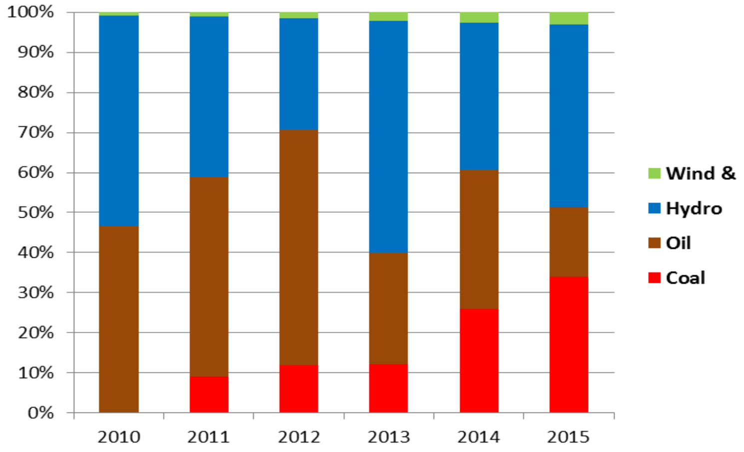


Figure 1.4 power generation of Sri Lanka

In 2011 coal share was around 10% and it was around 35% in 2015. It drastically reduces the oil generation share from 45% to 15%.

Source	GWh
Coal	4443
CEB oil	1050
IPP oil	1225
Major Hydr	4904
Mini Hydro	1065
Wind	343
Other NCRI	59
Total	**13089**

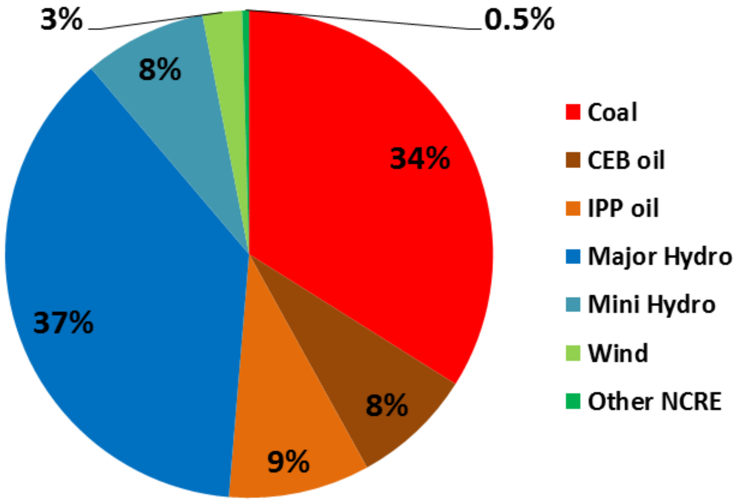


Figure 1.5 power generation share based on source (2015)

Above all interpretations are based on 2015 data. As per the Ceylon Electricity Board web site on 16th January 2017, given values have small deviation. At Lakvijaya power station total generation was 750MW. Unit 1 was running at half load due to maintenance issue. Figure 1.6 shows the generation mix on 16th January 2017.

Electricity Generated on : January 16, 2017

Peak Power Demand	2282.1 MW
Reservoir Storage	425.8 GWh

Energy		Percentage %
CEB Thermal (Coal)	16.17 GWh	42.22
CEB Thermal (Oil)	8.77 GWh	22.89
IPP Thermal (Oil)	7.02 GWh	18.33
Laxapana Complex Hydro	2.59 GWh	6.76
Mahaweli Complex Hydro	1.92 GWh	5.01
Samanala Wewa	0.68 GWh	1.77
Kukule Ganga	0.29 GWh	0.76
CEB (Small Hydro)	0.1 GWh	0.26
Wind	0.7 GWh	1.84

Figure 1.6 CEB generation data 16th January 2017

Source: CEB web site

Lakvijaya Power Station is governing a major role in Sri Lankan power sector. Now its capacity is 900 MW, which provides around 50% of daily energy demand of Sri Lanka. It produces around 21.6 GWh, when all three units are running at full load. Generally coal power stations are operated for base load requirement. But in Sri Lanka, base load energy demand is not much high and it is varying time to time. Therefore sometimes coal power units load level needs to be de-loaded, as per the instruction given by the System Control Centre (SCC).

As per the data given by CEB when two units are operating 34.74% of energy is generated by Coal power plant. It is 52.26% when all three units are running.

This study is looking for relationship not only to improve efficiency of power plant assets but also to grow concerns about the environmental impacts of power generation without compromising their market competitiveness. To meet this challenge, this study demonstrates the application of SPPS (Statistical Package for Social Sciences) in Lakvijaya Power Station. The main purpose is to determine which factors have a great impact on cost function and identify the relationship. The amount of fuel energy input needed to produce electrical energy output (heat rate, kJ/kWh) is the key factor to measure the overall efficiency of the plant. This power station produces the electrical power by using the good quality of bituminous coal and is installed with Flue Gas Desulfurization (FGD), Electrostatic Precipitator (ESP), Low Nitrogen Oxide (NOx) Burner, and environment management equipment.

Technical data of the coal is given in Table 1.1

Table 1.1 Specification of Coal

Parameter	**Value/Range**
Particle Size	< 50 mm
Moisture Content	< 12 %
Gross Calorific Value	5800 - 6300 kCal/kg
Ash Content	< 15 %
Bulk Density	0.8-0.85 t/m3
Sulphur content	0.2 –1.2 %
Volatile matter	> 22 %
Fixed carbon	> 43 %

1.3 Efficiency of Power Plants

Measuring coal fired power plant efficiency consistently is particularly important at the global level, yet significant regional differences exist. Similarly at the local level the performance of individual generating units and power plants can only be compared if measured consistently. Although variations in efficiency may arise from differences in plant design and maintenance practices, the practical and operational constraints associated with different fuel sources. Local ambient conditions and electricity dispatch all play significant roles. Misunderstanding these factors can result in the misinterpretation of efficiency data. There are many methodologies to evaluate the efficiency. The application of such a reference methodology would provide a potential route to gauge how coal might be deployed more cleanly and efficiently in the future.

When all three machines are running at full-load it consumes around 8000 tons of coal per day and it cost around 120 Million Rupees for coal per day. If coal consumption of one unit can be reduced by 1 t/h, it saves around 1 Million rupees per day. In this study I’m not going to find the efficiency of the plant. But the results give hints to improve the efficiency, hence saving to the nation.

1.4 Factors Affecting to the Efficiency of the Power Plant

There are many factors that can be affected to the efficiency of the power plant. Based on the variation of those factors, coal consumption rate required to generate same amount of energy may vary. Some of the factors which can be affected to the plant efficiency and hence plant cost function.

- Ambient temperature
- Cooling water temperature
- Excess O2 of flue gas
- Mill temperature
- Main Steam Temperature
- Main Steam Pressure
- Power output

More details of those factors and their behaviors will be discussed next chapter. From above parameters ambient temperature, cooling water temperature cannot be controlled. But other all concerned parameters (Excess O2 of flue gas, Mill temperature, Main

Steam Temperature, Main Steam Pressure, Power output) are operating conditions. So they are controllable.

1.5 Cost Function

Thermal generator costs are typically represented by one or other of the following four curves

- input/output (I/O) curve
- fuel-cost curve
- heat-rate curve
- incremental cost curve

The Input Output curve plots fuel input (in MBtu/hr) versus net MW output. Typical variation is shown in figure 1.7.

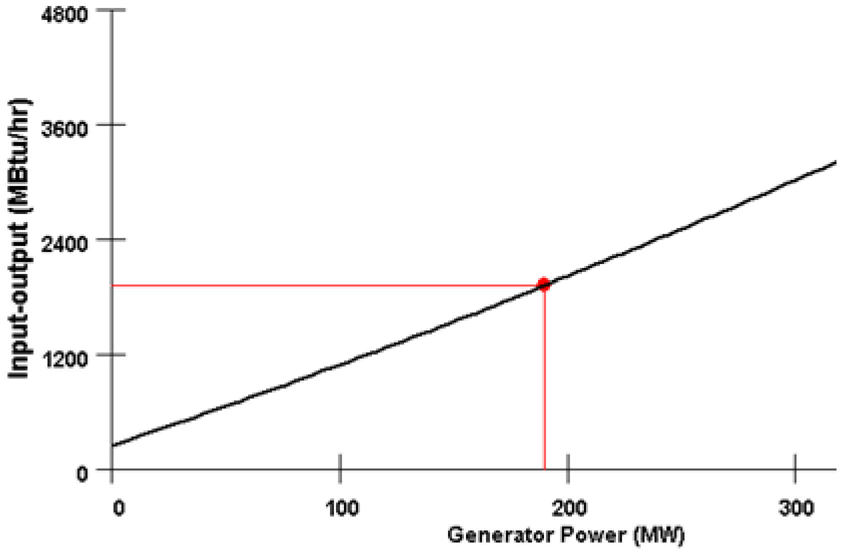


Figure 1.7 Input output relationship of a power plant

The fuel-cost curve is derived by the Input/output curve multiplied by the fuel cost. Heat rate curve plots the average number of MBtu/hr of fuel input needed per MW of output.

Heat-rate curve is derived by input/output curve divided by MW output (Figure 1.8). These graphs are helpful to prepare the merit order of power plant dispatching. Especially incremental cost graph which is derived from this is needed.

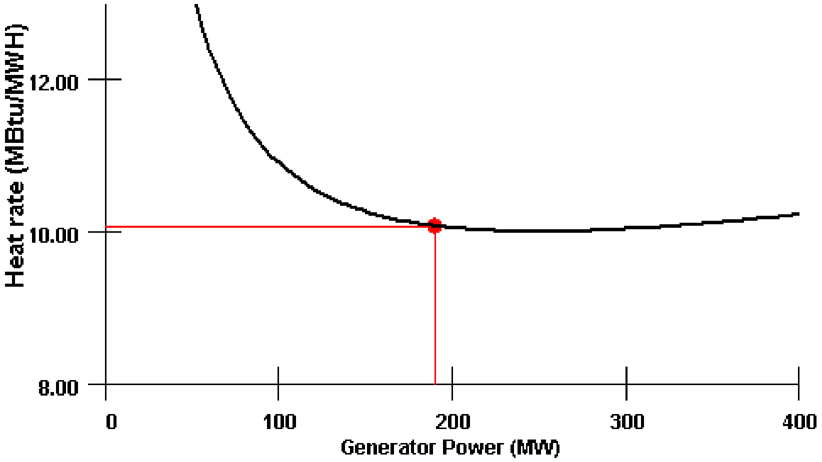


Figure 1.8 Heat rate curve

Incremental cost curve plots the incremental \$/MWh as a function of MW. It is derived by differentiating the cost curve. Generator cost curves are usually not smooth. However the curves can usually be adequately approximated using piece-wise smooth, functions. Two approximations predominate:

1. quadratic or cubic functions
2. piecewise linear functions

We'll assume a quadratic approximation:

Cost function is given as the function of power. It is a quadratic equation of power.

$$F = A + BP + CP^2$$

Where F – Cost
A, B, C – Coefficients
P – Power Output

Normal condition, coefficients A, B, C are considered as constants. But actually in different conditions A, B and C are not constants. They are also varying. This study is to identify those factors which affect to the coefficient of cost function and to determine the relationship. Then this can be used to minimize the cost by saving fuel and finally huge saving to the power plant.

1.6 Research Area

As we all aware Lakvijaya power station is the most important power plant in Sri Lanka. But still not much study was carried out to estimate the plant efficiency and any other improvement methods were proposed. By decreasing the coal consumption by 1 T/h, it can save more than 1 million rupees per day. There are two main targets of this research.

1. To identify the most important parameters which are highly affected to plant performance and
2. To get the relationship of those parameters to the cost function of the power plant.

Next chapter will describe the parameters which are affected to the cost function. Then in third chapter methodology used will be discussed. Final results and the validation of the results will be discussed in the fourth chapter. Conclusion of the research in chapter five.

Chapter 2

PARAMETERS AFFECTING TO THE COST FUNCTION

2.1 Introduction

This section explores aspects of power plant parameters and operation that influence the coal consumption. The section also reviews the relevance of current power plant performance measurement standards and how these might be reconciled using a common methodology to allow performance benchmarking. The section continues with a summary of the reporting bases and the required information sources for calculating the efficiency of a whole plant according to national standards.

There are many factors which can be affected to the coal consumption of the power plant.

- fuel moisture content (influences latent and sensible heat losses)
- fuel ash content (impacts on heat transfer and auxiliary plant load)
- fuel sulphur content (sets design limits on boiler flue gas discharge temperature)
- use of closed-circuit, once-through or coastal cooling-water systems (determines cooling-water temperature);
- normal ambient air temperature and humidity;
- Use of flue gas cleaning technologies flue gas desulphurization (FGD) and CO2 capture (all increase on-site power demand); and
- Use of low-NOx combustion systems (requires excess combustion air and increases unburned carbon).

In this study, basically following parameters were considered.

2.2 Power output

Even though coal power stations are designed for base load requirement, load of Lakvijaya Power Station (LVPS) is being varied as per the instruction given by the System Control Centre (SCC). During the off-peak time due to the low demand, LVPS units are being de-loaded. Then again demand increases, load need to be increased. Load variation during a day (24hr) is shown in below figure 2.1.

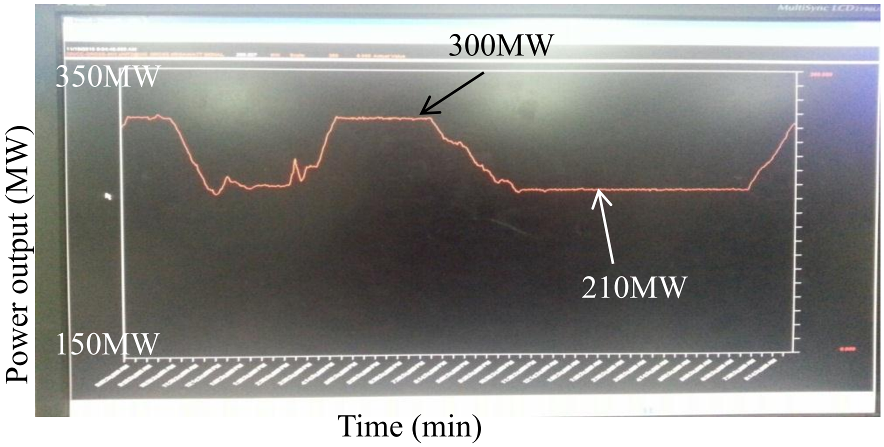


Figure 2.1 Daily Load Variations on 11-11-2015

Within the time period of one month (30 days), we can see large variation of the unit load (figure 2.2) .Top most value is 300MW and lowest value is 210MW.

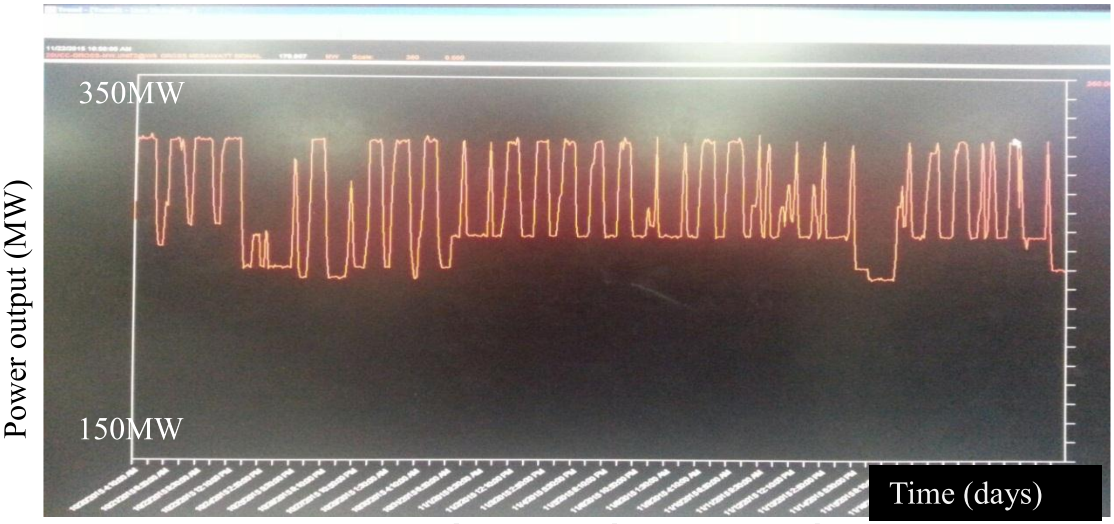


Figure 2.2 Load variations during one month time

Plants which are being operated with a low average output will return low efficiencies compared to their full-load design efficiency. Steam turbine heat consumption is characterized by a relationship known as the “Willans line”, shown in Figure 2.3 for an example turbine. This line shows that total heat consumption comprises a fixed element and an incremental element at zero load, the heat consumption is not zero. This relationship is normally derived by undertaking a number of heat consumption tests on a turbine at different loads and then plotting a best-fit line through the observed values.

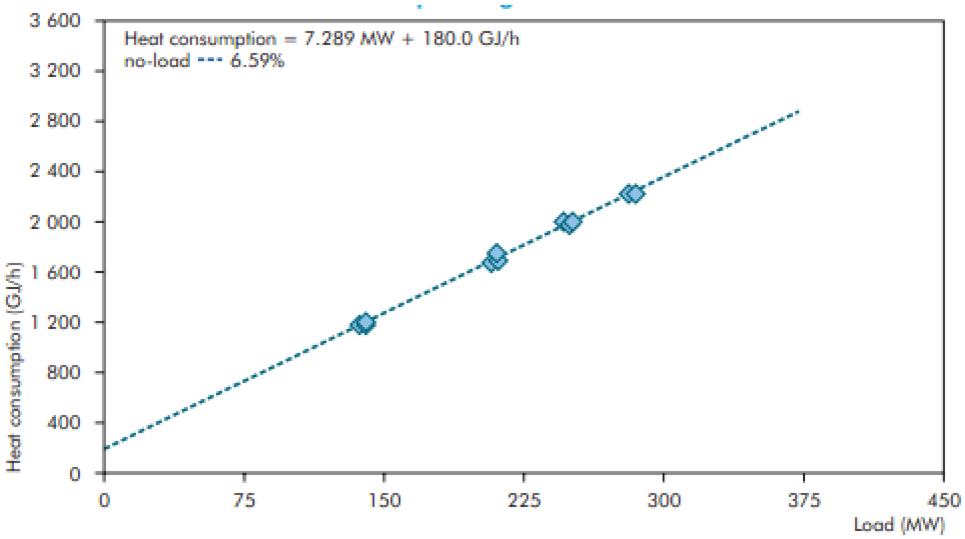


Figure 2.3 Typical relationship between steam turbine heat consumption and operating load

Source: IEA

The overall energy consumption of a plant can be similarly characterized by a fixed element and a variable element proportional to output. Hence, overall efficiency will decline as load is reduced and the no-load portion becomes a greater fraction of the total heat.

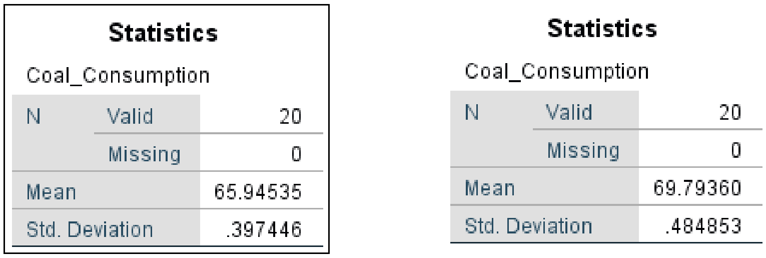
Another related consideration is that, working power will account for a greater percentage of generated power at part load, because the no-load running losses of electrical equipment increase relative to useful output and because certain activities must be carried out, irrespective of unit load.

For these reasons, power plants may formally record “part-load loss” as a penalty incurred purely as a result of being asked to operate the plant at a lower than optimum output.

At each load level coal consumption per generating energy unit (T/kWh) is not a constant. Due to efficiency matters it varies with the load. I have considered one hour time frame which was constantly operated at the same load and measure the coal consumption.

$$coal\ consumption \quad = \sum_{=1}^{n} \frac{coal\ cons.\ of\ one\ hr\ time}{n}$$

When the load is taken to a certain value, actually it takes some time to settle the parameters and stable the system. All the reading given below are taken at stable condition. Actual energy generated and actual coal consumption during that particular hour were recorded. One time frame(1 hour) is not enough to get a correct idea, so for a particular load thirty number of such condition took into consideration and mean coal consumption was recorded. From the generated large number of data set (Table 2.1). at each load value, relevent mean coal consumption and standard deviation was calculated using SPPS software (Figure 2.4).



Statistics

Coal_Consumption

N	Valid	20
	Missing	0
Mean		65.94535
Std. Deviation		.397446

Statistics

Coal_Consumption

N	Valid	20
	Missing	0
Mean		69.79360
Std. Deviation		.484853

Figure 2.4 SPSS output for load 170MW and 180MW

Table 2.1 Input/Output at different loads

Power(MW)	**Energy(MWh)**	**Coal(Tons)**	**kg/kWh**
170	170.294	65.663	0.3856
180	180.202	69.062	0.3832
210	210.18	80.247	0.3780
220	220.199	82.678	0.3755
230	229.816	83.769	0.3701
260	259.943	94.301	0.3628
280	280.104	101.395	0.3620
300	300.403	107.891	0.3592

During the above all load conditions, no oil guns were fired.

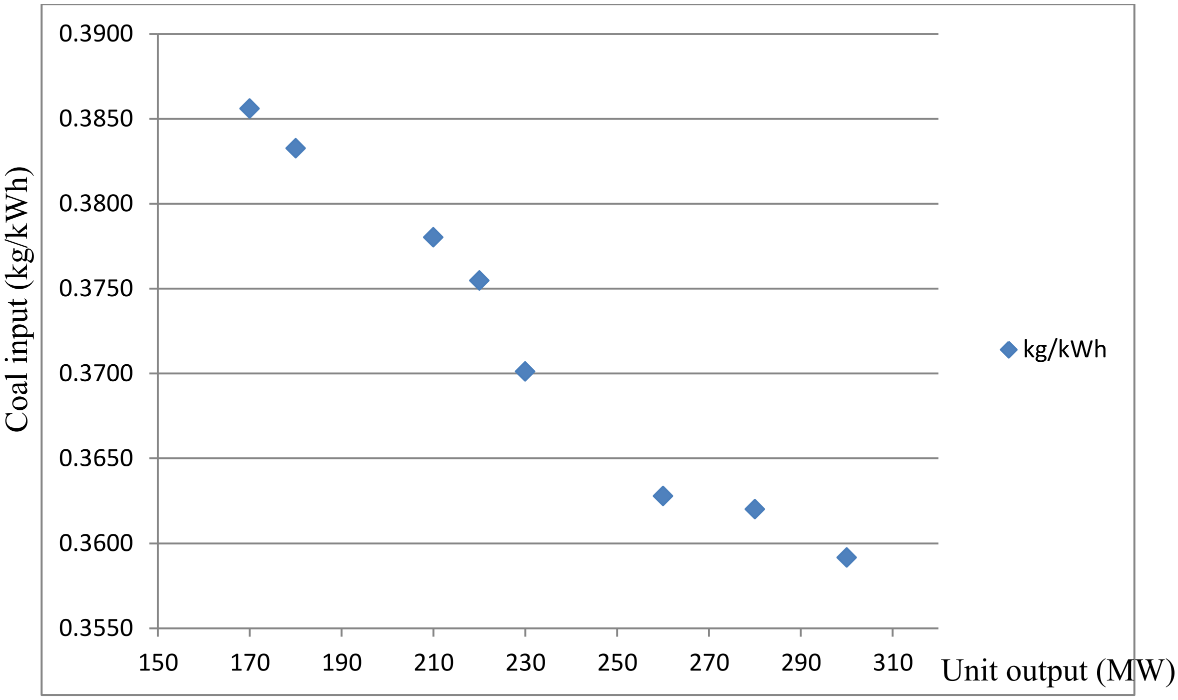


Figure 2.5 Average coal consumption Vs unit load

This graph (figure 2.5) shows straight relationship between load and the average coal consumption for one energy unit generated. Under low load condition efficiency of the plant is decreased. Therefore more coal is required to generate one energy unit. But in Sri Lanka, this load variation is unavoidable. So the plant is running at low efficiency conditions due to system requirement.

2.3 Cooling Water Temperature

Sea water is used as cooling water at Lakvijaya Power Station. This cooling water is used as the coolant of the condenser which contains 16,000 of titanium mixed alloy tubes to carry the sea water inside the condenser. More than 50,000 Tons of cooling water quantity is required for one hour. Sea water intake is around 400m away from the beach. It has temperature increment around 6 °C – 7 °C between inlet and outlet of the condenser.

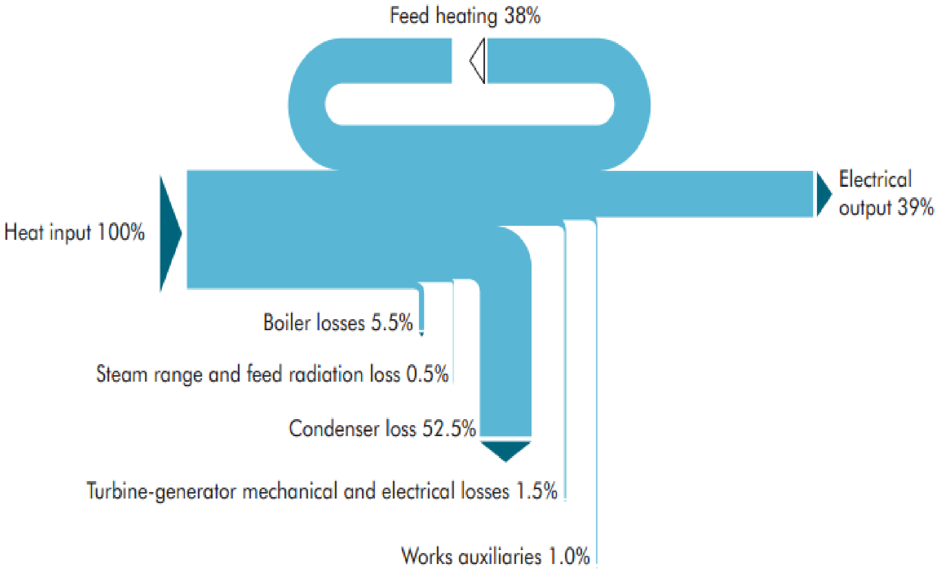


Figure 2.6 example energy flows in a typical 300 MW subcritical pulverized coal-fired boiler

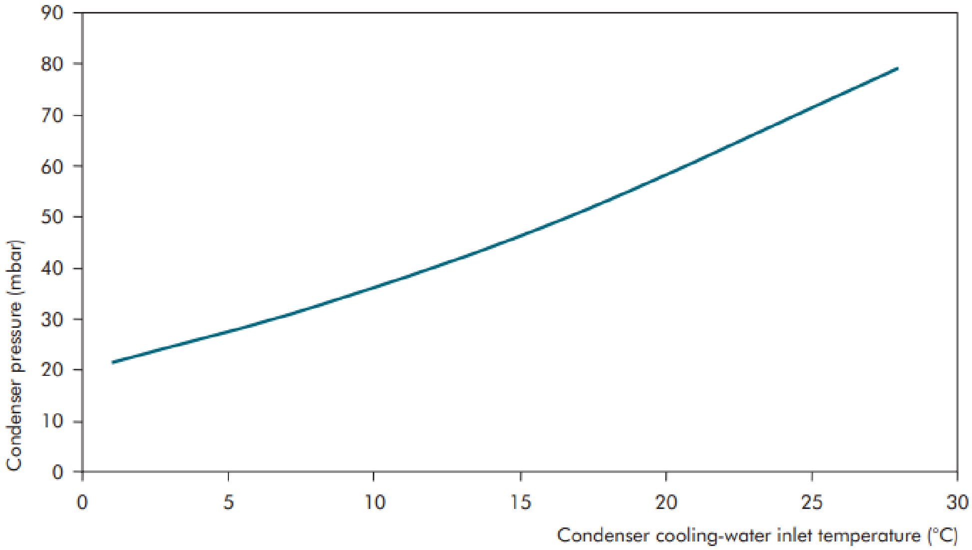
Source: International Energy Authority

The Figure 2.6 shows example heat flows in a typical 300 MW subcritical pulverized Coal-fired boiler, where the electrical output is 39% of the heat input and the heat rejected by the condenser to the cooling water is 52.5%. This example illustrates that it is the thermodynamics of the steam cycle, and not the fuel combustion process, which is a limiting factor for conventional power plant efficiency. Where the rejected heat can be utilized, this can provide significant improvements to the overall cycle efficiency.

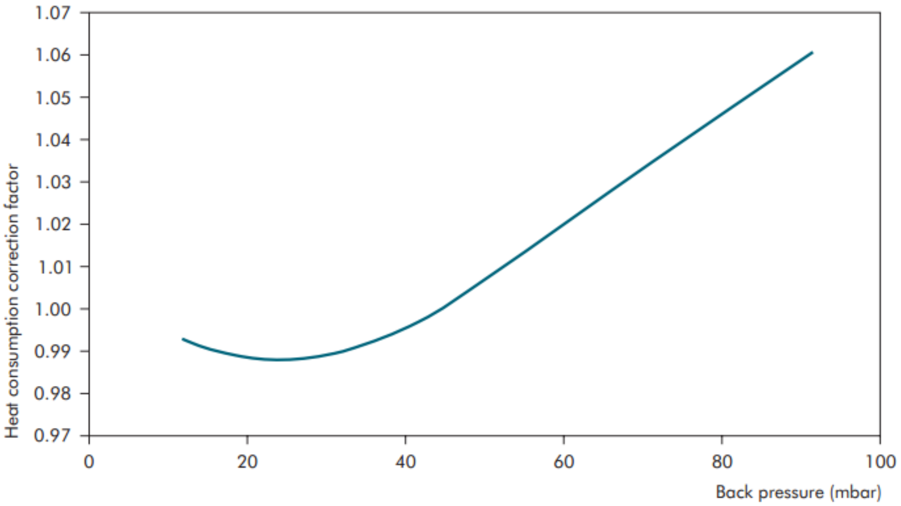
A relatively small change in condenser pressure, in the order of thousandths of a bar (or hundreds of Pascal), can bring about seemingly disproportionately large changes in plant efficiency. To achieve similar changes in efficiency at the high-temperature end of the cycle would require more significant changes in steam conditions. A major factor governing the condenser pressure is the availability of a cold heat sink for heat rejection. This is often provided in the form of a large body of water such as the sea at lakvijaya, although heat can also be rejected using closed circuit wet, semi-dry or dry cooling systems. The temperature and quantity of cooling medium available to the condenser have a significant impact on performance. Since economics generally determine the heat exchanger size, and the capacity of the cooling system, a major factor determining real plant performance becomes the cooling-water supply temperature to the condenser. This tends to be lowest for coastal sites in the northern hemisphere and highest for sites in locations with high ambient temperatures and limited water supplies.

The precise impacts of cooling-water temperature on condenser pressure, and the associated impact of condenser pressure on heat rate, are site-specific. However, within reasonable limits, some approximations can be made. In general, the impact of cooling-water temperature on condenser pressure is about 2 mbar per 1°C change in inlet temperature, and the associated impact on heat rate is in the order of 0.1% of station heat consumption per 1 mbar. Thus a difference of 5° C in cooling water inlet temperature might change unit heat consumption by around 1%.

Ambient conditions change both seasonally and diurnally. Examples of the impact of cooling-water temperature on condenser pressure and the impact of condenser pressure on heat consumption in conventional steam plants are shown in Figure 2.7 and 2.8.



Figures 2.7 impact of cooling-water temperature on condenser pressure for constant unit load



Figures 2.8 impact of condenser pressure on heat consumption

During day time and night time inlet cooling water temperature is being varied between 28°C to 32°C. The variation of inlet cooling water temperature during month of October, 2015 is given below (Figure 2.9). Recorded maximum temperature is 31.4°C and minimum temperature is 28.6 °C. Effect of this variation to the cost function of the LVPS will be analyzed in this study.

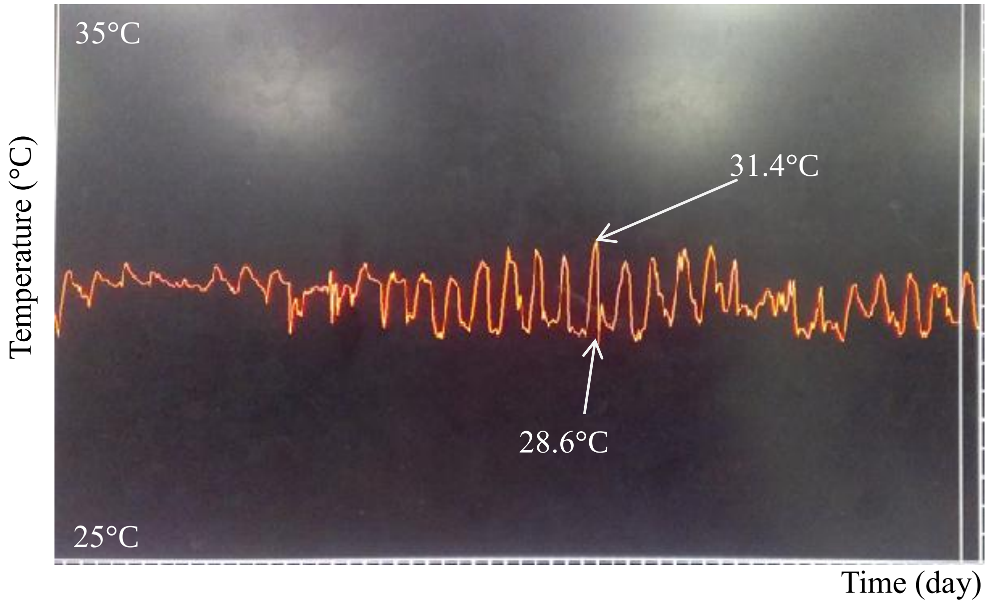


Figure 2.9 Variation of cooling water temperature at LVPS (One month)

2.4 Ambient Temperature

There are two main air intakes at each unit of Lakvijaya Power Plant (LVPS). One is primary air inlet which is used to convey pulverized coal to boiler from the coal mill. Other one is secondary air inlet which is used to provide sufficient air to the combustion. During the production of electricity, steam generators require oxygen during combustion and water during the cooling process. Ambient air is drawn into the combustion chamber to provide oxygen which is consumed in an exothermic combustion reaction whose heat is used to convert water to steam. The steam drives a turbine and generates electricity. Once the steam has expended its useful energy, it is cooled (at condenser), re-condensing it into water to be boiled again.

Oxygen in the air is used for combustion and enters the plant at ambient temperatures usually below 50° C. Energy is expended raising the temperature of the incoming air to the combustion temperature. Air entering the boiler at 40° C requires relatively less energy to increase its temperature to 540° C than air entering the boiler at -10°C. Therefore, warmer air is expected to provide an efficiency boost to a steam boiler. Air taken from the atmosphere is heated up to around 200 °C by air preheater before entering to the combustion area.

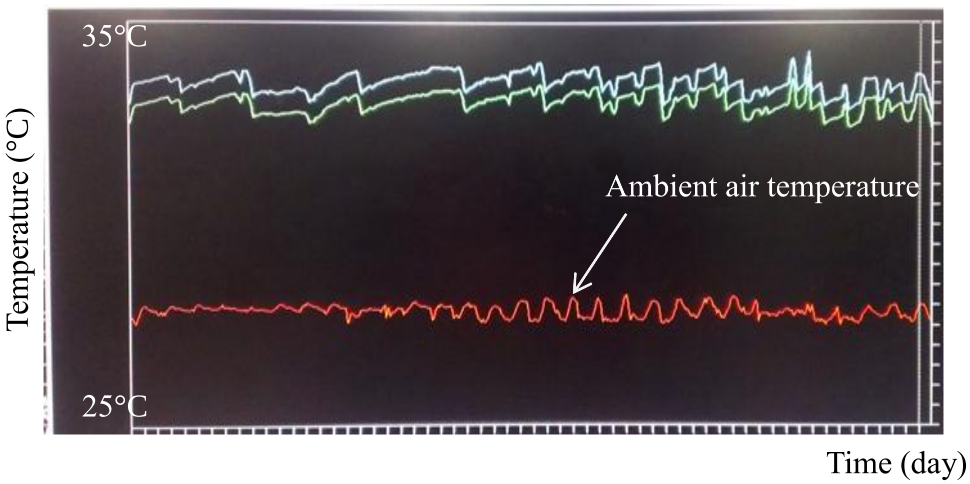


Figure 2.10 Variations of Ambient air temperature (One month)

Figure 2.10 shows how the ambient air temperature is varied at LVPS during the month October 2015. Red colour line shows the air temperature at primary air inlet. Other green and blue colour lines show the inlet temperature after the air preheater. Maximum and minimum temperatures recorded during the month are 33°C and 25°C respectively. There is a considerable variation of ambient temperature compared to the cooling water temperature.

2.5 Economizer Excess O_2 Content

This is a measurement of excess oxygen which is drawn from the boiler. This value is highly important to ensure the full combustion. If excess oxygen content is zero, it gives the information that there is not enough oxygen to the combustion and reduces the boiler efficiency. If this is very high it ensures the proper combustion but it withdraws energy of the boiler as flue gas. So it is clear that excess oxygen content should have upper and lower limits.

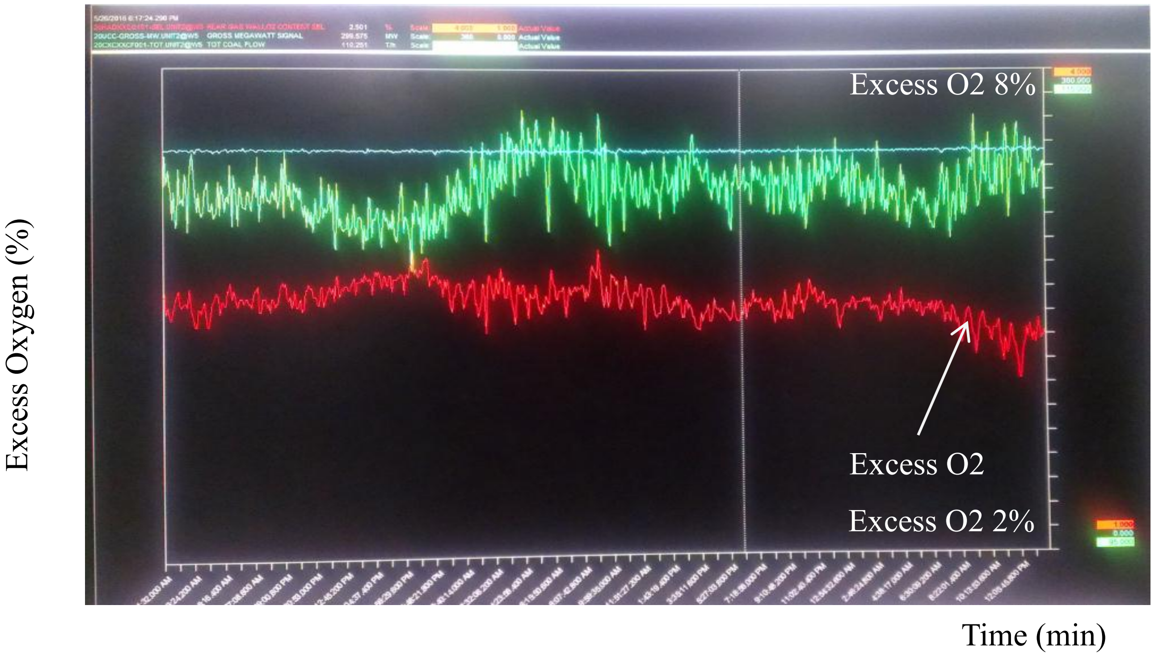


Figure 2.11 Excess oxygen variation at LVPS

Actually to get the maximum boiler efficiency, excess oxygen content must be maintained at an optimum value. So it clear that this parameter should be considered to analyze the cost function of the power plant. The amount of excess oxygen is defined by the system, depends on the unit load. But the operation engineer can adjust that value. That person is allowed to change the air supply to the boiler. Sometimes partial combustion may results in low quality fly ash production. Excess oxygen variation within five hour time frame is given in figure 2.11.

2.6 Main Steam Temperature (MST)

Main Steam Temperature (MST) is the steam temperature which comes out from the boiler and enters to the high pressure turbine. The design value of MST is 538 °C. Variation of MST can be influenced to the efficiency of the turbine. So this parameter also selected to study the influence to the cost function. At normal operation it has the variation of about maximum temperature of 542°C and minimum temperature of 534°C. Enthalpy of steam is a function of temperature and pressure. At lower temperature, enthalpy will be low, work done by the turbine will be low, turbine efficiency will be low and hence steam consumption for the required output will be higher. In other words, at higher steam inlet temperature, heat extraction by the turbine will be higher and hence for the required output, steam consumption will reduce. Figure 2.12 and 2.13 represents the effects of steam inlet temperature on steam consumption and turbine efficiency respectively, keeping all other factors constant for the condensing type turbine.

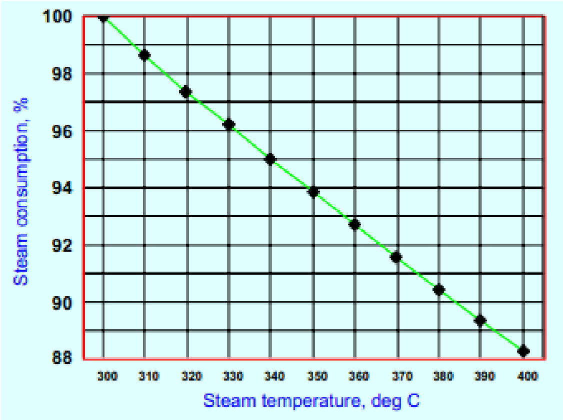


Figure 2.12 Effect of steam temperature on steam consumption in condensing type turbine

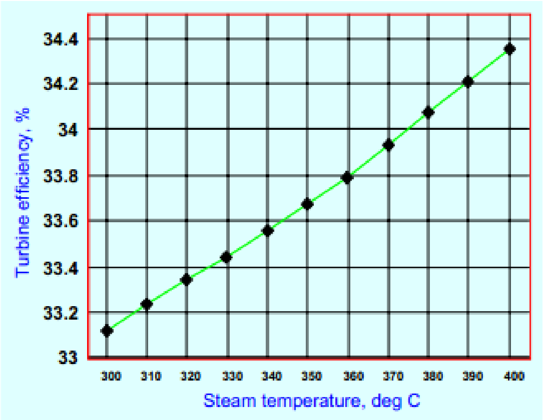


Figure 2.13 Effect of steam temperature on turbine efficiency in condensing type turbine

Source: International Energy Agency

2.7 Coal Mill Temperature

Coal mills are used to pulverize the coal particles and with the help of primary air it is conveyed to the boiler. Normally coal particles are at room temperature and to increase the boiler efficiency pulverized coal temperature is increased by using hot primary air. Even though high temperature is favorable for the boiler efficiency, it has the hazardous condition of firing. So there is an optimum value to maintain the mill temperature. It has the variation from 65°C to 73°C at normal operating condition. Finally Mill temperature is also an important parameter to be considered.

Another important thing is, heating coal reduces the moisture content in large scale before enters to the boiler. Otherwise additional energy should be given to evaporate the moisture. Unfortunately, plants that utilize high-moisture coal pay a substantial price in efficiency. When such coals are burned in utility boilers, about 7% of the fuel heat input is used to evaporate and superheat the moisture in the fuel. Most of this lost heat can be attributed to the energy needed to evaporate the moisture in the fuel. Furthermore, high-moisture, low-heating value coals result in higher fuel and flue gas flow rates, auxiliary power requirements, net unit heat rate, and increased mill, coal pipe, and burner maintenance compared to bituminous (hard) coals. Conversely, a reduction in coal moisture through thermal drying improves boiler and unit efficiency, plant operation, and economics while reducing CO_2 and criteria emissions.

METHODOLOGY

3.1 Introduction

SPSS (Statistical Package for the Social Sciences) package was used for the statistical data analysis of the research. Unknown parameters were identified by using regression method. At step one quadratic regression and step two multiple regression were done.

3.1.1 Regression

In statistics, regression analysis is a process for estimating the relationships among variables. It includes many techniques for modeling and analyzing several variables, when the focus is on the relationship between a dependent variable and one or more independent variables. More specifically, regression analysis helps to understand how the typical value of the dependent variable (or 'criterion variable') changes when any one of the independent variables is varied, while the other independent variables are held fixed. Most commonly regression analysis estimates the conditional expectation (it is the expected value of one variable given the value(s) of one or more other variables) of the dependent variable given the independent variables – that is, the average value of the dependent variable when the independent variables are fixed. In all cases, the estimation target is a function of the independent variables called the regression function. Regression analysis is widely used for prediction and forecasting.

Regression analysis also can be used to understand which among the independent variables are related to the dependent variable, and to explore the forms of these relationships.

Many techniques for carrying out regression analysis have been developed. Familiar methods such as linear regression and ordinary least squares regression are parametric, in that the regression function is defined in terms of a finite number of unknown parameters that are estimated from the data. Nonparametric regression refers to techniques that allow the regression function to lie in a specified set of functions, which may be infinite-dimensional.

To use regression analysis for prediction, data are collected on the variable that is to be predicted, called the dependent variable or response variable, and on one or more variables whose values are hypothesized to influence it, called independent variables or explanatory variables, in this coefficient of cost function was taken as dependent variable and the parameters selected as independent variables.

A functional form, often linear, is hypothesized for the postulated causal relationship, and the parameters of the function are estimated from the data, that is, are chosen so as to optimize is some way the fit of the function, thus parameterized, to the data. That is the estimation step. For the prediction step, explanatory variable values that are deemed relevant to future (or current but not yet observed) values of the dependent variable are input to the parameterized function to generate predictions for the dependent variable.

3.1.2 Quadratic Regression

A quadratic regression is the process of finding the equation of the parabola that best fits a set of data. As a result, we get an equation of the form:

$$Y = aX^2 + bX + c$$

where a≠0 .

The best way to find this equation manually is by using the least squares method. That is, we need to find the values of a, b, and c such that the squared vertical distance between each point (xi,yi) and the quadratic curve y=ax2+bx+c is minimal. The matrix equation for the quadratic curve is given by:

$$\begin{bmatrix} \sum {x_i}^4 & \sum {x_i}^3 & \sum {x_i}^2 \\ \sum {x_i}^3 & \sum {x_i}^2 & \sum x_i \\ \sum {x_i}^2 & \sum x_i & n \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} \sum {x_i}^2 y_i \\ \sum x_i y_i \\ \sum y_i \end{bmatrix}$$

The relative predictive power of a quadratic model is denoted by R^2 . The value of R^2 varies between 0 and 1. The closer the value is to 1 , when the model is more accurate.

Initially to identify the coefficient of the cost function, quadratic regression was done several times at different defined conditions.

3.1.3 Multiple Regression

There are standard in build functions (which has tested for their reliability) in software solutions such as MS excel, Statistical Package for Social Sciences (SPSS), Matrix Laboratory (MATLAB) to perform multiple liner regression and estimate regression coefficients.

After identifying coefficient by quadratic regression, then the variations of those coefficient with the selected variables variation was identified by using multiple regression.

3.1.3.1 Theoretical equations of multiple linear regression analysis

Simple linear regression is used when there is only one independent parameter. Famous $y_i = mx_i + c$ linear equation can be taken as the basic where m and c need to be found. Here,

$$m = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sum(x_i - \bar{x})^2}$$

$$c = \bar{y} - m\bar{x}$$

When the number of independent variables is more than one, multiple regression analysis needs to be used. The multiple liner regression equation can be written as,

$$y = X\beta + u,$$

Where $y = (y_1 , \ldots , y_n)$ is the data vector consisting of n observations on the response dependent variable, X is an $n \times (p + 1)$ matrix of independent variables, the first of which is a column ones, $\beta = (\beta_0 , \ldots , \beta_p)$ is a $(p + 1) \times 1$ vector of regression parameters, assumed to be nonrandom and $u = (u_1 , \ldots , u_n)$ is an $n \times 1$ vector of random errors. Denote the columns of the X matrix by $x_0 , . . . , x_p$. Each column x_j gives the n values of the j^{th} independent variable, corresponding to the n observations in y.

The coefficient β_j measures the change in the regression function**,**

$E\ [y \mid X] = X\ \beta = \sum_{k=0}^{p} x_k \beta_k$

Which corresponding to a unit change in the j^{th} independent variable, if the model is correct, and all other independent variables are held constant.

To estimate regression coefficient (β) from the observed data (y), 'the least square estimator' can be used. The least square estimator is the value of β* which minimizes the criterion function,

$(y - X\ \beta^*)'(y - X\ \beta^*)$ which has a solution given by $b = (X\ 'X)^{-1} X\ 'y$.

The j^{th} entry b_j is the coefficient of x_j in the fitted model,

$\hat{y} = Xb = \sum_{k=0}^{p} x_k \beta_k$.

Therefore bj can be taken as an estimate of the change in the expected value of the dependent variable y, corresponding to a unit change in the independent variable x_j, if all other independent variables are held fixed, assuming the model is correct [4].

3.1.3.2 Coefficient of correlation (R)

In a process of finding a relationship between one or more independent variables and a dependent variable, a special quantity is taken into consideration which is called as the coefficient of correlation denoted by R. The quantity R measures the strength and the direction of a linear relationship between two variables.

The mathematical formula for computing R for simple linear regression is called Pearson's formula.

$$R = \frac{n\sum xy - (\sum x)(\sum y)}{\sqrt{n(\sum x^2) - (\sum x^2)^2}\sqrt{n(\sum y^2) - (\sum y^2)^2}}$$

x – Data points of independent variable

y – Observation of the response of dependent variable

n – Number of pairs of data

The value of R is such that -1 < R < +1. The + and – signs are used for positive linear correlation and negative linear correlation, respectively.

Positive correlation: If x and y have a strong positive linear correlation, R is close to +1. R value of exactly +1 indicates a perfect positive fit. Positive values indicate a relationship between x and y variables such that as values for x increase, values for y also increases.

Negative correlation: If x and y have a strong negative linear correlation, R is close to -1. An r value of exactly -1 indicates a perfect negative fit. Negative values indicate a relationship between x and y such that as values for x increase, values for y decrease.

No correlation: If there is no linear correlation or a weak linear correlation, r is close to 0. A value near zero means that there is a random, nonlinear relationship between the two variables.

A perfect correlation of ± 1 occurs only when the data points all lie exactly on a straight line. If R = +1, the slope of this line is positive. If R = -1, the slope of this line is negative. R is a dimensionless quantity which means it does not depend on the units employed.

In multiple liner regression analysis R is used to address the correlation of a set of independent parameters to a dependent parameter. A correlation greater than 0.8 is generally described as strong, whereas a correlation less than 0.5 is generally described as weak.

3.1.3.3 Difference between standard and stepwise analysis

In standard multiple regression all independent (predictor) variables are entered into the regression equation at once. It gives an overall R value which presents the strength of the relationship of all independent parameters as a set to the dependent parameter.

Stepwise multiple regressions would focus on finding out what is the best combination of independent (predictor) variables would be to predict the dependent (predicted) variable. In a stepwise regression, independent variables are entered into the regression equation one at a time based upon statistical criteria. At each step in the analysis the independent variable that contributes the most to the prediction equation in terms of increasing the multiple correlation, R, is entered first. This process is continued only if additional variables add anything statistically to the regression equation. When no additional independent variables add anything statistically meaningful to the regression equation, the analysis stops. Thus, not all predictor variables may enter the equation in stepwise regression.

In analyzing the relationship of operating parameters to fuel cost there should be a way to estimates the influence of each parameter to fuel cost and relationship with each other. Because of that step wise analysis was chosen.

3.1.4 Software selection

Regression analysis could be performed from MS excel, SPSS or from MATLAB. Rather than the traditional MS excel and MATLAB, SPSS is far more popular in modern day regression analysis.

SPSS is a software solution provided by International Business Machines (IBM) Corporation which initially called as Predictive Analytic Software (PASW). Since SPSS is specially build for statistical analysis it is highly user friendly than excel in regressions and higher number of tutorials are available and far more user friendly than MATLAB. To perform a regression analysis for large amount of data, excel would take relatively high time than SPSS. Further the number of built in functions are relatively high in SPSS resulting specific algorithm development is not required.

Considering all advantages SPSS version 21 was chosen for the step wise multiple regression analysis.

3.2 Step 1- Identify the Coefficient of Cost Function

$$F = A + BP + CP^2$$

A, B and C are the coefficient. P is the power and F is the cost. For a certain P value, cost can be calculated. For power P_1 estimated cost is F_1.

$$F_1 = A \quad + B \quad P_1 + C \quad {P_1}^2$$

$$F_2 = A \quad + B \quad P_2 + C \quad {P_2}^2$$

$$\cdot \qquad \cdot$$

$$\cdot \qquad \cdot$$

$$F_n = A \quad + B \quad P_n + C \quad {P_n}^2$$

Measurements are taken at constant operating condition. Thirty numbers of data sets were considered and to calculate the cost, price of 1kg of coal is considered as Rs.15.00. Average coal consumption was calculated using the SPSS software. No oil guns were fired during the below selected load conditions.

At load is 170MW, average coal consumption is 65.9454 T/h, so the equation becomes as below. As those load variation was done in same operating condition, assume A, B and C are constant. Hence,

At 170 MW, $65.9454\, x\, 15 = A \quad + B \quad * 170 + C \quad 170^2$

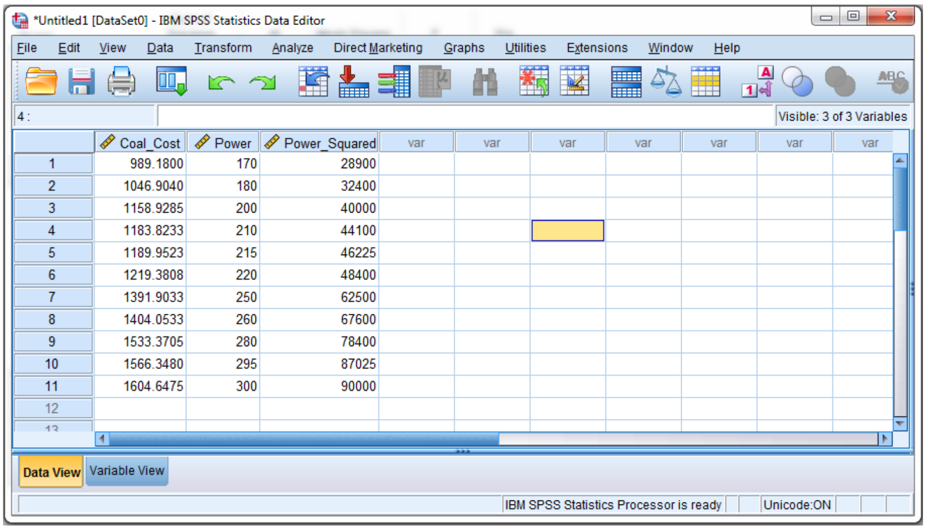
At 180 MW, $69.7936\, x\, 15 = A \quad + B \quad * 180 + C \quad 180^2$

Likewise eleven (11) load conditions were considered at same operating condition. All the calculated values at each load is given below (Table 3.1).

Table 3.1 Cost of coal Vs load at constant load condition

Power(MW)	**Average Coal Cons.(T/h)**	**Cost(Rs. ‘000/h)**
170	65.9454	989.18
180	69.7936	1046.904
200	77.2169	1158.9285
210	78.9216	1183.8233
215	79.3302	1189.9523
220	81.2921	1219.3808
250	92.7936	1391.9033
260	93.6036	1404.0533
280	102.2251	1533.3765
295	104.4232	1566.348
300	106.9765	1604.6475

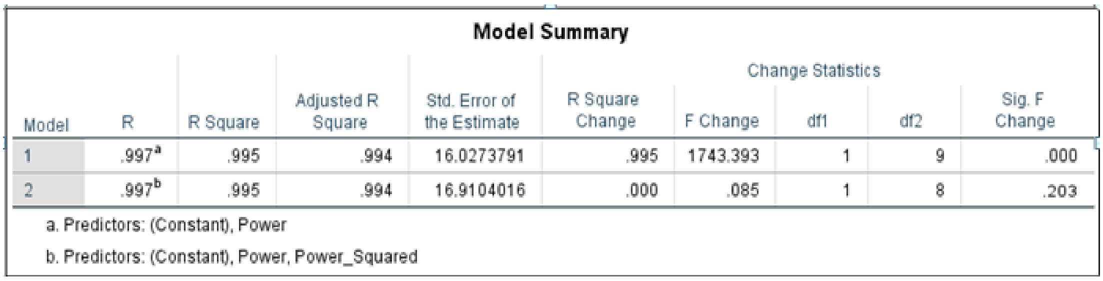
Then by quadratic regression, coefficients A, B and C were calculated.



	Coal_Cost	Power	Power_Squared	var	var	var	var	var	var	var
1	989.1800	170	28900							
2	1046.9040	180	32400							
3	1158.9285	200	40000							
4	1183.8233	210	44100							
5	1189.9523	215	46225							
6	1219.3808	220	48400							
7	1391.9033	250	62500							
8	1404.0533	260	67600							
9	1533.3705	280	78400							
10	1566.3480	295	87025							
11	1604.6475	300	90000							
12										

Figure 3.1 Finding Coefficients by quadratic regression

SPSS results, Model summary, Coefficient and Anova table given below Figure 3.2, Figure 3.3 and Figure 3.4 respectively.



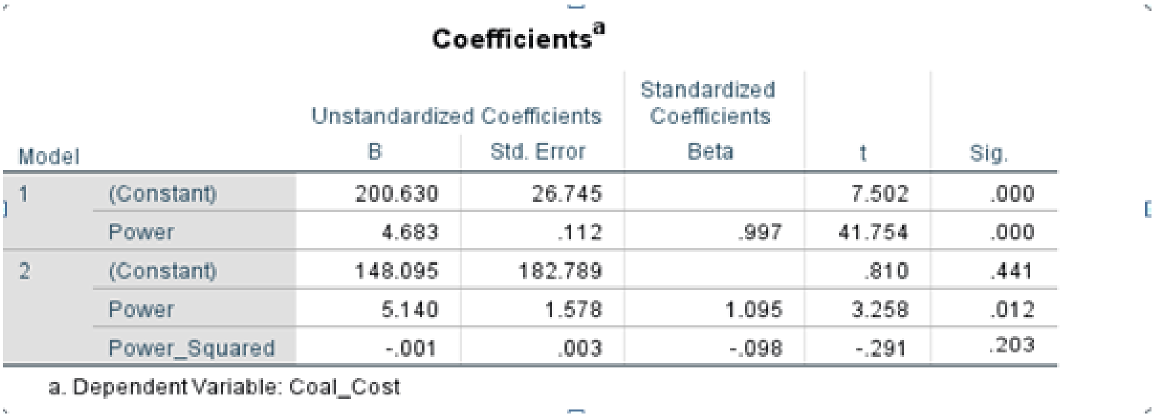
Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	.997[a]	.995	.994	16.0273791	.995	1743.393	1	9	.000
2	.997[b]	.995	.994	16.9104016	.000	.085	1	8	.203

a. Predictors: (Constant), Power

b. Predictors: (Constant), Power, Power_Squared

Figure 3.2 Summary

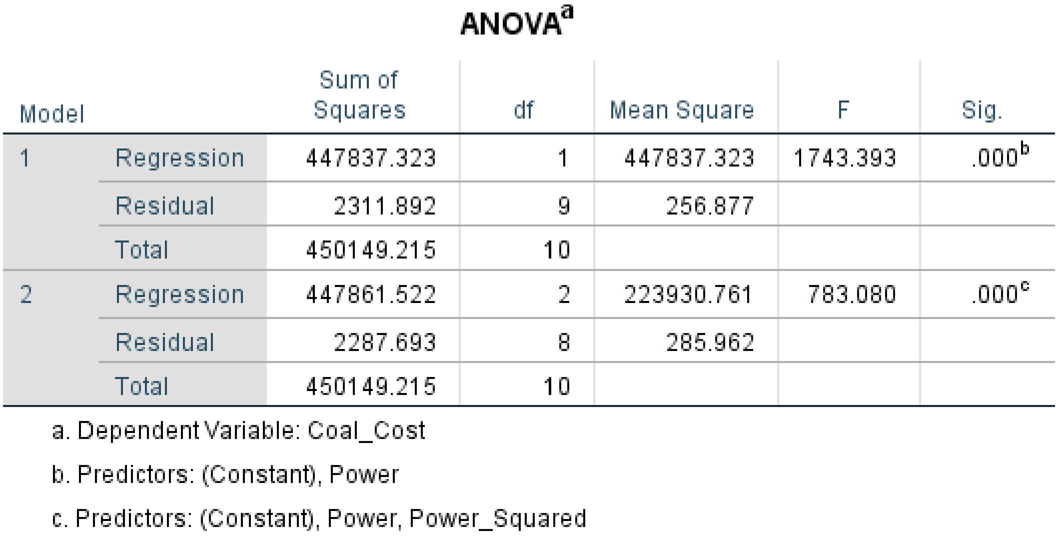


Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	200.630	26.745		7.502	.000
	Power	4.683	.112	.997	41.754	.000
2	(Constant)	148.095	182.789		.810	.441
	Power	5.140	1.578	1.095	3.258	.012
	Power_Squared	-.001	.003	-.098	-.291	.203

a. Dependent Variable: Coal_Cost

Figure 3.3 Cofficients



ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	447837.323	1	447837.323	1743.393	.000[b]
	Residual	2311.892	9	256.877		
	Total	450149.215	10			
2	Regression	447861.522	2	223930.761	783.080	.000[c]
	Residual	2287.693	8	285.962		
	Total	450149.215	10			

a. Dependent Variable: Coal_Cost

b. Predictors: (Constant), Power

c. Predictors: (Constant), Power, Power_Squared

Figure 3.4 Anova table of the result

Final results

A = 148.095

B = 5.14

C = -0.001

Hence, cost function at given condition is

$$F = 148.095 + 5.14P \; - \; 0.001P^2$$

Value of A, B and C for other different operating conditions will be discussed in next chapter. This is very important parameter in economic dispatch model. This gives an idea how the load and the related cost is varying.

Same way again the programme was executed to find more different value for coefficient A, B and C for more different operating condition. Details of the operating conditions will be discussed in next chapter. Final results were shown in below table 3.2. the methodology is same as above calculation.

Table 3.2 Coefficient for different conditions

	A Coefficient	**B Coefficient**	**C Coefficient**
Condition 1	148.10	5.140	-.0010
Condition 2	162.18	5.047	-.0010
Condition 3	206.38	4.718	-.0001
Condition 4	250.01	4.287	.0010
Condition 5	308.35	4.074	.0010

3.3 Main Factors

Actually above A, B and C are not constant, for the further analysis five variables are selected and identify the correlation to the dependent variable. They are,

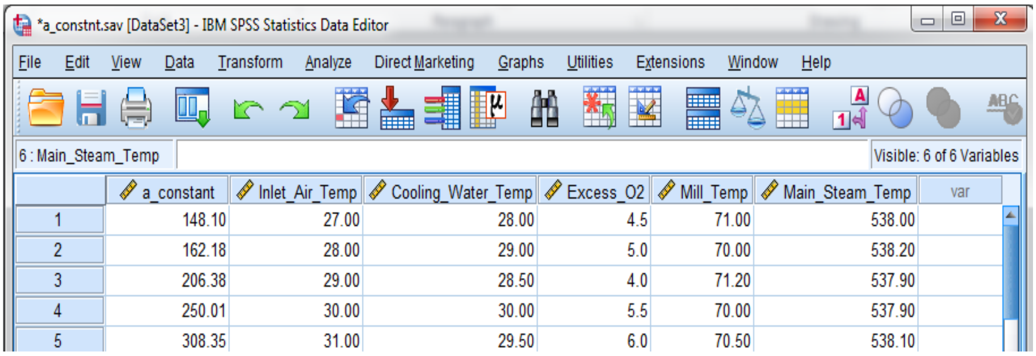
- Inlet air temperature
- Cooling water temperature
- Excess Oxygen content
- Coal mill temperature
- Main Steam Temperature

Again run the SPSS programme to identify the correlation to the coefficient ‘A’. Main reason for selecting only five parameters is, they are the only variables have more significant variation with time and time limitation of the research period. These factors have significant impact on plant efficiency according to the past studies.

Some variable (temperature) values, it is not possible to get an exact value. For those variables ranges are defined. Mean value of the range is taken for the calculation. So when temperature value is given, it denotes a range. This is applicable to above all variables

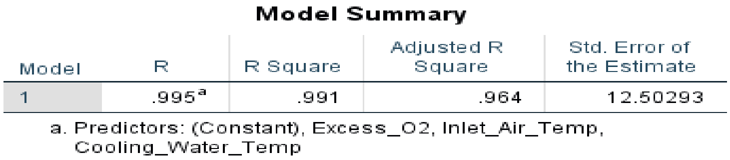
- Inlet air temperature(mean) ± 0.5°C
- Cooling water temperature(mean) ± 0.25°C
- Excess Oxygen content(mean) ± 0.25%
- Coal mill temperature(mean) ± 0.25°C
- Main Steam Temperature(mean) ± 0.05°C

Data entry sheet to find correlation among those variables is given in figure 3.5



	a_constant	Inlet_Air_Temp	Cooling_Water_Temp	Excess_O2	Mill_Temp	Main_Steam_Temp	var
1	148.10	27.00	28.00	4.5	71.00	538.00	
2	162.18	28.00	29.00	5.0	70.00	538.20	
3	206.38	29.00	28.50	4.0	71.20	537.90	
4	250.01	30.00	30.00	5.5	70.00	537.90	
5	308.35	31.00	29.50	6.0	70.50	538.10	

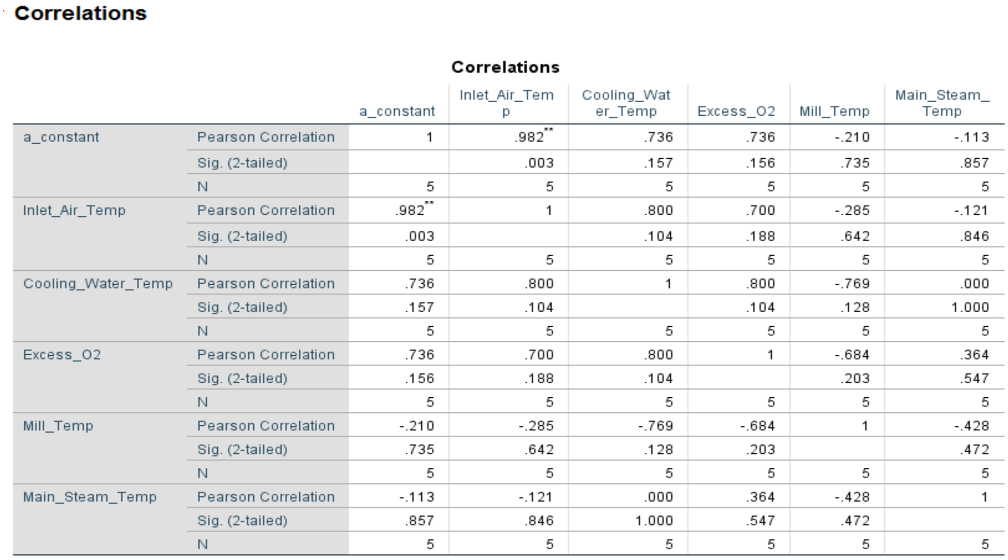
Figure 3.5 Data entry to identify the correlation



Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.995^a	.991	.964	12.50293

a. Predictors: (Constant), Excess_O2, Inlet_Air_Temp, Cooling_Water_Temp



Correlations

Correlations

		a_constant	Inlet_Air_Temp	Cooling_Water_Temp	Excess_O2	Mill_Temp	Main_Steam_Temp
a_constant	Pearson Correlation	1	.982**	.736	.736	-.210	-.113
	Sig. (2-tailed)		.003	.157	.156	.735	.857
	N	5	5	5	5	5	5
Inlet_Air_Temp	Pearson Correlation	.982**	1	.800	.700	-.285	-.121
	Sig. (2-tailed)	.003		.104	.188	.642	.846
	N	5	5	5	5	5	5
Cooling_Water_Temp	Pearson Correlation	.736	.800	1	.800	-.769	.000
	Sig. (2-tailed)	.157	.104		.104	.128	1.000
	N	5	5	5	5	5	5
Excess_O2	Pearson Correlation	.736	.700	.800	1	-.684	.364
	Sig. (2-tailed)	.156	.188	.104		.203	.547
	N	5	5	5	5	5	5
Mill_Temp	Pearson Correlation	-.210	-.285	-.769	-.684	1	-.428
	Sig. (2-tailed)	.735	.642	.128	.203		.472
	N	5	5	5	5	5	5
Main_Steam_Temp	Pearson Correlation	-.113	-.121	.000	.364	-.428	1
	Sig. (2-tailed)	.857	.846	1.000	.547	.472	
	N	5	5	5	5	5	5

Figure 3.6 Correlation table

According to the correlation table correlation between A coefficient and other selected variable is given in below table 3.3.

Table 3.3 Correlation summary

Variable	**Pearson Correlation**
Inlet air temperature	0.982
Cooling water temperature	0.736
Excess Oxygen content	0.736
Coal mill temperature	-0.210
Main Steam Temperature	-0.113

It seems that Inlet air temperature, cooling water temperature and Excess oxygen content has more significant impact on cost function coefficient.

When going to the depth of the research, three most significant variables were selected and identified the relationship between them and coefficients A, B, and C. More variables can be taken into consideration in future studies.

RESULTS AND VERIFICATION

4.1 Defining Data Set

In the previous chapter, first step of the calculation was performed. Five conditions were introduced to get the correlation among the variables. So the selected five conditions based on the variation of the selected parameters are given in the table 4.1 below.

Table 4.1 Selected parameter ranges

	Inlet Air Temp. (°C)	**Cooling water Temp(°C)**	**Excess O2(%)**
Condition 1	27	28	4.5
Condition 2	28	29	5.0
Condition 3	29	28.5	4.0
Condition 4	30	30	5.5
Condition 5	31	29.5	6.0

4.2 Step 2 – Identify the Variation of Coefficients

For an example condition 1 is described as inlet air temperature 27°C, cooling water temperature 28°C and Excess oxygen content 4.5%. Allowable variation of above parameters defined in chapter 3 is considered. By using quadratic regression coefficient A, B and C of cost function was calculated (chapter 3).

$$F = 148.095 + 5.14P - 0.001P^2$$

Likewise same calculation was done for all five conditions and got five sets of A, B, C values. Then the cost functions came down as,

$$F = 162.18 + 5.047P - .0010P^2$$

$$F = 206.38 + 4.718\text{P} - .0001P^2$$

$$F = 250.01 + 4.287\text{P} + .0010P^2$$

$$F = 308.35 + 4.074P + .0010P^2$$

Summarized output is given in the below table 4.2.

Table 4.2 Values of coefficient for each condition

	A Coefficient	**B Coefficient**	**C Coefficient**
Condition 1	148.10	5.140	-.0010
Condition 2	162.18	5.047	-.0010
Condition 3	206.38	4.718	-.0001
Condition 4	250.01	4.287	.0010
Condition 5	308.35	4.074	.0010

It is very clear that there coefficient of cost function are not constants, they are varying when the conditions are changing. So for each coefficient can be denoted by following linear equations,

$$\text{A} = \text{D} + \alpha T_I + \beta T_C + \gamma E$$

Where,

α, β, γ are constants and Inlet air temperature(T_I), Cooling water temperature (T_C), and Economizer O2 content (E) . Same manner coefficient B and C also can be denoted by,

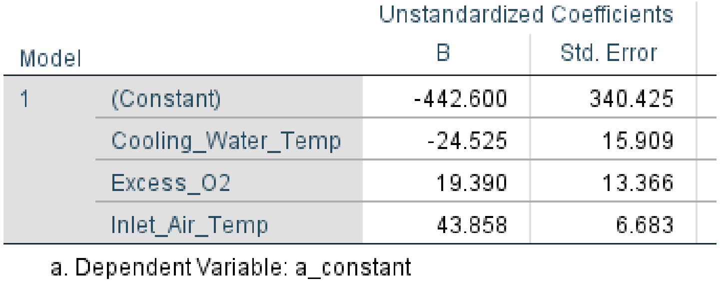
$$\text{B} = \text{E} + \varepsilon T_I + \eta T_C + \tau E$$

$$\text{C} = \text{F} + \varphi T_I + \upsilon T_C + \theta E$$

Where ε, η, τ, φ, υ and θ are constants..

The main reason for selecting only three parameters is, high correlation value from the correlation analysis.

Results for constants α, β, γ, ε, η, τ, φ, υ and θ were obtained by multiple regressions using SPSS. For coefficient A following result was obtained (Figure 4.1).



Model		Unstandardized Coefficients B	Std. Error
1	(Constant)	-442.600	340.425
	Cooling_Water_Temp	-24.525	15.909
	Excess_O2	19.390	13.366
	Inlet_Air_Temp	43.858	6.683

a. Dependent Variable: a_constant

Figure 4.1 SPSS output for Coefficient A

Then,

$$A = -442.6+43.858T_I - 24.525T_C +19.39\ E$$

Again run the multiple regression from using SPSS, following results were obtained for coefficient B and C.

$$B = 7.508 - 0.053\ T_I + 0.015\ T_C - 0.277E$$

$$C= - 0.0016 + 0.00001\ T_I + 0.00001\ T_C\ - 0.000015\ E$$

4.3 Verification

4.3.1 Verification of Derived Cost Function

At condition 1, unit is running at 240MW. Actual coal consumption is 88.8 T/h. coal consumption can be calculated from the derived equation,

$F = 148.095 + 5.14 \times 240 \; - \; 0.001 \times 240^2$

= 1324.095

Therefor coal consumption is,

= 1324.095/15

= 88.273 T/h

Deviation,

= 88.808-88.273

$$\% \; error = \frac{88.808 - 88.273}{88.808} \times 100\%$$

= 0.602 %

The change is very insignificant. It seems that the derived cost function has a meaning.

4.3.2 Verification of Coefficients Variation

Coefficient B has the major influence on cost function. Following calculation prove that.

Eg. At 300MW, Cost function as follows.

$$F = 148.095 + 5.14P \; - \; 0.001P^2$$

$$1{,}604.64 = 148.095 + 5.14 \; x \; 300 \; - \; 0.001 \; x \; 300^2$$

$=$ (148.095-90) + 1542

=58+1542 Million Rupees

So it is very clear that contribution of coefficient B of cost function has considerable influence on cost function. So the function for the coefficient B is considered.

B = 7.508 - 0.053 T_I + 0.015 T_C - 0.277E

4.3.2.1 Case 01

When Inlet air temperature increases, boiler need less energy to increase the temperature of entered gas rather than high temperature air inlet. So improves the boiler efficiency, hence coal consumption will be reduced.

From the equation for coefficient B and cost function

$F = \mathrm{A} + \mathrm{B}P + \mathrm{C}P^2$

B = 7.508 - 0.053 T_I + 0.015 T_C - 0.277E

When T_I increases, B decreases. So cost decreases. So it implies that function of coefficient B is satisfied the real condition.

4.3.2.2 Case 02

When cooling water temperature increases, it reduces the heat absorption from the condenser. Hence condenser vacuum reduces. So turbine efficiency will be reduced. This causes to increase the coal consumption. From the cost function and function of coefficient B, it is very clear that when T_C increases, B increases. Finally this causes to increase cost (F). For this condition is also satisfied by the equation.

4.3.2.3 Case 03

When excess oxygen content increases by increasing air flow, it helps to have full combustion in the boiler. So it helps to boiler efficiency. If excess oxygen content is low, it is not possible to ensure proper combustion, hence reduce the boiler efficiency. So this relationship also nicely interpreted by derived solution.

Finally cost function becomes

$$\boldsymbol{F} = (-442.6 + 43.858\boldsymbol{T_I} - 24.525\boldsymbol{T_C} + 19.39\,\boldsymbol{E}) + (7.508 \\ - 0.053\,\boldsymbol{T_I} + 0.015\,\boldsymbol{T_C} - 0.277\boldsymbol{E})\boldsymbol{P} + (-\,0.0016 + 0.00001\,\boldsymbol{T_I} \\ + 0.00001\,\boldsymbol{T_C} - 0.000015\,\boldsymbol{E})\boldsymbol{P^2}$$

Where,

$25°C < T_I < 35°C$

$25°C < T_C < 35°C$

$0<E$

Final solution verification, actual operating conditions on 15th January 2017 at LVPS,

T_I - 28.5°C, T_C - 26.5°C E - 5.5%, P=300MW, F= 110.2 T/h

From above derived cost function,

F = 264.08 + 1461.45 -101.925

=1623.606/15

=108.24 T/h

$$\%\ error = \frac{108.24 - 110.2}{110.2} \times 100\%$$

= -1.77%

Chapter 5

CONCLUSION AND RECOMMENDATIONS

Developed relationship can be used for the predictions of the plant efficiency and take the required measurement to enhance the plant performance. It is very easy to understand the influencing capability of different parameters to the plant efficiency. Final solution is given below,

$$\boldsymbol{F} = (-442.6 + 43.858\boldsymbol{T_I} - 24.525\boldsymbol{T_C} + 19.39\,\boldsymbol{E}) + (12.508 - 0.053\,\boldsymbol{T_I} + 0.015\,\boldsymbol{T_C} - 0.277\boldsymbol{E})\boldsymbol{P} + (-\,0.022 + 0.00001\,\boldsymbol{T_I} + 0.00001\,\boldsymbol{T_C} - 0.001\,\boldsymbol{E})\boldsymbol{P^2}$$

Where,

T_I - Inlet air temperature (°C)

T_C - Cooling water temperature (°C)

E - Economizer O2 content (%)

P – Power output (MW)

Model can be recommended for Ceylon Electricity Board, System Control Centre to use for efficiency improvement measures of Lakvijaya Power Station and improve the understanding. This relationship provides good information for decision making based on plant efficiency.

When the unit is running at full load (300MW), it consumes average of 110 Tons of coal per hour. According to the given relationship, if one unit can reduce the coal consumption by one ton per hour, it saves million to the CEB and country. This is main target of this research.

This model will be the small but first step of analyzing the cost function of LVPS. Recommend for further work/follow-up research, which can be identified more parameters.

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