MULTI-OBJECTIVE OPTIMIZATION OF A SUPERCRITICAL COAL FIRED POWER PLANT USING 5-E (ENERGY, EXERGY, ECONOMIC, EXERGOECONOMIC AND ENVIRONMENTAL) ANALYSIS IN INDIA

A Thesis

Submitted in partial fulfillment of the requirements for the award of the degree of

DOCTOR OF PHILOSOPHY

in

(MECHANICAL ENGINEERING)

By

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Co-Supervised by **Dr. Ravindra D. Jilte**

Transforming Education Transforming India

LOVELY PROFESSIONAL UNIVERSITY

PUNJAB

2021

2021 March

CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in this thesis, entitled " **Multi-Objective Optimization of a Supercritical Coal Fired Power Plant using 5-E (Energy, Exergy, Economic, Exergoeconomic and Environmental) Analysis in India**" for the fulfillment of the requirements for the award of the Degree of Doctor of Philosophy and submitted in the Department of Mechanical Engineering of Lovely Professional University, Punjab, India is an authentic record of my own work carried out under the supervision of Dr. Ravinder Kumar, Associate Professor, Department of Mechanical Engineering, Lovely Professional University, Punjab, India and Dr. Ravindra Jilte , Department of Mechanical Engineering, Lovely Professional University, Punjab, India. The thesis is an original piece of research work and embodies the findings made by me.

The matter presented in this thesis has not been submitted in part or in full for the award of any other degree/diploma of this or any other University/Institute.

Date: 15/03/2021

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CERTIFICATE

This is to certify that the thesis entitled "**Multi-Objective Optimization of a Supercritical Coal Fired Power Plant using 5-E (Energy, Exergy, Economic, Exergoeconomic and Environmental) Analysis in India**", being submitted by Mr.Keval Chandrakant Nikam (Reg. No. 41700270) to the Department of Mechanical, Lovely Professional University, Punjab, India for the award of Degree of 'Doctor of Philosophy' in Mechanical Engineering, is a bonafide research work carried out by him under my supervision and guidance. His thesis has reached the standard of fulfilling the requirements of regulations relating to degree.

The results presented have not been submitted in part or in full to any other University/Institute for the award of any other degree or diploma.

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ABSTRACT

Energy consumption in India is increasing drastically due to the increase in its population every year. In this severe condition, it is highly desirable to focus on the performance of existing and upcoming power plants in India using thermal performance analysis of each plant. The subcritical power plants are going to be replaced by supercritical power plants (SUPP) in the present scenario in the country. The present research deals with the thermal performance analysis of a 660MW coal-fired SUPP situated in western India. The thermodynamic modeling with empirical relation of each of its components is done and executed in MATLAB programming interface. The pure sliding pressure with variation in plant load is taken for constructing the semi-empirical model. The properties of steam are considered as per the IAPWS IF-97 standard. The results obtained from the semi-empirical model are validated with actual operational data of the plant. The amount of coal consumption rate, steam mass flow rate, plant overall energy efficiency with variation in plant load is analyzed and compared with the operational data. The output obtained from the simulated program was found to be satisfactory by comparing it with the actual operational plant data under study. The condenser rejects 36.42% of total heat to cooling water. The predicted steam generator efficiency of 86.04% is validated with actual steam generator efficiency. The energy demand is increasing exponentially day by day. It has become compulsory to upgrade the thermal equipment to reduce energy losses in quality terms. Most of the existing power plants have been designed according to Energy analysis, where the quality of energy was neglected. Second law thermodynamic focused on the quality of energy, which leads to exergy analysis. The present study deals with exergy analysis of 660MW coal-fired power plant using excel spreadsheet approach. The XSteam solver plug-in is utilized in excel to evaluate the specific enthalpy, specific entropy at various locations. The study also provides the formulation to find the exergetic efficiency of components involved in the plant. Overall second law efficiency of the plant has been evaluated as 35.28%. Condenser contributes to low exergetic efficiency of 34.91%. The validation of the excel sheet model approach is done with the available literature. The study reveals that the excel sheet approach is a highly accurate and less time-consuming method to evaluate

exergy at different points in the system. This study will also help the researcher to develop such a simplified strategy in other thermal sectors. The results of such exergy analysis have direct implications over application decisions. Hence it is necessary to identify low exergetic efficiency components of the newly installed plant. The exergetic efficiency of each component is determined by dividing streams into fuel and product approach. In this study, preliminary exergy analysis is performed using an excel sheet approach to evaluate the exergetic efficiency of various components such as turbines, condenser, heaters, deaerator, and boiler.

The study also covers the economic and exergoeconomic analysis of the 660MW coal-fired supercritical unit. The economic analysis is carried out using the present worth method. The lifetime cost in terms of fuel, maintenance, insurance, labor, pumping, revenue generated, operating expenses, total capital investment, and net present value is studied varying plant life, plant load, and interest rate. In addition to economic analysis, exergoeconomic analysis is performed with specific exergy costing method. The payback period for the supercritical power plant is evaluated to 4.5 years for a 9% of interest rate and plant life of 30 years. The relative cost difference and exergoeconomic factor are studied for various components available at the plant. This study reveals that the steam generator exhibits maximum exergy destruction rate and capital cost. The present study also investigates the capital cost of the turbine can be reduced in the expense of exergetic efficiency. The exergoeconomic analysis reveals that performance of high-pressure heater 1 can be improved by reducing a significant decrease in exergy destruction rate. The components with work as input parameters show higher relative cost difference. The analysis is performed using the MATLAB programming environment.

This work also presents the exergy and exergoenvironmental analysis of the 660 MW supercritical coal-fired unit situated in western India. The study is based upon the SPECO approach, which is followed in the case of exergoeconomic analysis. The proposed research includes evaluating values of exergy of each stream, using F and P principal to find out exergy of fuel, each component's product, and its exegetic efficiency. It further includes, allocation of Eco-indicator 99 assessment grading values to perform a life cycle assessment of each component, solving simultaneous equations by suitable solver formed from the environmental impact of components to calculate the exergo-environmental factor of each stream. The exergy efficiency obtained for the supercritical unit is 35.54%. The effect of variation of exergetic efficiency with an inlet pressure of high-pressure turbine for major components is studied. An increase of environmental impact in the exergy flows has been identified for components with having heat, work, or fuel at the inlet. The cooling water used in condenser and flues gases exhausted from the supercritical power plant represents the environmental impact rate per unit electricity generated of 2.89 and 3.689mPtskWh^{-1}. The electricity generated had an environmental impact rate of 39.71mPtskWh^{-1}. The environmental impact per unit of electricity generated for the 660 MW supercritical power plant is evaluated as 46.29mPtskWh^{-1}.The exergo-environmental variable for the steam generator offers a high potential to reduce environmental impact by introducing an exhaust gas treatment unit.

The newly set up power plant have been committed to fulfil the power supply-demand of the world. It becomes necessary to optimize operating variables within constraints of varying power demand. The present study covers the multi-objective optimization of a 660MW capacity coal-fired SUPP. The overall plant efficiency, exergetic efficiency and cost of electricity are been taken as objective functions. The Particle Swarm Optimization (PSO) technique is been employed along with semi-empirical model of energy, exergy and economic analysis of coal-fired SUPP. The varying power outputs, coal calorific value, amount of coal consumption, inlet temperature, and pressure conditions of turbines set are decision variables taken for the study. The maximum value of plant efficiency 41.643% and exergy efficiency 39.8347% with minimum cost of electricity 3.1456Rs/Unit have been evaluated using multi-objective particle swarm optimization. The optimized value of decision variables will reduce the dependency of high-grade coal from energy, exergy and economic point of view is the outcome of the present study. The outcome of the present study will explore the scope for future researchers and engineers.

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NOMENCLATURE

SUPP	Supercritical Power Plant
OTB	Once Through Boiler
BFP	Boiler feed pump
CEP	Condensate Extraction Pump
GCV	Coal gross calorific value (kcal/kg of coal)
HPTr	High-pressure expansion turbine
IPTr	The intermediate pressure expansion turbine
LPTr	Low-pressure expansion turbine
COND	Condenser
HPH	High-pressure feed water heater
HPH_{1i},HPH_{2i},HPH_{3i}	The first set of High-pressure feedwater heaters
HPH_{1ii},HPH_{2ii},HPH_{3ii}	The second set of High-pressure feedwater heaters
LPH	Low-pressure feedwater heater
DR	Deaerator
DC	Drain cooler
TTD	Terminal temperature difference(℃)
ETD	Entry temperature difference(℃)
G	Generator

CEP	Condensate Extraction Pump
BFP	Boiler Feed Pump
PDT	Pump Drive Turbine
RH	Re-heater
LCA	Life Cycle Assessment
SPECO	Specific Exergy Costing
F and P	Fuel and Product
IAPWS	International Association for the Properties of Water and Steam
BOP	Balance of plant
C	Cost
NPV	Net Present Value
PWF	Present Worth Factor
PEC	Purchased Equipment Cost
TSP	Total Suspended Particles
MP	Material Particulate
$\dot{W}_{Pump}$	Power consumed by pumps (kW)
$\dot{W}_{Turbine}$	Turbine work output (kW)
z_j	The fractional mass flow rate of steam at 'j^{th}' state

z_x	The fractional mass flow rate of steam at '*x*' stream
h	Specific Enthalpy(kJ/kg)
$h_{st(j)}$	Specific Enthalpy of superheated steam(kJ/kg)
$h_{l(j)}$	Specific Enthalpy of feedwater at exit (kJ/kg)
$h_{l(j+1)}$	Specific Enthalpy of feedwater at entry (kJ/kg)
$h_{cond(j)}$	Specific Enthalpy of condensate(kJ/kg)
P	Pressure in bar
s	Entropy (kJ / kg K)
Cp_w	Specific capacity of water at constant pressure (kJ / ℃/kg)
W_{revhpt}, W_{revipt}, W_{revlpt}	Work output from High, Intermediate and Low pressure turbine
E_x	Exergy flow of stream(kW)
r_k	Relative cost difference
f_k	Exergoeconomic factor
ξ	Engineering & Plant startup expenses
C_x	Specific cost of Exergy
Z_x	Levelized cost rates
s_g	Specific entropy at dry saturated vapor (kJ kg^{-1} K^{-1})
s_f	Specific entropy at dry saturated fluid (kJ kg^{-1} K^{-1})
h_g	Specific enthalpy at dry saturated vapor(kJ kg^{-1})

h_f	Specific enthalpy at dry saturated fluid (kJ kg^{-1})
h_{sup}	Superheated specific enthalpy (kJ kg^{-1})
h_0,s_0,T_0	Thermodynamic properties at reference state ((kJ kg^{-1}, kJ kg^{-1} K^{-1},K)
B_x	Environmental Impact factor(mPts s^{-1})
r_b	Exergo-environmental variable(%)
fb	Exergo-environmental factor(%)
E*	Exergo-environmental impact of steam(kW)
η_{plant}	Overall plant efficiency (%)
η_{Pump}	Pump efficiency (%)
Ψ	Exergetic Efficiency (%)

CHAPTER 1

1. INTRODUCTION

1.1 Background

This chapter presents an overview of India's present condition of the existing a thermal power plants. The chapter also covers the classification of thermal power plant based upon their capacity and technology. Over the years, engineering systems like coal-fueled thermal power plants have become more complex and highly sophisticated. Heavy finance is involved annually in the operation and maintenance of such complex power production plants at the desired availability level. Performance prediction of such thermal systems is becoming increasingly important because of increasing cost, competition, and public demand in one way, while the risk of failure on the other. The most widely utilized means for generating electricity is coal-fired power plants, where coal is generally used as a common fuel. This generated electricity plays an important role in raising the modern economy for industry, agriculture, transport, and household for any nation. The growing energy demand has increased energy consumption in the entire world. According to the data published by the Central Electricity Authority (CEA, 2018) of India reported that per capita consumption has heightened from 15 kWh in 1950 to about 1,122 kWh in the year 2016. The electrification of Indian Villages has been reached to 99.25% as on 31.03.2017. Efforts are being taken by the government of India to fulfill the needs of the citizen by increasing generation units from about 5.1 Billion units in 1950 to 1,242 Billion units in the year 2016. Coal-fired power plants are ruling over the power sector for past decades and will continue to remain in the top position in India due to its availability of coal. The installed capacity of India till 2017 year was 3,26,833.01MW constitute of 59% of coal-fired power plants as compared to other power sources as shown in the figure.1.1

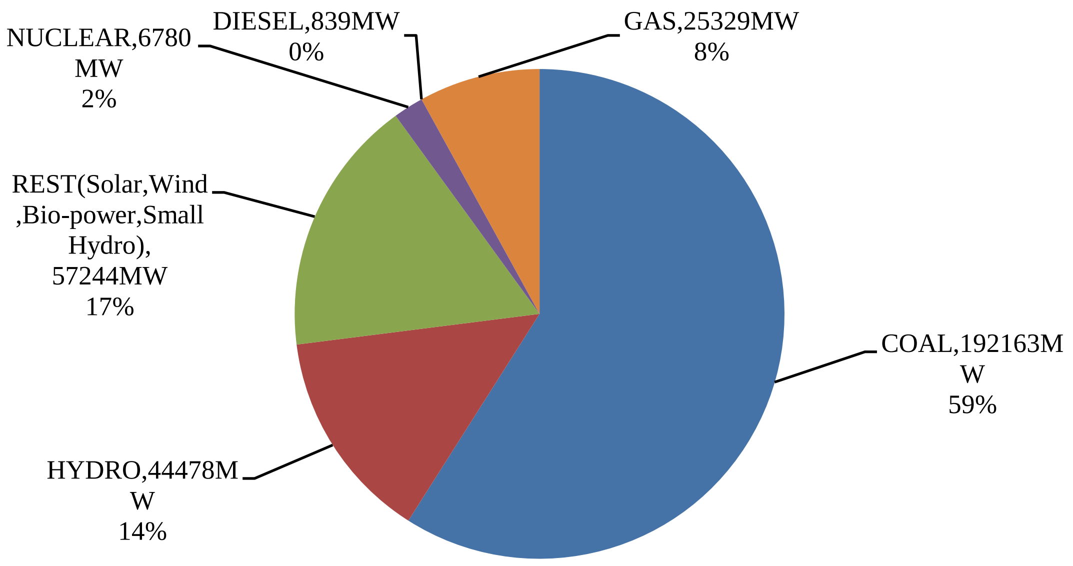


Figure 1.1: All India equipped capacity as of 31-03-2017 (CEA 2018)

To optimized coal usage and hold control on emission from the power sector, India has adopted supercritical technology for its future coal-based power plants. The number of subcritical and supercritical coal-fired power plants in India is shown in figures 1.2-1.3.

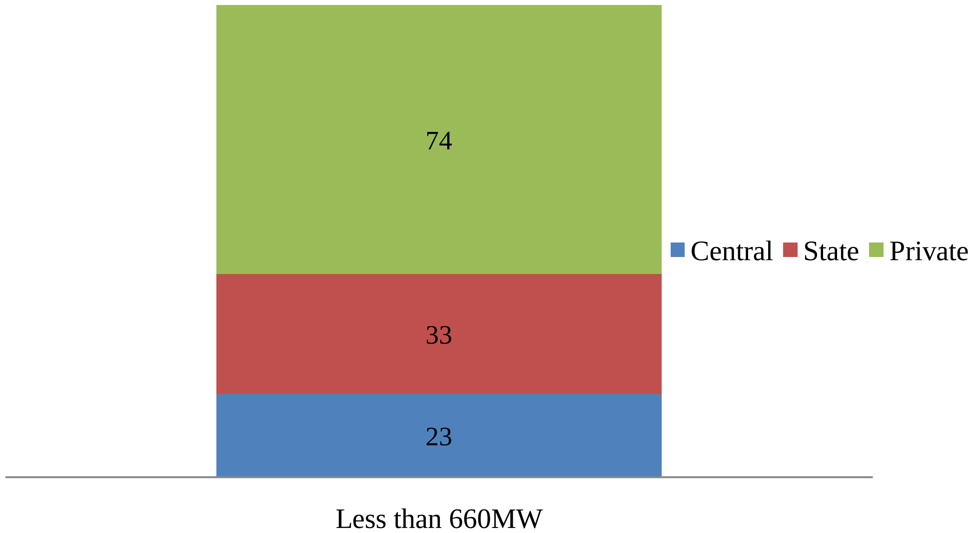


Figure 1.2: Subcritical units in India (CEA 2018)

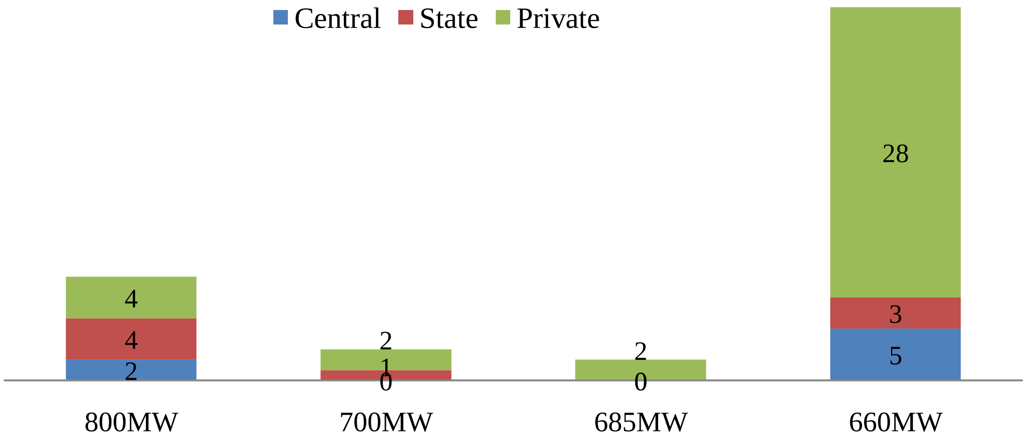


Figure 1.3: Supercritical technology units in India (CEA 2018)

Supercritical units had recently gained popularity in India's power sector. But worldwide researchers and engineers are working on its overall efficiency improvement from last decades using energy, exergy, and economic analysis.

Energy analysis is not able to distinguish energy deterioration in a thermodynamic process and the factors answerable for low plant efficiency. So, exergy analysis is getting its importance. This method helps in designing pact and approach for using energy effectively in functioning plants. Hence, it is a robust tool for the measurement of energy quality, thereby helps to make convoluted thermodynamic systems more efficient. The increasing energy consumption at a rapid rate is the main reason that coal is still one of the main sources of electricity worldwide and cannot be instantaneously replaced by renewable energy sources. The initial capital investment is the deciding factor for the long term feasibility of any power generation system. The various uncertainties of power generation plant related expected returns and cost factors decide whether to invest in the project or think of an alternative generation setup. The increasing supply from end-users leads us to think about the cash flow involved in thermal power systems from site preparation to working final installation. As 70% to 80% cost of the thermal power system setup is involved in plant mechanical equipment, electrical systems, civil work, etc. cost components of each subsystem play a vital role. Because of this, the formulation for cost analysis of thermal power plant, construction of objective function by integrating availability analysis module and thermal analysis module with constraints on redundancies on various components/subsystems had been worked out. The energy consumption per person drastically has increased in the 21st century. Thus, it is necessary to construct a thermodynamic model of a shortly commence thermal power plant. The country has adapted a strategy to build and convert existing power plants into a supercritical power plant (SUPP) of 660MW capacity. The thermodynamic analysis is performed using the thermodynamic first law, where the energy and mass balance formulations are used to tabulate the losses. The limitation of energy analysis is overcome by exergy analysis. This method helps design equipment utilization and strategies for using energy to the maximum extent in newly installed plants. Some previous attempts were made to predict thermodynamic performance in terms of energy and exergy related to a subcritical power plants in India(A. Kumar, K.C. Nikam 2020; Kumar 2017; Kumar, Jilte, Ahmadi, et al. 2019). The ozone layer depletion and increase in temperature of earth had lead technocrats to think about the complex system from environmental impact points of view. Thermal power systems burning fossil fuels are a major source to emit emission of carbon dioxide (CO_2), Carbon monoxide (CO), Nitrogen Oxide (NO_X), Sulfur dioxide (SO_X). These emissions affect human health and natural habitat. Thus many countries are upgrading thermal power generation by keeping coal as a primary fuel and integrating it with carbon capture technology(Ahmadi et al. 2019; Kumar, Jilte, and Nikam 2019). On the other side, the efficiency of the power generation plant is an important factor that can reduce the overall environmental impact. The improvement in the efficiency of power plants leads to a reduction in the consumption of fuel to a great extent and preserves the energy source for future power generation. Many attempts were carried out to increase the efficiency of the power plant. The energy analysis only gives the idea about the quantity of energy, but the exergy analysis has proven to be a better option to monitor the quality of energy produced and the quality of energy loss to the surrounding. The initial capital investment is the deciding factor for the long term feasibility of any thermal power plant. The various uncertainties in the case of thermal power plant-related expected returns and cost factors decide whether to invest in the project or think of alternative generation setup. The increasing supply from end-users leads us to think about cash flow involved in thermal power systems from site preparation to working final installation. As 70% to 80% cost of the thermal power system setup is involved in plant mechanical equipment, electrical systems, civil work etc., cost components of each subsystem plays vital role. Because of this, the formulation for cost analysis of thermal power plant, construction of objective function by integrating availability analysis module and thermal analysis module with constraints on redundancies on various components/subsystems had been worked out. Many researchers had attempted different approaches to reduce the cost function for some crucial areas in the power sector considering the current status of the economics of the country. The effect of coal cost , initial investment on the referenced cost of electricity were analyzed by comparing binary and conventional power generating coal-fired power plant. The previous attempts were carried out to link Exergy and Economics to find cost-effective components from an exergy point of view. This methodology of exergoeconomic was developed based upon specific exergy costing approach known as SPECO (Lazzaretto and Tsatsaronis 2006; Mohammadi et al. 2017). The ozone layer depletion and increase in temperature of earth had lead technocrats to think about the complex system from environmental impact points of view. Thermal power systems burning fossil fuels are a major source to emit emission of carbon dioxide(CO_2), Carbon monoxide(CO), Nitrogen Oxide (NO_X), Sulfur dioxide (SO_X). These emissions affect human health and natural habitat. Because of this, many countries are upgrading thermal power generation by keeping coal as a primary fuel and integrating with carbon capture technology. The exergoenvironmental analysis is performed in the same manner as that of exergoeconomic analysis by allocating cost to the exergy flow of components by the SPECO method

1.2 Motivation to select this research

So far, not much focus has been done on 5-E (energy, exergy, exergoeconomic, economic and environmental) analysis with change of boiler type. Most of research work on coal fired power plant is related to 4E (energy, exergy, exergoeconomic and economic). However, very less attention is provided in the published literature on constructing simulated model for pure sliding pressure with variation in load. The limited literatures are available on effect of variation in calorific value of coal on coal consumption rate, variation in plant load on coal consumption rate with pure sliding pressure.

In this research comparison of 5E analysis of super critical power plant is performed. Simulation model using semi-imperial module with multi objective optimization will be dueled to predict thermodynamic performance and environment analysis of coal fired power plants. This will help out to identify optimum design parameters of plant for further improvement. This research presents a simulation model for a 660 MW supercritical unit using a modern tool package MATLAB with IAPWS IF97 standard formulation.

1.3 Statement of the Problem

In the present study, the semi-empirical model was developed using mass balance and energy balance equations for SUPP. The parameters such as coal consumption rate, boiler efficiency, and steam mass flow rate are evaluated from the semi empirical model. The results of the semi-empirical model are validated with the actual operating parameters. However, very little attention is provided in the published literature on constructing a simulated model for pure sliding pressure with variation in load. The semi-empirical model also revealed the trends of variation in calorific value of coal with coal consumption rate, variation in plant load with coal consumption rate for pure sliding pressure operation. To accomplish the work, the performance analysis of a 660 MW unit is proposed with variation in pressure concerning variation in plant load and validated with the actual operational plant in India. This study presents a simulation model for a 660 MW SUPP using a modern tool package MATLAB with IAPWS IF97 standard formulation. The Sankey diagram has been generated based on the amount of heat involved at various stages of the power plant. However, a detailed thermodynamic analysis of a supercritical power plant (SUPP) is possible under several assumptions. The supercritical power plant runs with uniform pressure and pure sliding pressure due to variation in supply-demand. The thermodynamic performance gets affected due to a change in pressure operation. Most of the available literature on thermodynamics analysis of SUPP was based upon constant pressure operation.

The present study also deals with economic analysis of a supercritical power plant of capacity 660MW in the form of Capital cost, Present worth value, and Net Present value over 30 years of project life. To accomplish the work, equipment cost and other costing data were directly taken from the actual working plant situated in western India. The semi-empirical module of economic analysis was constructed in the MATLAB package. Coal-fueled power generation is the backbone of the Indian power sector and will also continue to leading power generation in the coming years. On the other side, the effective and efficient use of energy can lead the world in sustainable development. This has created an interest in the efficiency enhancement and multi-objective optimization of newly installed power generation system. The present study also focused on identifying the environmental impact of the components of the supercritical power plant. The limited research is available on a semi-empirical model correlated with exergo-environmental analysis of supercritical power plant of capacity 660MW. The present study proposed the semi-empirical model to evaluate the exergy and environmental impact rate of the stream. The possible outcome of the semi-empirical model is to reduce the time for judgment to be taken to run an existing plant from an environmental point of view. In this study, exergo-environmental analysis is performed, and the exergetic efficiency of plant components is also evaluated. The Grassman diagram of components exergy destruction as a percentage of total input exergy has been generated in the present study.

1.4 The Layout of the Thesis

The whole thesis has been divided into five chapters. The organization of each chapter is described as:

Chapter 1: Introduction

This chapter gives the background and statement of the problem.

Chapter 2: Literature Survey

This chapter discusses past work on six broad areas: energy analysis, exergy analysis, economic analysis, exergoeconomic analysis, exergo-environmental analysis, and multi-objective optimization of the coal-fired thermal power plant. Finally, the objectives of the present work are presented.

Chapter 3: Research Methodology

In this chapter, the description of supercritical power plant of capacity 660MW is incorporated. The formulation of individual sub-systems and systems as a whole is carried out on the basis of mass balance, energy balance, exergy balance, economic relations, exergoeconomic balance, and exergoenvironmental balance equations. The relations are tabulated for all sub-systems present in coal-fueled supercritical power plant. This chapter also contains a methodology for multi-objective optimization using particle swarm optimization.

Chapter 4: Result and Discussion

This chapter highlights the results obtained from energy analysis, exergy analysis, economic analysis, exergoeconomic analysis, exergoenvironmental analysis, and multi-objective optimization. The chapter also includes the validation of results with the relevant source and available literature.

Chapter 5: Conclusions and Scope of the Future Work Finally, significant conclusions derived from the present work were discussed. The scope of future work is also discussed in this chapter.

CHAPTER 2

2. LITERATURE SURVEY

In this chapter, the literature review of energy, exergy, economic, exergoeconomic, exergoenvironmental and optimization of coal-fired power plant are performed.

2.1 Energy Analysis

With respect to the analysis of super and ultra-critical power plant, India is much behind in the global scenario. Only a few numbers of researchers in India have done work related to subcritical and supercritical power plants.

(Rosen and Dincer 2003)modified and developed globally accepted relation between thermodynamic losses and capital cost for newly installed coal-fired power plant. The methodology for mass balance equation was discussed in detail along with component significance.

(LV et al. 2011)worked on energy and exergy analysis on 300MW Thermal power plant, which resulted as combustion process and heat transfer between large surfaces leads to most destructive components.

(Adibhatla and Kaushik 2014)carried out energy and exergy calculation considering sliding pressure for various load conditions, which was found to be the better option. The sliding pressure working condition were taken in analysis to obtain maximum overall efficiency.

(Goyal et al. 2014) used of first law efficiency and second law efficiency of thermodynamic to carry out energy and exergy analysis of super thermal power plant in India which resulted in the boiler to be the major contributor of energy loss and condenser to be a significant contributor for exergy destructor.

(Adibhatla and Kaushik 2014) revealed the advantages of pure sliding pressure operation over a boiler feed pump power output in plant operating beyond 221bar pressure. The study compared the constant pressure with pure sliding pressure operation for 660MW SUPP in India.

(R. Kumar, Sharma, and Tewari 2015)investigated the impact of various factors that directly affect a subcritical coal-fired power plant. This analysis predict the values of the parameters in view to get maximum overall efficiency.

(Parsa, Vahidian Kamyad, and Naghibi Sistani 2015)considered boiler as a multi-input and multi-output component in thermal power plant and optimized the combustion efficiency by gaining access control over the amount of excess air supplied during the combustion process. Data mining algorithm was used, making the combustion process more efficient.

(D. P. Hanak et al. 2015) concluded that steam flow rate, coal consumption rate are uncertain parameters while constructing the predicting power plant model. The work also confirmed that regression analysis is suitable for the simulation process.

(Bolatturk, Coskun, and Geredelioglu 2015) planned out an idea about the need for optimum burning of fuel, which could be monitor and figured out during the installation of the project itself.

(Mohammadi et al. 2016) performed energy analysis on combined cycle power plant at different load conditions. It revealed that the temperature of the inlet of the turbine is the deciding parameter for part-load operations.

(S. Chen et al. 2017)studied multiple factor disturbance method by separating pressures and temperatures at different stages in steam power plant and comparing results with single-factor method.

(C. Chen, Zhou, and Bollas 2017)simulated stability and flexibility of regulating control of subcritical coal-fired power plant by varying coal load with 5%, 10%, and 15%. The effect of variation of coal load shows positive increment in the overall efficiency

(Khankari 2017)performed 4 E analyses to improve the overall efficiency of the coal-fired power plant, and results were compared with the combined heat power plant. The CO_2 reduction rate was calculated separately at different loads.

(N. Kumar, Mohanta, and Kispotta 2017)proposed novel method to reduce energy loss from the condenser section using refrigerant instead of water for heat transfer. Some Indian authors also contributed in the direction of using different optimization techniques for energy, exergy analysis.

(Noroozian et al. 2017) proposed improvement in terms of uniform power output was achieved by reducing the usage of water in thermal power plants. The optimal usage of water was established using prediction model.

(Park et al. 2018)investigated the efficiency and cost of electricity of supercritical CO_2 power plant by developing simulation in ASPEN PLUS software and compared the result with the supercritical steam power plant.

(Sun et al. 2018)proposed the new method of using cascade concept for recovery of maximum energy from fuel gas in supercritical CO_2 coal-fired power plant. The cascade concept was proven to be better solution as compare with conventional power system.

(Y. Liu et al. 2018)proposed new modified power plant based on energy analysis in which flue gas was used to heat the partial condensate and air supplied to combustion was preheated by some part of steam which increases the efficiency of overall plant 1.27%.

(J. Xu et al. 2018)analyzed 1000 MW plant and gave useful modifications in the reheating system to reduce pressure drop and increase the overall efficiency of CO_2 supercritical power plant.

(Yongming Zhao et al. 2018)used a unique integration of heat cycle with different compressor used in power plant to increase the overall efficiency. The outlet pressure of compressor was closely monitored for the analysis.

(Y. Liu et al. 2018) modified the path of flue gases to heat condensate, and flow rate of air required for combustion is adjusted with the flow rate of condensate resulted in an increase in the overall efficiency of the ultra supercritical power plant by 1.27%. Authored focused on the utilization of low-grade energy in an efficient way.

(Y. Zhang et al. 2018)proposed three different arrangements between water heating equipment to utilize the maximum fuel gas energy to maximum extent to improve the plant efficiency of the supercritical power plant.

(Yongliang Zhao, Wang, et al. 2018) developed a software-based model of 660MW supercritical power plant to study dynamic flexibility of plant by introducing a number of throttled valves to bypass part of steam, results in an increase in overall efficiency.

(C. Wang et al. 2018)proposed optimum value water fuel ratio for supercritical coal-fired unit. The reduction in coal consumption was observed.

(Y. Liu et al. 2018) proposed improvement in the overall efficiency of modern power plants by the effective use of waste energy through flues gases for the constant load.

(Zhai et al. 2018; Dawid P. Hanak, Biliyok, and Manovic 2015) concluded that an ammonia carbon capture technology system is feasible for 660MW SUPP for constant plant load.

(C. Xu et al. 2018) improved overall efficiency of modern power plants by introducing turbines working on steam bled for constant load. The exergy destruction of heaters was reduced by 20%.

(Tontu, Sahin, and Bilgili 2019a)confirmed 0.78% increment in overall efficiency by the inclusion of multigenerational system to 660MW SUPP for uniform plant load.

(Tontu, Sahin, and Bilgili 2019b)compared modern coal-fired power plant with the conventional plant on the basis of energy and exergy analysis. The results were computed for constant load, and the first law efficiency was evaluated for constant load condition.

(R. Kumar, Jilte, et al. 2019; R. Kumar 2016)built semi-empirical model with pressure variation for change in the plant load for subcritical power plant. A similar kind of approach was seen in the case of 210MW and 250MW capacity subcritical power plant in India to evaluate coal consumption rate, steam mass flow rate and overall plant efficiency with various load conditions.

(Dawid P. Hanak, Biliyok, and Manovic 2016; X. Zhang and Song 2019)concluded that the heat integration, along with calcium looping technology, could reduce the power required for carbon capture technology without affecting the overall efficiency of the plant. The simulation was performed considering constant plant load.

(Surywanshi et al. 2020) claimed that a chemical looping combustion system with metal oxide is a feasible technology for carbon capture. The technical parameters such as varying pressure and temperature were studied to find the exergy at various point in power plant.

(Zhang, 2020) reviewed for energy requirement for carbon capture storage and utilization technology.

(Surywanshi et al. 2020) concluded that SUPP and ultra SUPP systems are the most feasible system than the convention power plant at constant plant load. It is observed that due to unavoidable reasons thermal power plant has to run under different load conditions.

2.2 Exergy Analysis

(Esen et al. 2007) studied variation in temperature of ambient on exergetic efficiency of the heat-exchanger. The exergy rate at various stream was calculated considering standard temperature and pressure condition.

(Nozdrenko et al. 2009)compared the results of exergetic efficiency, cost of the existing boiler with high-pressure boiler and found an optimal initial solution for the condition of vapor in structure as overall efficiency is a concern.

(Ozdemir, Hepbasli, and Eskin 2010)determined the energy and exergy cost of fluidized bed combustion by calculating the efficiency of different components. Cash flow equations were constructed based on it.

(Regulagadda, Dincer, and Naterer 2010) performed exergy analysis and found boiler as the most destructive component in subcritical power plant by performing exergy analysis and environmental impact.

(Hasti, Aroonwilas, and Veawab 2013)proposed a computer-based model to study exergy destruction at various components available in an ultra supercritical the power plant.

(Ege and Şahin 2014)studied uncertainties in energy and exergy of power plant by considering fuel input and demand characteristics change in Microsoft excel.

(Siva Reddy, Kaushik, and Tyagi 2014) investigated energetic power loss in the condenser and exergetic power loss in the boiler of coal-fueled and gas-fueled power plant.

(Ameri, Mokhtari, and Bahrami 2016)stated that exergy analysis helps in finding the losses taking place in a supercritical power plant and identified the different parameters to be studied under multi-objective optimization. Amount of air, pressure on high sides were considered as optimized components.

(Ege and Şahin 2016)studied uncertainties in constant entropy process and exergetic efficiency in high-pressure turbine power plant result that dependency of uncertainty parameters are more rely on the pressure as compared to temperature.

(Ege and Şahin 2016) studied uncertainties in constant entropy process and exergetic efficiency in high-pressure turbine power plant result that dependency of uncertainty parameters are more rely on the pressure as compared to temperature.

(Murav'ev, Kochetkov, and Glazova 2016; Dincer and Rosen 2013) had used the excel sheet approach as a tool for exergy analysis of various components present in the steam power plant

(Adibhatla and Kaushik 2017)performed exergy analysis on sub-critical thermal power plant assisted with solar aided feed water heating unit found to a better option than the installed plant.

(Si et al. 2017)performed exergy analysis to study the effect on the efficiency due to steam exhaust pressure, temperature, and pressure of incoming water, variable load.

(Zhou et al. 2018)identified exergy destruction components, namely water wall, screen heater, primary heater, which are different components than a conventional power plant.

(Ghaebi et al. 2018) performed 4E analyses were done using the city gas station to ensure the vapor generator as key parameters the responsible components for the exergy destructor. The unit cost and CO_2 emission cost were estimated involved in the production plant of hydrogen.

(Nikam, Kumar, and Jilte 2020b) implied how nearly the systems operation approaches the ideal conditions. The solver of XSteam was used to evaluate the properties of the steam at different points.

(Nikam, Kumar, and Jilte 2020a)perfomed exergy analysis has direct implication over application decision. Hence it is necessary to identify low exergetic efficiency components of the newly installed plant. The previous attempt was made to build a model using MATLAB Packages, which has the limitation of programming skills.

(Qureshy and Dincer 2020) performed exergy analysis to reveals the performance of integrated energy sources constructed using solar collectors and solar receivers. The proposed system reduces dependency on fossil fuel with exergetic efficiency of 31.01% in the hydrogen production plant.

(Yang et al. 2020) implemented exergy analysis to improvise the existing power generation cycle. The effect of reducing temperature of bled steam shows increment in exergetic efficiency.

(Bamisile, Huang, Li, et al. 2020) performed exergy analysis for different combinations of the conventional renewable energy generation systems. It reveals the exergetic efficiency of the components, which affects the plant environmental impact.

(Zueco et al. 2020) evaluated exergy rate and losses at the different sections of the stream was represented by the Grassman diagram. The Grassman diagram was constructed to indicate the exegetic efficiency of the steam power plant along with losses that occurs in the combustion process.

2.3 Economic Analysis

(Bekdemir, Öztürk, and Yumurtac 2003) attempted different approaches to reduce the cost function for some crucial areas in the power sector, considering the current status of the economics of the country. The study also covers optimized condenser design parameters by taking into account condenser cost, energy generation cost and developed numerical approach in Fluent code.

(Anozie and Odejobi 2011)studied the effect of the condenser water flow rate unit is responsible for the change is overall efficiency and cost of the plant to a large extent.

(L. Wang et al. 2014)compared the existing supercritical plant with economically design plant which suggested that electricity cost can be lowered by 2% to 4% by considering temperature at various stages. In comparison, efficiency can be increased by 2%.

(Manesh et al. 2014) modified and developed a globally accepted relation between thermodynamic losses and capital cost for newly installed coal-fired power plant.

(R. Kumar, Sharma, and Tewari 2014) performed cost-effective analysis is the other key factor in the installation of coal-fired power plants. The investigation on the impact of various factors that directly affect a subcritical coal-fired power plant was performed

(Ameri, Mokhtari, and Mostafavi Sani 2018; Mohammadi et al. 2016) evaluated the price of electricity generated from the combined cycle power plant was taken into account as an objective function to carry out an economic analysis of the power generating plant.

(Uysal, Kurt, and Kwak 2017)discussed various thermoeconomic analysis from which modified productive structure and specific exergy costing were considered for exergetic and thermo-economic along with the cost of electricity prediction.

(Lara et al. 2017)analyzed the effect of three pressure levels on combined power plant as per process, economic and ecology is concerned. The decrease in the cost is the outcome of using three pressure levels.

(R. Kumar 2017) reviewed 4- E analysis of various fueled power plants. The author compared various fueled operating power plant on account of the exergy and energy.

(M. Liu et al. 2018)reduced the exergy destruction by implementing the low-pressure economizer concept in supercritical CO_2 power plant and optimized thermodynamically by using optimization techniques. From the economic point of view, low-pressure economizer was found to be a better option for heat recovery.

(Yongliang Zhao, Liu, et al. 2018)proposed extracting steam from the low-pressure side rather than the high-pressure side as per economy, energy security, and operational flexibility.

(Park et al. 2018; R. Kumar 2017; Javadi, Ahmadi, and Khalaji 2019; Marques et al. 2020) discussed various thermo-economic analysis from which modified productive structure and specific exergy costing was taken into account for exergetic and thermo-economic along with the cost of electricity prediction

(M. Liu et al. 2018) studied reduction in the exergy destruction by implementing low-pressure economizer concept in supercritical CO_2 power plant and optimized thermodynamically using optimization techniques. From the economic point of view, low-pressure economizer found a good way for heat recovery. The payback period was estimated by performing an economic analysis of the waste recovery system involved in the coal-fired power plant.

(Farooqui et al. 2018) carried out the economic analysis to evaluate the capital cost involved in proposing a power plant operating with natural gas as a fuel.

(Eduardo J.C. Cavalcanti, De Souza, and Lima 2018) studied incremental air temperature variation found significantly increasing impact on specific cost rate of steam and electricity produced from natural gas-fired cogeneration system.

(M. H. Ahmadi et al. 2019) reviewed economic analysis of different fuel thermal power plants and identified that economic optimization is complicated for coal-fired power plant.

(Hoon et al. 2019) analyzed modern thermal power plant operating above a critical point of water economically based on fuel tax and biomass combustion. The feasibility of the plant was cross-verified by evaluating the Net Present Value (NPV), the benefit to cost ratio, and internal rate of return(IRR).

(R. Kumar, Jilte, and Nikam 2019; R. Kumar, Ahmadi, et al. 2019) identified financial hurdles of carbon capture technology involving initial investment and penalty charges were analyzed, and an incentive-based approach was proposed by some of the researchers in the literature.

2.4 Exergoeconomic Analysis

(Cziesla and Tsatsaronis 2002)suggested fuzzy logic optimization is a suitable technique for exergoeconomic analysis of simple cogeneration power plant. The independent variables which directly affect the economic performance of the power plant were selected for exergoeconomic analysis.

(Lazzaretto and Tsatsaronis 2006; Mohammadi et al. 2017)combined exergy and economics to find the cost-effective components from an exergy point of view. This methodology of exergoeconomic was developed based upon a specific exergy costing approach known as SPECO. The research was extended to reveal the exergoeconomic variables for 660MW supercritical power plant by SPECO analysis.

(Bolatturk, Coskun, and Geredelioglu 2015)planned out an idea about the need for optimum burning of fuel, which should be monitor and figure out during the installation of the project itself. Thermodynamics and exergoeconomic tell us maximum exergy destruction takes place at fuel-burning chamber followed by steam carrying pipes.

(C. Chen, Zhou, and Bollas 2017)performed economic, environmental, exergoeconomic analysis of thermal power plant to increase the feasibility of thermal power plant in the future. The coal consumption was found decreased using the proposed model.

(Uysal, Kurt, and Kwak 2017)discussed various thermoeconomic analyses from which modified productive structure analysis and specific exergy costing were considered for exergetic and thermo economic analysis and prediction of cost of electricity was done.

(Hofmann and Tsatsaronis 2018)performed a comparative study of exergoeconomic proposed idea about secondary rankine cycle that helped to reduce fuel dependency, reduction in emission, and reduction in the cost of electricity to end-user.

(J. Souza et al. 2020)evaluated specific cost of the product, and the fuel from exergoeconomics analysis of various systems. The temperature of working fluid had great influence over exergoeconomic analysis.

(Ansarinasab, Mehrpooya, and Sadeghzadeh 2019) performed exergoeconomic analysis in the hydrogen liquefaction plant, to check the feasibility of components from economic perspectives.

(Eduardo J.C. Cavalcanti, Carvalho, and Ochoa 2019) performed exergoeconomic analysis for the evaluation of the specific cost of blended diesel-fueled direction injection engine system. The intake of fuel increases the exergoeconomic and exergoenvironmental variables.

2.5 Exergoenvironmental Analysis

(Bayón et al. 2006)developed emission model in a numerical way for the hydrothermal system to solve minimization problem related to SO_2 and NO_X emission and proven its ability to apply the same algorithm to practical application.

(Meyer, Castillo, et al. 2009) used biomass in the form of wood chips as fuel in power generation technology from environmental perspectives.

(Meyer, Tsatsaronis, et al. 2009) developed exergo-environmental analysis methodology for energy conversion technology. The Sankey diagram approach was constructed to represent the effect of various components on environment impact.

(G. Xu, Lu, and Yang 2010)analyzed environmental evaluation criteria to investigate the effect on the performance of a 600 MW power plant. This kind of approach can be used specifically for multi-objective evaluation and optimization of the design parameters.

(H. Barzegar Avval, P. Ahmadi,y 2011) evaluated environmental impact by thermoenvironomic analysis by calculating exergetic efficiency in gas turbine power plant.

(Boyano et al. 2011) studied exergo-environmental analysis for the hydrogen reforming process using LCA methodology. The change in technical parameter in construction of production of fuel is varied with exergoeconomic and exergoenvironmental impact.

(Petrakopoulou et al. 2011)checked feasibility of implementing carbon capture technology to the oxy-fuel power generation plant based on the economic and environmental aspects.

(Petrakopoulou et al. 2012) performed exergo-environmental analysis on a combined cycle power plant to identify the effect of the environmental impact of some components, which has negligible effects.

(P. Ahmadi, Dincer, and Rosen 2013)discussed environment impact by assessing multi-generation system and potential in reduction of CO2 and CO emission were considered as significant parameters. Various designs were considered studying energy, exergy efficiency.

(Manesh et al. 2014) performed exergo-environmental analysis on gas-fired steam power plant by using computer programming skills. The accessory components of steam power plant are considered along with major components to carry out exergoenvironmental analysis and the effect of it was studied.

(Agrawal et al. 2014) implemented LCA methodology to reveals the environmental impact of natural gas combined power plant. The natural gas fuel power plant found to better option for developing countries for replacement with coal and oil.

(Hentschel, Babić, and Spliethoff 2016) identified CO_2 emission and corresponding penalties of the conventional coal-fired power plants with the lower efficiency needs improvement and should be less cost-effective.

(Ameri, Mokhtari, and Bahrami 2016; Mohammadi et al. 2016) compared the coal-fired power plant with and without selective emission-reducing technologies and stated predicted possible environmental outcomes. Few investigators also focused only on reducing the carbon dioxide emissions from fossil fuel thermal power plants by optimizing operating parameters.

(Restrepo and Bazzo 2016) studied the environmental impact of using coal and rice straw as fuels in power plant and found a significant reduction in the environmental impact variable.

(Sultanov, Konstantinov, and Ivanitckii 2017)focused on environmental aspect by optimizing the operating parameter like fuel supply and cost of electricity in Russia. Also, hydrogen additive in the combustion chamber is found to be modern promising modern as emissions are concerned.

(Uysal, Kurt, and Kwak 2017)(C. Chen, Zhou, and Bollas 2017) analyzed of the coal-fired power plant was performed in terms of economic, environmental, and exergoeconomic to increase the feasibility of thermal power plant in the future.

(Ghaebi et al. 2018) performed 4E analyses for city gas station to ensure vapor generator as key parameters the responsible components for exergy destructor. The mass balance in form of mass fraction is used for equalizing the incoming and outgoing mass of the components.

(Wu et al. 2018) suggested various measures to the government of China regarding boiler load low operation stability and environmental techniques to reduce pollution from the coal-fired power plant.

(Fan et al. 2018) addressed the modern thermal power generation technology working with coal as a fuel and achievable target to reduce climatic changes.

(Hong et al. 2018) carried out a study on simulation of exergo-environmental analysis where the combustion chamber had contributed to maximum environmental impact.

(R. Kumar, Jilte, and Nikam 2019) focused on carbon emission from the steam generating unit and suggested various solutions to reduce it. The status and quality of coal available in India is discussed in the review article.

(R. Kumar, Jilte, and Nikam 2019; M. H. Ahmadi et al. 2019) identified thermal power systems burning fossil fuels are a significant source to emit emission of carbon dioxide(CO_2), Carbon monoxide(CO), Nitrogen Oxide (NO_X), Sulfur dioxide (SO_X). These emissions affect human health and natural habitat. Thus, many countries are upgrading thermal power generation by keeping coal as a primary fuel and integrating it with carbon capture technology.

(Ansarinasab, Mehrpooya, and Sadeghzadeh 2019) performed exergoenvironmental analysis in the hydrogen liquefaction plant to reveals the environmental load of the specific components such as expander and compressor. The eco-indicator 99 methodology was employed to derive external attributes from calculating the stream environmental rate.

(Yürüsoy and Keçebaş 2017; Keçebaş 2016; Chahartaghi et al. 2019) performed exergy and exergo-environmental analysis on other complicated systems such as geothermal heating applications where the comparison with convection heating is made from an environmental perspective. Ambient temperature also plays a vital role in limiting environmental impact in such a complicated system.

(Thorne et al. 2019) proposed environmental impact by the LCA tool for fossil fuel power plant with and without post-combustion chemical looping carbon capture technology.

(Sciubba 2019) concluded the exergy flow formulation of the complex system that plays a vital role in environmental impact analysis. The emerging approach from exergy analysis is discussed and compared.

(Eduardo J.C. Cavalcanti, Carvalho, and da Silva 2020) implemented SPECO approach was also seen to carry out exergoenvironmental analysis of traditional sugarcane bagasse cogeneration plant.

(Eduardo José Cidade Cavalcanti 2017; Arabkoohsar and Sadi 2020) studied increased electricity produced and a decrease in environmental impact by combining solar technology with the steam/gas cycle was also proposed. The integration of solar technology with conventional power plant has proven a better option to reduce the environmental load to a great extent.

(Bamisile, Huang, Dagbasi, et al. 2020) proved concentrated solar technology as upgraded option for the fully utilization of incident solar radiation. The details formulation of exergy of components are represented in the article.

(Hirbodi, Enjavi-Arsanjani, and Yaghoubi 2020) extended research on using exergo-environmental analysis in solar technology combined with conventional technology to reduce the environmental impact.

(Ghofrani and Moosavi 2020; Mousavi and Mehrpooya 2020) performed exergo-environmental analysis is gaining popularity in refrigeration and air conditioning systems for revealing the environmental impact of components.

Likewise, other researchers analyzed the Exergoenvironment based upon the LCA approach to study environmental impact factors.

2.6 Optimization Approach

(Bekdemir, Öztürk, and Yumurtac 2003)optimized condenser design parameters by considering condenser cost, energy generation cost, and developed numerical approach in Fluent code.

(Lopez et al. 2008) employed particle swarm optimization for optimization of nonlinear function concern with the improvement of biomass power plant profitability index.

(Seyyedi, Ajam, and Farahat 2010)developed simple structural optimization procedure and used for large scale thermal power plant by considering the objective of minimization of total operating cost flow during installation.

(Tzolakis et al. 2010)done optimization of the operation of a thermal power plant using control variables as different mass flow rates extracted from separate turbine sections available. The thermal efficiency of the steam/water cycle was considered as main objective function.

(L. Chen, Feng, and Sun 2011)investigated optimized results of different heat interaction sections from the combined cooling heating power plant by taking maximum profit as an objective function within stipulated time.

(P. Ahmadi, Dincer, and Rosen 2011)demonstrated optimization, which resulted that by proper selection of components and accessing control on the fuel can leads to colossal emission reduction.

(W. Zhao, Zhang, and Tang 2012)used the power electronic technology of the optimization for operational target to raise power efficiency, reduce supplying electric of coal consumption and emission of contaminants. This technique was applied to a 300MW existing thermal power plant.

(Groniewsky 2013) implemented PSO optimization technique and succeeded in the reduction of the capital cost of the overall system at the expense of overall second law efficiency.

(Dong, Yu, and Zhang 2014) minimized economic cost rate per unit exergy of fuel consumed by using a genetic algorithm to obtain the optimal solution.

(L. Wang et al. 2015)developed generic superstructure-free optimization for synthesis and design of thermal power plant with a different combination at various levels.

(L. Wang et al. 2015) proposed generic superstructure free optimization approach to formulate distributed energy supply systems and identifies highly efficient and complex structures featuring multi-stage reheating and feed water preheating.

(Wang et al. 2015) modeled the evolution algorithm with a deterministic approach to synthesis the thermal power plant with maximizing thermal efficiency to be a primary objective.

(Baghsheikhi and Sayyaadi 2016)provided full proof a real-time optimization considering different power conditions and identified profits from a separate section of power plants.

(Kowalczyk et al. 2016)discussed three different optimization methods approach for 900MW ultra-critical power plant considering plant gross efficiency to be as an objective variable and extensive set of the independent variable.

(D. A. Lyalin 2016)applied optimization technique to maximum working efficiency by reducing energy consumption during the plant starting point.

(Murav'ev, Kochetkov, and Glazova 2016)constructed an algorithm to determine the availability and various options available in structural changes for the cooling systems in all stages of the life cycle of a plant.

(Güçyetmez and Çam 2016)developed hybrid genetic teaching learning-based optimization algorithm considering the fuel cost as a minimization objective. This newly developed algorithm was applied to the existing thermal power plant, and results were compared to the reference optimization algorithm.

(Kler, Zharkov, and Epishkin 2016)developed a new approach to solve the optimization problem of various parameters of the ultra thermal power plant. In this optimization problem, relative residuals and relative investment capital is considered as minimization objective and net efficiency as maximization objective. This is a unique paper in which optimization of ultra critical power plant is done.

(P. R. Kumar, Raju, and Kumar 2016)studied the optimized value of exegetic loss for an increase in exergetic efficiency, and higher fuel utilization in case of subcritical, supercritical, and ultracritical essential conditions of steam.

(Joshi 2016)used the optimization technique in the pulverization process in coal-fired thermal power plant by considering different loads, load factor, air purity which leads to environmental effects.

(Kler, Zharkov, and Epishkin 2016)developed a new approach to solve the optimization problem of various parameters of the ultra thermal power plant.

(L. Wang et al. 2016)proposed multi-objective superstructure free synthesis framework is most suitable for a complex problem in the synthesis of thermal power plants. In this optimization problem, relative residuals and relative investment capital is considered as minimization objective and net efficiency as maximization objective.

(Ameri, Mokhtari, and Bahrami 2016) performed optimization technique along with energy and exergy analysis to find optimal point at which CO_2 production rate is low in steam generation plants.

(Güçyetmez and Çam 2016) performed thermodynamic and exergoeconomic modeling to indicate the maximum exergy destruction occur at a fuel-burning chamber followed by steam carrying pipes. The study was enriched by optimization by developing a hybrid genetic teaching learning-based optimization algorithm considering the fuel cost as a minimization objective.

(Baghsheikhi and Sayyaadi 2016) performed optimization using fuzzy interface system to study the effect of variation of power load on profit for exergoeconomic analysis of 250MW subcritical power plant.

(Kowalczyk et al. 2016) optimize a single objective function of supercritical power plant energetic efficiency by using three approaches. The Rosenbrock method was proven to a better approach for optimization of a single objective function with multiple independent variables.

(Damodaran and Kumar 2017) implemented harmony Search optimization technique to analyze economic, and emission, as a minimization objective function, and the result was compared with the PSO algorithm based on minimum parameters, less computational steps and easiness of implementation.

(Khorshidi, Pour, and Zarei 2018)used Genetic algorithm for optimization in power plant considering maximization goal as efficiency and minimization objective as further energy losses and identified exergy destructing component.

(Fathia et al. 2018) studied the effect of coal cost, initial investment on the referenced cost of electricity were analyzed by comparing binary and conventional power generating coal-fired power plant. Presently no thermal system works alone to produce the power; it is always associated with subsystems of multidisciplinary areas. Some literature has been studied in multidisciplinary directions and is also included in the following section. The multi-objective optimization was carried out considering the generation cost produced from the desalination unit integrated with the thermal power unit.

(Noroozian, Naeimi, and Bidi 2019; Chahartaghi et al. 2019) performed optimization by taking product cost ratio as a minimization objective to find out suitable working fluid in case of an organic ranking cycle for thermal recovery from low-grade geothermal water.

(Kheshti and Ding 2018) revealed optimize the value of fuel cost and power output by fulfilling the condition of variation in load demand.

(Elahifar, Assareh, and Nedaei 2018) utilized firefly optimization to find the second law efficiency of the thermal power plant and result compared with results obtained from another metaheuristic approach.

(Jagtap et al. 2020; Kumar 2017; Malik and Tewari 2020) performed the optimization in the field of availability for generators, feed-water systems, coal handling systems of a subcritical power plant using Particle Swarm Optimization and Simulated Annealing to schedule advanced maintenance of the mentioned systems.

(Panahizadeh et al. 2020) optimized exergy coefficient of performance and annual operation costing using particle swarm optimization of chiller plant and claimed 3.24% reduction in annual operation and maintenance cost.

2.7 Multi-Objective Optimization Approach

(Zhou, Cen, and Fan 2005) applied combined artificial neural network and genetic algorithm to perform multi-objective optimization to maximize boiler efficiency and minimize NOx emission concentration as objective functions. The ability of combined ANN and GA technique is proven better on the basis of lower computation time and online integration with the existing system.

(Alrashidi et al. 2010) reviewed the application of PSO optimization with fuel cost and emission produced from the power plant as multiple objectives functions.

(Ahmadi, Dincer, and Rosen 2011) performed multi objective optimization on a combined cycle power plant by minimizing CO_2 pollutants, minimizing total cost rate, and maximizing exergy efficiency. The Genetic algorithm was utilized,and found decrement in environmental impacts can be achieved by selecting proper components and low fuel flow rate.

(Ahmadi and Dincer 2011) performed multi-objective optimization of gas turbine power plant by using non dominated sorting genetic algorithm. The maximizing exergy efficiency, minimizing the cost rate of product, and environmental impact are objective functions to optimize.

(H. Barzegar Avval, P. Ahmadi,y 2011) performed multi-objective optimization of gas turbine power plant using genetic algorithm with exergy efficiency, cost rate, and CO_2 emission concentration as multiple objectives. The relations were developed between three objective functions from the Pareto frontier to find the optimal solutions.

(Sayyaadi, Babaie, and Farmani 2011) performed multi-objective optimization with particle swarm optimization of cogeneration system in which maximizing second law efficiency and minimizing cost rate and environmental impact rate are taken objective functions.

(Harkin, Hoadley, and Hooper 2012) utilized the multi-objective genetic algorithm technique to optimize the power output, CO_2 capture rate, and cost of electricity. The significant outcome of the reduction in the cost of electricity of 25% to 30% is achieved from optimization. The variation of flue gas temperature on the differential cost of electricity was studied in the research.

(Baghernejad and Yaghoubi 2013) utilized particle swarm optimization technique to minimize the cost of electricity and exergy destruction cost of the hydro, solar power plant. The SPECO approach was implemented to exergoeconomic analysis.

(Urech et al. 2014) studied the Pareto frontier curve of CO_2 capture rate and overall efficiency by performing multi-objective optimization by taking potassium carbonate capture process integrated with a coal-fired power plant.

(Wang et al. 2014) developed differential evolution multi-objectives optimization techniques to maximize first law efficiency and minimize total cost rate of electricity of coal-fired 1100MW capacity thermal power plant. The realistic view was taken into account to compare the results from multi objectives optimization. The results show 2% increase in first law efficiency and a 2% to 4% decrement in the cost of electricity as compared with actual available practical data.

(Dong, Yu, and Zhang 2014)suggested a multi-objective multi-constraint nonlinear programming approach to study the exergoeconomic considering heat, mass, and pressure as parameters. The results were validated by the MATLAB code.

(L. Wang et al. 2014)proposed algorithm for enhancement multi-objective differential evolution for finding the relation between dependent and independent variables.

(Zhang, Wang, and Ji 2015) review the application of particle swarm optimization in the field of the interdisciplinary engineering field and proven to better optimization techniques with multiple objectives.

(Mahmoodabadi, Ghavimi, and Mahmoudi 2015) revealed that the exergetic efficiency increase with the increase in the total cost rate by performing multi-objective optimization with the PSO and GA technique.

(Ameri, Mokhtari, and Bahrami 2016) found optimized values of excess air concentration by performing multi-objective optimization with cost function from economic analysis, exergy efficiency, and CO2 emissions.

(Kler, Zharkov, and Epishkin 2016) developed an optimization approach to maximize the overall efficiency and minimize the initial investment of 660 MW supercritical power plant. The validation was performed by comparing the previous literature result with the new system.

(L. Wang et al. 2016)constructed multi-objective algorithm for complex problems, including more variables and objective functions. The author focused on the need for cost functions as an objective in current industrial practices.

(Roque, Fontes, and Fontes 2017) carried multi-objective optimization by minimizing economic and environmental objectives. The biased random key based GA technique was proposed and proven to be better than other approaches from a diversity performance point of view. The tradeoff curves and CPU time were compared.

(Shamoushaki, Ehyaei, and Ghanatir 2017) involved genetic algorithm for multi-objective optimization of gas turbine power plant by maximizing exergy efficiency and minimizing the cost of electricity. The study also covers a variation of increase of fuel cell stack temperature on exergy efficiency of the cycle shows 3.6% increment on gas turbine and 3.7% decrement on fuel cell power.

(Di Somma et al. 2017) aimed to reduce yearly electricity cost and improvement in exergy efficiency as an objective functions. The result of the optimization study gave a 21% to 36% reduction in the configuration as compared with the existing thermal power section.

(Ameri, Mokhtari, and Mostafavi Sani 2018) performed multi-objective optimization on natural gas-fired combined cycle power plant. The genetic algorithm technique was involved in maximizing exergy efficiency and minimizing electricity cost. The choice of objective function plays an important role in comparing the Pareto curve obtained by using natural gas and liquid fuel.

(Rahat et al. 2018) proposed a new multi-objective optimization technique based on Gaussian process, and minimized oxide of nitrogen, maximized efficiency of 330MW coal-fired power plant.

(Naserabad, Mehrpanahi, and Ahmadi 2018) implemented genetic algorithm for multi-objectives optimization where overall exergy efficiency, power output are maximizing objectives and cost of electricity are minimizing objective function. The heat recovery steam generator was recommended to install in an existing power plant as the study's outcomes.

(Miar Naeimi, Eftekhari Yazdi, and Reza Salehi 2019) performed multi-objective optimization to find the optimal solution of the objective function of exergetic efficiency, total cost rate of the overall system, and environmental impact rate of the comprehensive system.

(Opriş et al. 2020) resulted in effect of the presence of bled steam by applying multi-objective optimization of overall energy efficiency and investment. The inclusion of pre-heaters resulted in an improvement in overall efficiency and decrement in overall investment.

2.8 Research Gaps Identification

The following gaps were identified from the literature survey.

1. No comprehensive theoretical work exists that integrates 5-E analysis in coal-based power plants. Although, *work to represent the* energy, exergy, economic, exergoeconomic, and environmental analysis for various types of coal-based power plant *are available seperately.*
2. The semi-empirical model with 5-E analysis of SUPP in modern programming software is missing in Opel literature. The limited literature is available for pure sliding operation of SUPP and its consequences on thermal performance.
3. Multi-objective optimization using 5-E analysis through literature is also a research gap for this study. The traditional approaches for optimization are highly iterative and time-consuming especially for complex systems. Thus, a suitable non-traditional/metaheuristic optimization technique of particle swarm optimization has been used for multi-objective optimization.

2.9 Research Objectives

The research objectives for the present study are as follows.

1. To analyze the thermal performance (Energy and Exergy) analysis of a supercritical coal-fired power plant.
2. Economic and Exergoeconomic analysis of a supercritical coal-fired power plant.
3. Environmental analysis of a supercritical coal-fired power plant.
4. Multi-objective optimization of supercritical coal-fired power plants using a suitable non-traditional optimization technique.

2.10 Scope of the study

In the present study, more emphasis is given on multi-objective optimization of coal-fired power plant with different boiler types using 5E (energy, exergy, exergoeconomic, economic, and environment) analysis. Through a literature survey, it was concluded that implementation of such kind of study is missing. Simulation of the actual supercritical coal-fired power plant is done based on energy, exergy, exergoeconomic, economic, and environmental.

CHAPTER 3

3. RESEARCH METHODOLOGY

In this chapter, the layout of SUPP of capacity 660MW is described. The chapter also covers the formulation of thermodynamic modeling based on mass balance and energy balance equation followed by cost analysis equation formulation, exergy analysis equation formulation, exergoeconomic analysis equation formulation, exergoenvironmental analysis equation formulation.

3.1 Power plant description

The TS diagram of 660MW capacity supercritical power plant is shown in figure 3.1.The schematic diagram of the 660 MW supercritical power plant is shown in figure 3.2. The supercritical coal-fired power plant of 660 MW has been selected for the analysis. It is consists of three turbine stages, namely a high-pressure turbine with having an inlet pressure of 247 bar, an intermediate pressure turbine with having inlet pressure of 50.5292 bar, and a low-pressure turbine having a pressure of 5.8221 bar. 2 Steam bled are extracted from the high-pressure turbine and allowed into high-pressure heaters 1, and 2. Bled coming out from intermediate pressure turbine is allowed to pass through high-pressure heaters 3, pump drive turbine, and lower pressure heaters 1. Remaining steam bled from the low-pressure turbine is allowed to pass through low-pressure heater 2, 3, and 4. Re-heater is included between the high-pressure turbine and intermediate pressure turbine, which results in an increase in temperature from 323.216 ℃to 593 ℃. Wet steam coming out from a low-pressure turbine is passed through the condenser, where heat is rejected to cooling water at a pressure of 0.1047 bar. The fluid coming out from the condenser is pumped through a series of the arrangement of low-pressure heaters, deaerator, high-pressure heaters before entering the boiler section. A pump drive turbine is used to drive the boiler feed pump to increase the working fluid pressure before entering the once-through steam generator. Operating parameters are listed in appendix A. To increase the overall efficiency of the power plant, coal consumption plays a vital role. To reduce the coal consumption and heating time inside a boiler, water is preheated using the feedwater heater. These feedwater heaters used are of close shell, and tube type with drains cascaded backward. Steams bled from various sections of turbines are used to heat the feedwater. Steam gives sensible and latent heat to the feedwater and undergoes a phase change from the superheated region to the subcooled region. The feedwater heaters placed after the boiler feedwater pump is of high-pressure feedwater heaters, and those placed before are low-pressure feedwater heaters. In the case of a supercritical unit, three sets of high-pressure feedwater heaters are placed in series (see fig. 1). Deaerator is a direct contact combination spray tray-types feedwater, where feed water is sprinkled in the steam-filled region then allowed to collect in the tray and placed before high-pressure feedwater heaters section. The drain cooler is an integral part of the low-pressure feedwater heater in both the units. Gland Steam Condenser provision is made in both units. Its purpose is to prevent leakage of steam to the turbine. The values of specific enthalpy and specific entropy were formulated as per the IAPWS IF97 standard(Wagner W 2008). Designed thermodynamic properties of points in the 660 MW power cycle have been tabulated (see appendix A).

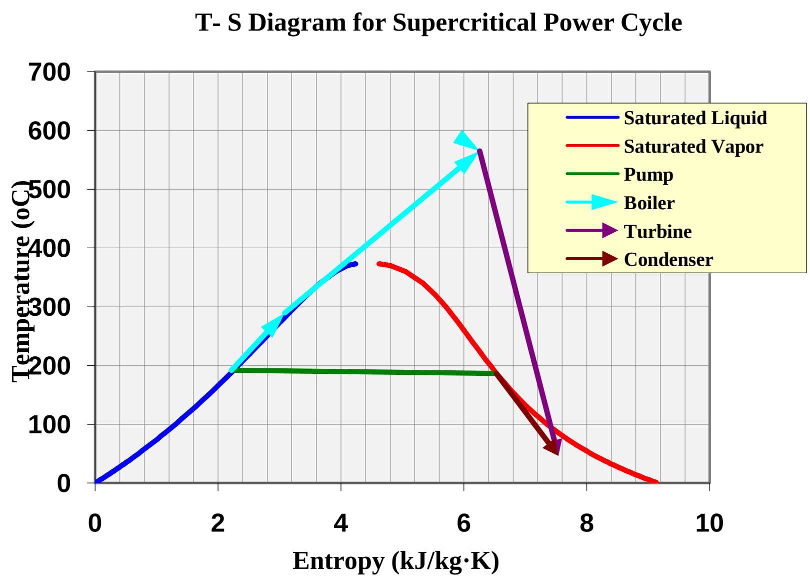


Figure 3.1:T-S Diagram for Supercritical power cycle

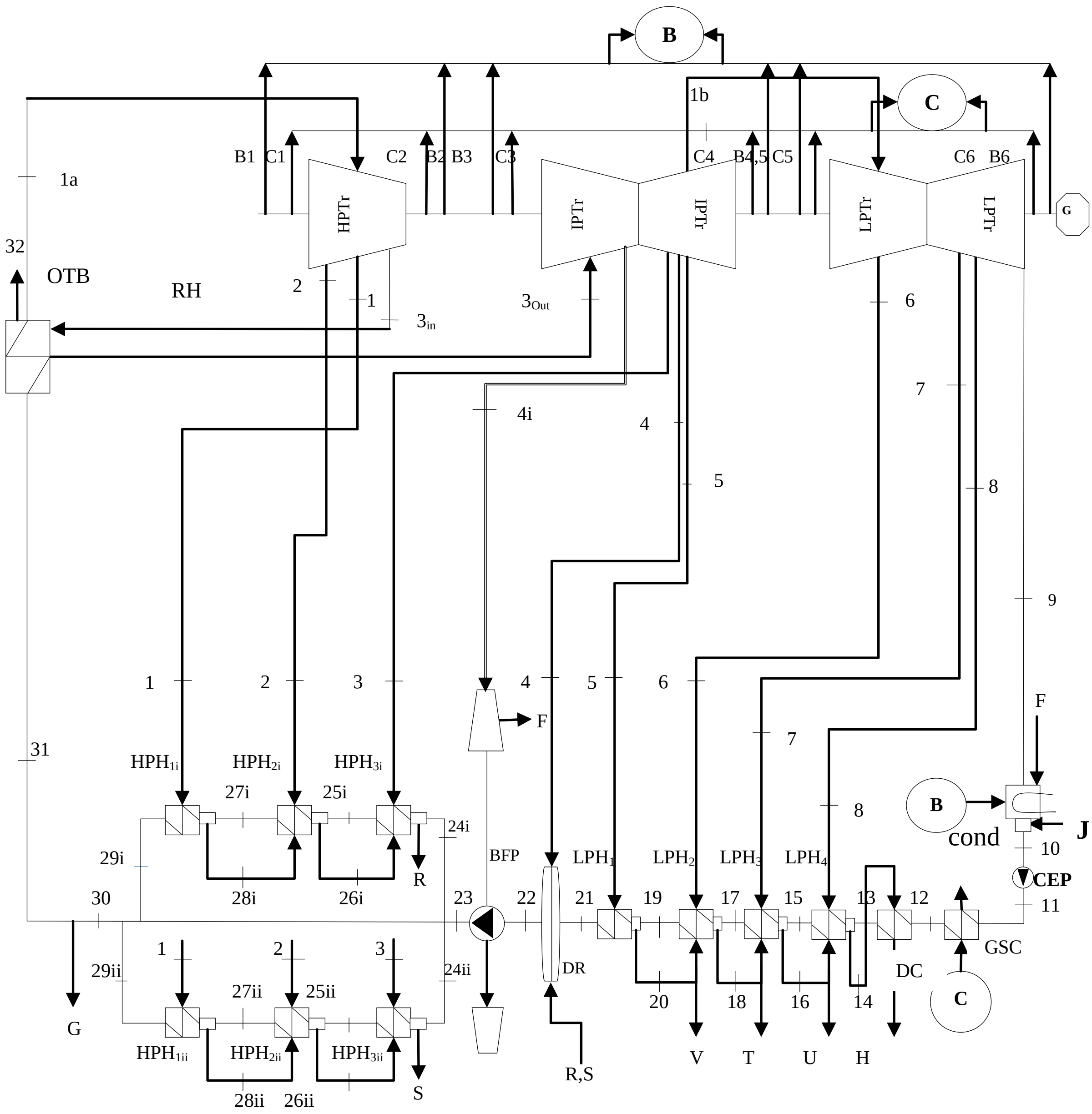


Figure 3.2: Schematic diagram of the SUPP of 660MW capacity

3.2 Energy Analysis Methodology

The basic strategy to develop the mathematical model is based on the mass and energy balance equations of all SUPP components. Energy and mass balance equations are written as follows and also tabulated in Table 5.

Mass balance equation:	$$\sum Z_{entry} = \sum Z_{exit} \quad (1)$$ Where, Z_{entry} & Z_{exit} are mass fraction at the entry and exit of equipment.
Energy balance equation:	$$\dot{Q} - \dot{W} = \sum \dot{Z}_j (h_{exit,j} - h_{entry,j}) \quad (2)$$ Where, $\dot{Q}$ *and* $\dot{W}$ are Heat Flow rate and Work done, $h_{exit,j}$ and $h_{entry,j}$ are specific enthalpy at the exit and entry of the equipment, $\dot{z}_j$ is mass fraction at j[th] component.
The power output of the turbine:	$$\dot{W}_{Turbine} = \dot{Z}\,\Delta h \quad (3)$$ Where, $\Delta h = h_{entry} - h_{exit}$, $\dot{W}_{Turbine}$ is work generated by turbine.
Power consumed by pumps:	$$\dot{W}_{pump} = \frac{\dot{Z}_{entry}(h_{exit} - h_{entry})}{\eta_{pump}} \quad (4)$$ Where, $\dot{W}_{pump}$ is work done by pump, η_{pump} is pump efficiency.
Net electrical power output:	$$\dot{W}_{Net} = \sum \dot{W}_{Turbine} - \sum \dot{W}_{Pump} \quad (5)$$ Where, $\dot{W}_{Net}$ is electrical power

The parameters such as pressure, temperature, enthalpy were determined based on the IAPWS IF-97 standard(Wagner and Pruß 2009) and taken into account from designed data per requirement. The simulated model is constructed in the MATLAB package using the XSteam function (Holmgren 2006). The steam generation process to net power produced is programmed as per the flowchart shown in figure 3.4. The circulation ratio lies in the range vary from 0.999 to 1.055 concerning power output in the present study. The program is designed as per norms set by the government for coal consumption in SUPP based on different coal grades available in India (Central Electricity Authority 2019),as shown in figure 3.3.

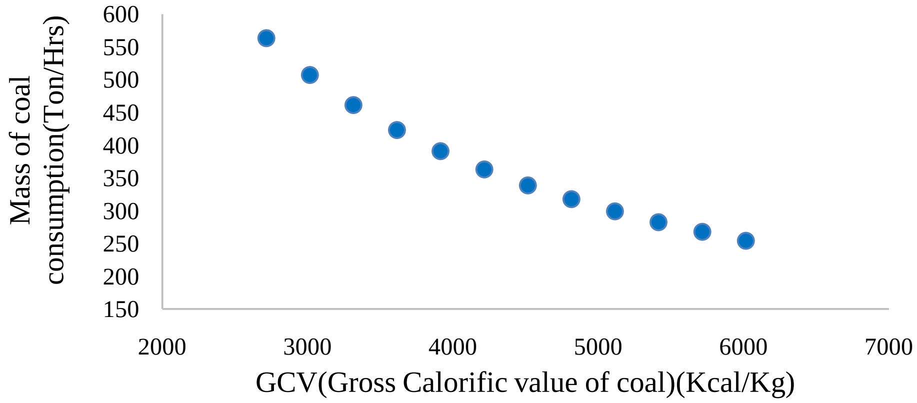


Figure 3.3: Coal consumption norms set by the government(Central Electricity Authority 2019)

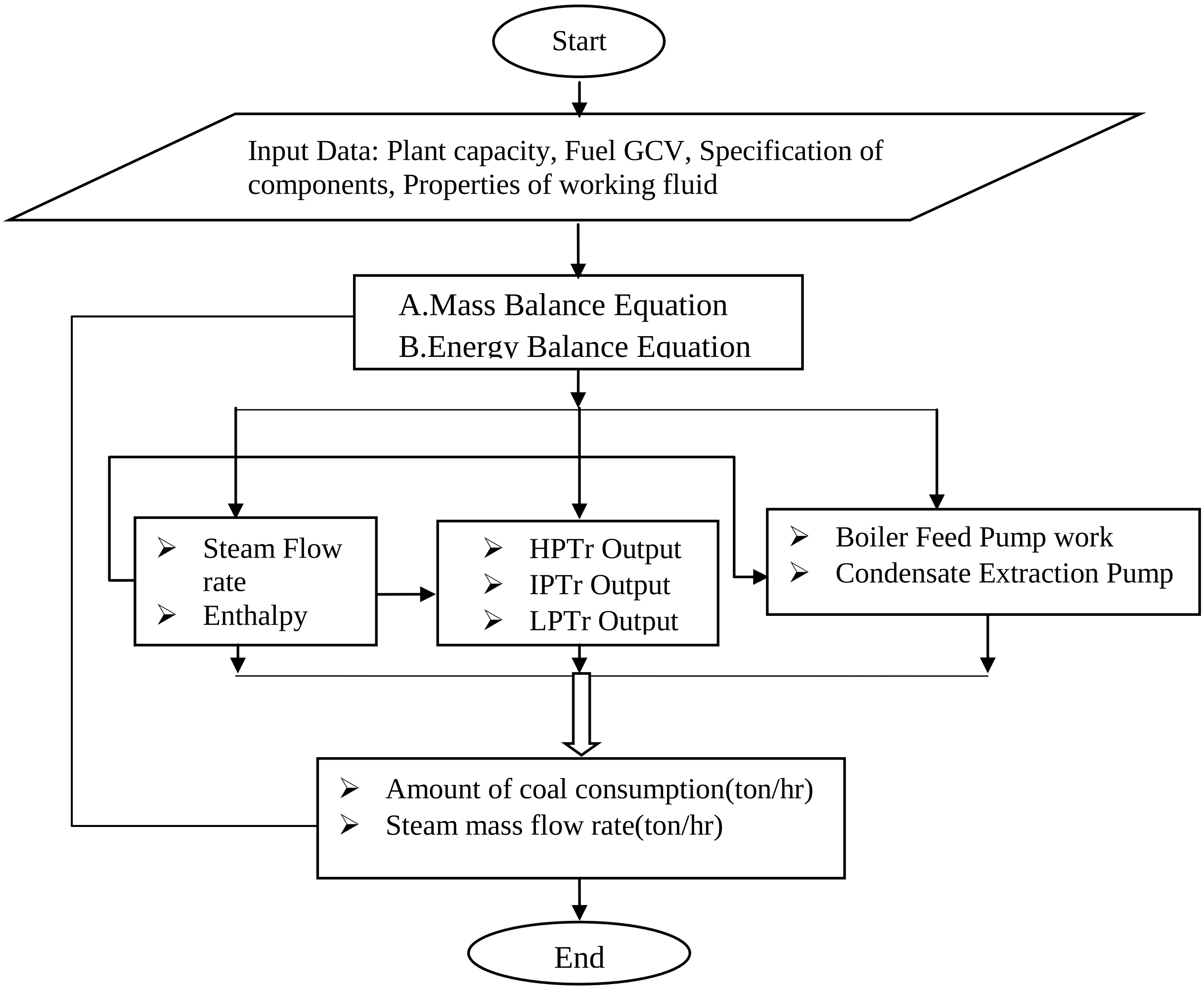


Figure 3.4: Flow chart for the plant simulation model

3.2.1 Modeling of supercritical unit components

The simulated model was built considering the terminal temperature difference in the range of 0°C to 7°C, as shown in table 3.1. The pictorial representations of components are shown in figures 3.5 to figures.3.13.

Table 3.1: Terminal temperature difference in feedwater heaters

Feedwater heaters	HPH_{1i}	HPH_{2i}	HPH_{3i}	HPH_{1ii}	HPH_{2ii}	HPH_{3ii}	LPH_1	LPH_2	LPH_3
Terminal temperature difference(°C)	1.458	1.295	1.096	1.458	1.295	1.096	5.931	2.551	3.094

3.2.1.1 High-Pressure Feedwater Heater (HPH_{1i})

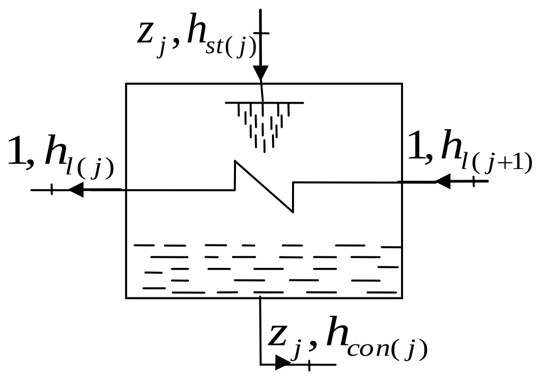


Figure 3.5: Energy balance diagram for high-pressure feedwater heater (HPH_{1i})

Energy balance: $$1 \times h_{l(j)} - 1 \times h_{l(j+1)} = z_j\,(h_{st(j)} - h_{con\,(j)}) \quad (6)$$

Where, z_j is mass fraction of steam bled, $h_{st(j)}$ is specific enthalpy of steam bled,$h_{l(j)}$ and $h_{l(j+1)}$ are exit and entry specific enthalpy of feed water, $h_{con(j)}$ is specific enthalpy of condensate.

Mass fraction of steam bled at j^{th} state

$$z_j = \frac{(h_{l(j)} - h_{l(J+1)})}{(h_{st\,(j)} - h_{con\,(j)})} \quad (7)$$

where,

$$h_{l(j)} = h_{(j)f} - TTD \times Cp_w \quad (8)$$

$$h_{con\,(j)} = h_{l(j+1)} + ETD \times Cp_w \quad (9)$$

Where, TTD is terminal temperature difference, ETD is exit temperature difference, Cp_w is specific heat capacity of water.

Similarly, thermodynamics modeling of high-pressure feedwater heater (HPH_{2i}, HPH_{3i}, HPH_{1ii}, HPH_{2ii}, HPH_{3ii}) is constructed.

3.2.1.2 Deaerator

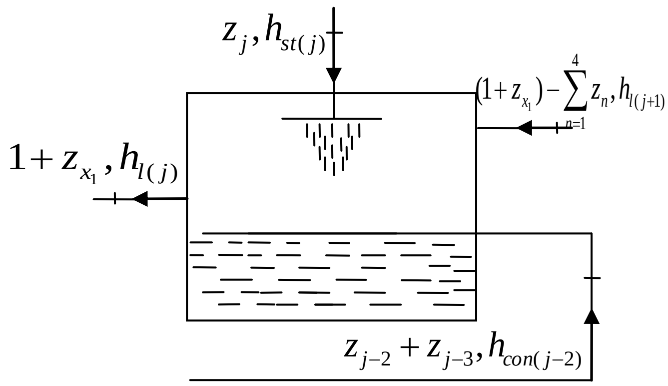


Figure 3.6: Energy balance diagram for Deaerator (DR)

Energy balance:

$$1 + z_{xl} \times h_{l(j)} - \left((1 + z_{xl}) - \textstyle\sum_{n=1}^{4} z_n\right) \times h_{l(j+1)} = z_j \times h_{st(j)} - (z_{j-2} + z_{j-3}) \times h_{con\,(j-2)} \quad (10)$$

The fractional mass flow rate of steam at 'jth state

$$z_j = (1 + z_{xl} \times h_{l(j)} - \left((1 + z_{xl}) - (z_n + z_{n-1} + z_{n-2} + z_{n-3} + z_{n-4})\right) \times h_{l(j+1)}) + (z_{j-2} + z_{j-3}) \times h_{con\,(j-2)})/h_{st(j)} \quad (11)$$

Where, z_j is mass fraction of steam bled, $h_{st(j)}$ is specific enthalpy of steam bled, $h_{l(j)}$ and $h_{l(j+1)}$ are exit and entry specific enthalpy of feed water, $h_{con(j-2)}$ is specific enthalpy of condensate, $1+z_{x1}$ is mass fraction of feed water at entry and exit of deaerator, $z_{j-2}+ z_{j-3}$ is mass fraction received from HPHr.

3.2.1.3 Low-Pressure Feedwater Heater (LPH_1)

Energy balance:

$$((1+z_{xl})-\sum_{n=1}^{4} z_n)\times h_{l(j)}-\left((1+z_{xl})-\sum_{n=1}^{4} z_n\right)\times h_{l(j+1)}=((1+z_{xl})-\sum_{n=1}^{4} z_n)\times h_{st(j)}-(z_j)*h_{con(j)} \quad (12)$$

The fractional mass flow rate of steam at ‘jth’ state

$$z_j=\left(\left((1+z_{xl})-\sum_{n=1}^{4} z_n\right)\times h_{l(j)}-\left((1+z_{xl})-\sum_{n=1}^{4} z_n\right)\times h_{l(j+1)}-((1+z_{xl})+\sum_{n=1}^{4} z_n)\times h_{st(j)}\right)/h_{con(j)} \quad (13)$$

where

$$h_{l(j)}=h_{f(l)}-TTD\times Cp_w \quad (14)$$

$$h_{con(j)}=h_{(j)l}-ETD\times Cp_w \quad (15)$$

Where, z_j is mass fraction of steam bled, $h_{st(j)}$ is specific enthalpy of steam bled,$h_{l(j)}$ and $h_{l(j+1)}$ are exit and entry specific enthalpy of feed water, $h_{con(j)}$ is specific enthalpy of condensate,$1+z_{x1}$ is mass fraction of feed water at entry and exit of dearator, z_n is mass fraction received from the nth components.

Similarly, the thermodynamic modeling of low-pressure heater 2,3,4 is done.

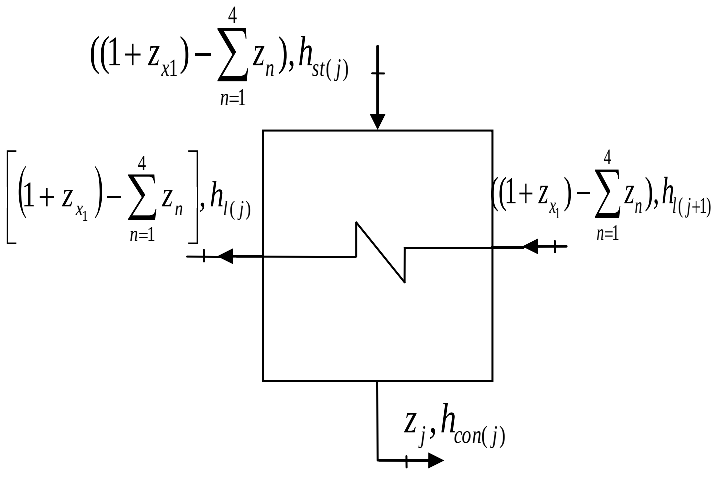


Figure 3.7: Energy balance diagram for low-pressure feedwater heater (LPH1)

3.2.1.4 Drain cooler

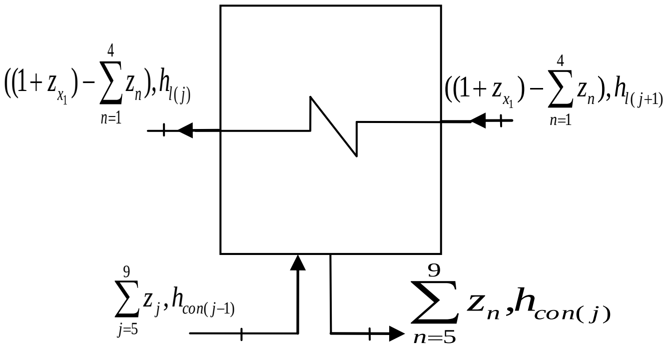


Figure 3.8: Energy balance diagram for Drain Cooler

Energy balance:

$$\left((1+z_{xl})-\sum_{n=1}^{4}z_n\right)\times h_{l(j)}-\left((1+z_{xl})-\sum_{n=1}^{4}z_n\right)\times h_{l(j+1)}=-\sum_{j=5}^{9}z_j\times h_{con\,(j-1)}+\sum_{n=5}^{9}z_n\times h_{con\,(j)} \quad (16)$$

Where, z_j is the mass fraction of steam bled, $h_{l(j)}$ and $h_{l(j+1)}$ are exit and entry specific enthalpy of feed water, $h_{con(j)}$ is specific enthalpy of condensate,$1+z_{x1}$ is mass fraction of feed water at entry and exit, z_n is mass fraction received from the n^{th} components.

The steam bled pressure was found out from the curve fitting of available reading, as shown in Table 3.2. The pure sliding pressures for variation in plant load are taken. The linear curve fitting equations were formed considering the value of constants and coefficient of determinations, as shown in Table 3.3. The linear equations are given by

$$P_{steambled} = A_1 \times MW + A_2 \quad (17)$$

Where, A_1 and A_2 are constants, MW is power output.

Table 3.2 : Constants and coefficient of determination formed from linear equations of bled steam extraction pressure

Pressure	P_{1a}	P_{z1}	P_{z2}	P_{z3}	P_{z4}	P_{z5}	P_{z6}	P_{z7}	P_{z8}
A_1	0.4254	0.1098	0.0778	0.0836	0.0344	0.0077	0.0028	0.0013	0.003
A_2	8.0769	3.8708	1.9126	0.9607	1.1301	0.6242	0.2373	0.1107	0.7469
R^2	0.9974	0.9993	0.999	0.9994	0.9994	0.998	0.9978	0.9974	0.9963

Table 3.3: Steam bled pressure value

		Steam bled (Bar)								
Sr. No.	**Unit Load (MW)**	P_{1a}	P_{z1}	P_{z2}	P_{z3}	P_{z4}	P_{z5}	P_{z6}	P_{z7}	P_{z8}
1	198	90	25.22	17.16	17.53	7.83	2.08	0.7567	0.3551	0.1511
2	330	150	40.03	27.27	28.14	12.45	3.24	1.17	0.5488	0.2303
3	396	180	47.89	33.19	34.4	14.88	3.72	1.35	0.6334	0.262
4	528	230	62.43	43.48	45.51	19.45	4.74	1.71	0.8072	0.3242
5	660	247	75.76	52.84	55.87	23.65	5.67	2.04	0.957	0.3691

3.2.1.5 Condenser

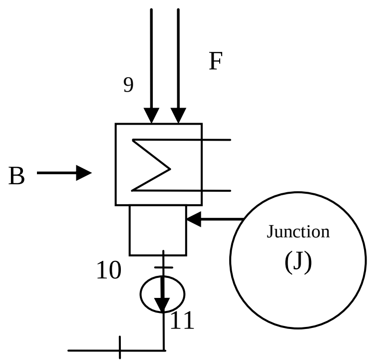


Figure 3.9: Flow diagram of condenser

Mass balance equation for the condenser is as follows

$$Z_{10} = Z_9 + \sum_{n=1}^{6} Z_{Bn} + Z_F + Z_{(G+H+I+J+T+V+U+X)} \tag{18}$$

Energy balance equation is given by

$$Z_{10}h_{10} = Z_9h_9 + \sum_{n=1}^{6} Z_{Bn}h_n + Z_Fh_F + (Z_{(G+H+I+J+T+V+U+X)} \times h_{(G+H+I+J+T+V+U+X)}) \tag{19}$$

$$h_{10} = (Z_9h_9 + \sum_{n=1}^{6} Z_{Bn}h_n + Z_Fh_F + (Z_{(G+H+I+J+T+V+U+X)} \times h_{(G+H+I+J+T+V+U+X)}))/Z_{10} \tag{20}$$

Where, $Z_{(F+G+H+I+J+T+V+U+X)}$ are a mass fraction of losses from the various point, $h_{(F+G+H+I+J+T+V+U+X)}$ are specific enthalpy of losses from the various points.

Heat given out to circulating water is given by

$$Q_{condenser} = x_w cp_w (T_{w,out} - T_{w,in}) = Z_9(h_9 - h_{10}) \tag{21}$$

Where, x_w is the amount of flowing water in the condenser, cp_w is the specific heat capacity of flowing water, $T_{w,out}$ and $T_{w,in}$ are the temperature at outlet and inlet of the condenser unit. The condition of condensed water is assumed to be saturated.

3.2.1.6 Gland Steam Condenser

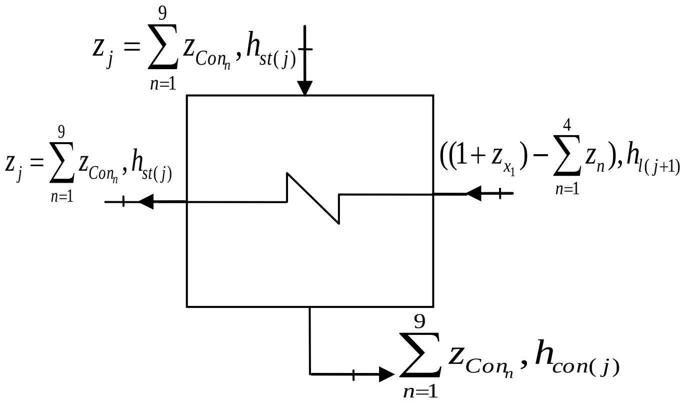


Figure 3.10: Energy balance diagram for Gland Steam Condenser (GSC)

Energy balance: $(\sum_{n=1}^{9} z_{conn}) \times h_{st\,(j)} - \left((1 + z_{xl}) - \sum_{n=1}^{4} z_n\right) \times h_{l\,(j+1)} = -\sum_{j=5}^{9} z_j \times h_{con\,(j-1)} + \sum_{n=1}^{9} z_{conn} \times h_{st\,(j)}$ (22)

Where, z_j is the mass fraction of steam bled, $h_{l(j)}$ and $h_{l(j+1)}$ are exit and entry specific enthalpy of feed water, $h_{con(j)}$ is specific enthalpy of condensate,$1+z_{x1}$ is mass fraction of feed water at entry and exit, z_n is the mass fraction received from the n^{th} components.

3.2.1.7 High-Pressure Expansion Turbines(HPTr)

Mass balance equation is given as

$$Z_{1a} = Z_{1c} + Z_1 + \sum_{n=1}^{2} Z_{Bn} + \sum_{n=1}^{2} Z_{Cn} \qquad (23)$$

High-pressure expansion turbine work output is given as

$$W_{HPTr} = Z_{1a} \times (h_{1a} - h_{z1}) + (Z_{1a} - \sum_{n=1}^{1} Z_n) \times (h_{Z1} - h_{z2}) + (Z_{1a} - \sum_{n=1}^{2} Z_n) \times (h_{Z2} - h_{z1b}) \qquad (24)$$

Where, W_{HPTr} is work done by HPTr,h_x is specific enthalpy of various points in control volume of HPTr, Z_x is the mass fraction of various point in control volumn of HPTr.

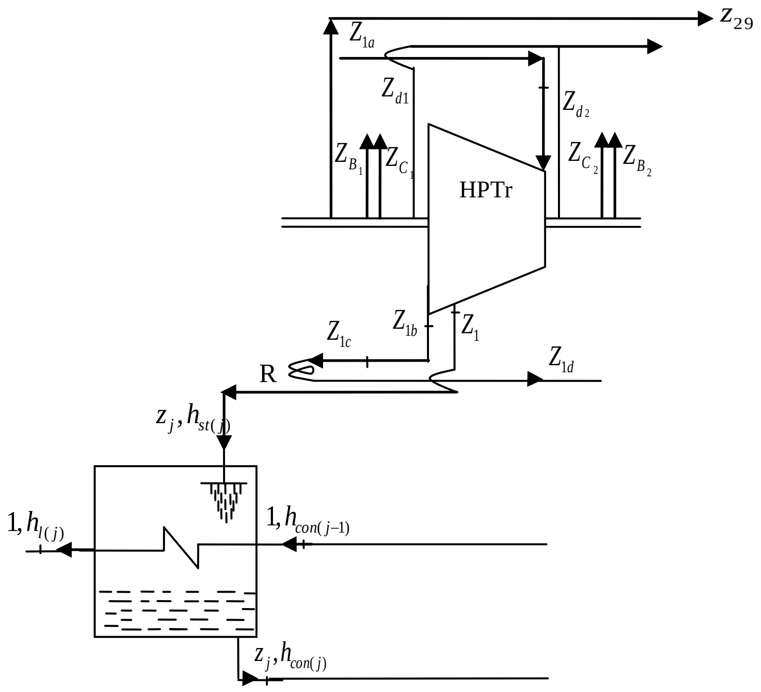


Figure 3.11: High-pressure turbine mass balance(HPTr)

3.2.1.8 Intermediate Pressure Expansion Turbines(IPTr)

Mass balance equation is given as

$$Z_{1d} = Z_{1b} + \sum_{n=3}^{4} Z_{Bn} + \sum_{n=3}^{4} Z_{Cn} + \sum_{n=3}^{5} Z_n \quad (25)$$

Intermediate pressure turbine work output is given as

$$W_{IPTr} = Z_{1d} \times (h_{1d} - h_3) + (Z_{1d} - \sum_{n=3}^{4} Z_n) \times (h_3 - h_4) + (Z_{1d} - \sum_{n=3}^{5} Z_n) \times (h_4 - h_5) \quad (26)$$

Where, W_{IPTr} is work done by IPTr, h_x is specific enthalpy of various point in control volumn of IPTr, Z_x is a mass fraction of various points in the control volume of IPTr.

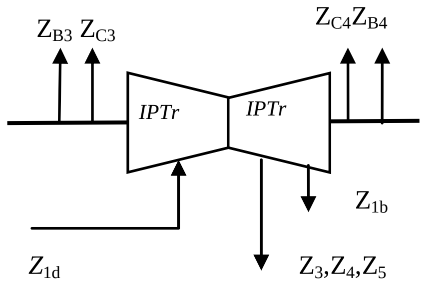


Figure 3.12: Intermediate pressure turbine mass balance (IPTr)

3.2.1.9 Low-Pressure Expansion Turbines(LPTr)

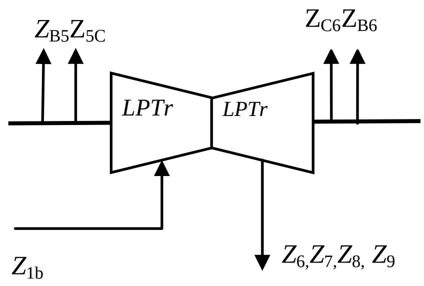


Figure 3.13: Low-pressure turbine mass balance (LPTr)

Mass balance equation is given as

$$Z_{1b} = \sum_{n=5}^{6} Z_{Bn} + \sum_{n=5}^{6} Z_{Cn} + \sum_{n=6}^{9} Z_n \qquad (27)$$

Low-pressure expansion turbine work output is given as

$$W_{LPTr} = Z_{1b} \times (h_{1b} - h_6) + (Z_{1b} - \sum_{n=6}^{7} Z_n) \times (h_6 - h_7) + (Z_{1b} - \sum_{n=7}^{8} Z_n) \times (h_7 - h_8) + (Z_{1b} - \sum_{n=8}^{9} Z_n) \times (h_8 - h_9) \qquad (28)$$

Where, W_{LPTr} is work done by LPTr, h_x is specific enthalpy of various points in control volume of LPTr, Z_x is a mass fraction of various points in control volume of LPTr.

3.2.1.10 Steam Generator

The thermodynamic modeling of the steam generator is formulated with an indirect loss measurement method in the present work and shown in table 3.4.

Table 3.4 : Once through boiler efficiency in the plant using the indirect method

Principle losses in boiler	**Reference equations**(Nikam et al. 2020c)
Loss of heat due to dry flue hot gas(L1)	$\frac{Z_{df} \times C_p \times (T_f - T_a)}{GCV\ of\ coal}$ (29) where, $Z_{df} = \sum(CO_2, SO_2, N_2\ in\ fuel, N_2\ in\ air\ supplied, O_2\ in\ flue\ gas)$ C_p= specific heat at constant pressure of flue gases=0.23kCal/ ^{o}C/ kg
Loss of heat due to the formation of water from H_2 in Fuel(L2)	$\frac{9 \times H_2 \times (584 + C_{psup} \times (T_f - T_a)}{GCV\ of\ coal}$ (30) where H_2 is the amount of H_2 in-unit kg of coal C_{psup} is the specific heat at a constant pressure of superheated steam = 0.45 kCal/ ^{o}C/ kg
Loss of heat due to moisture in Fuel(L3)	$\frac{Z' \times (584 \times C_{Psup} \times (T_f - T_a)}{GCV\ of\ coal}$ (31) where 'Z' is the amount of moisture in 1kg of coal constant 584 is latent heat with respect to the partial pressure of water vapor
Loss of heat due to moisture in the air(L4)	$\frac{Z_a \times hf \times C_p \times (T_f - T_a)}{GCV\ of\ coal}$ (32) where Z_a is the actual mass of air supplied per kg of coal, hf is humidity factor=0.0175.
Loss of heat due to the partial conversion of carbon to carbon monoxide(L5)	$\frac{CO \times C}{CO + CO_2} \times \frac{5654 \times 100}{GCV\ of\ coal}$ (33) where CO is the amount of carbon monoxide content in the coal sample, C is the amount of carbon content in the coal sample, CO_2 is the amount of carbon dioxide content in the coal sample.

Loss of heat due to unburnt carbon in fly ash(L6)	$\frac{M_{ash} \times Fly_{gcv}}{Coal_{gcv}}$ (34) Where, M_{ash} is ash collected per kg of coal burnt, Fly_{gcv} is GCV of flyash, $Coal_{gcv}$ is GCV of coal
Loss of heat due to unburnt carbon in bottom ash(L7)	$\frac{M_{ash} \times Bot_{gcv}}{Coal_{gcv}}$ (35) Where, M_{ash} is ash collected per kg of coal burnt, Bot_{gcv} is GCV of bottom ash, $Coal_{gcv}$ is GCV of coal
Loss of heat due to Radiation and Convection (L8)	0.21
Once trough boiler efficiency η	$100 - (\sum_{n=1}^{7} L_n \times 100) - L_8$ (36)
Practical mass of air supplied per unit kg of coal(Z_a)	$1 + \frac{O_2}{21 - O_2} \times [\{(11.6 \times C) + \left(34.8 \times H_2 - \frac{O_2}{8}\right) + (4.35 \times S)\}/100]$ (37)
Overall Plant Efficiency (η_{plant})	$1000 \times MW/(mcoal \times Coal_{GCV})$ (38)

The indirect method is preferred as errors that occurred while taking measurements do not significantly affect the steam generator's efficiency. The other losses are considered and reduced to estimate the steam generator efficiency. The actual operational data was supposed to find out the various losses. In the case of a SUPP, no separate region occurs between the two-phase of the working fluid. The drum structures boiler are replaced with tube strutures in a SUPP. The mass and Energy balance equations of all components are tabulated in Table 3.5.

Table 3.5: Mass and Energy Balance Equations of all components

S.No.	Components	Mass Balance	Energy Balance
1	High-Pressure Feedwater Heater(HPH_{1i})	$Z_{28i} = (Z_1/2)$ (39) $Z_{29i} = Z_{27i}$ (40)	$Z_{28i}h_{28i} = (Z_1/2)h_1$ (41) $Z_{29i}h_{29i} = Z_{27i}h_{27i}$ (42)
2	High-Pressure Feedwater Heater(HPH_{2i})	$Z_{26i} = Z_{28i} + (Z_2/2)$ (43) $Z_{27i} = Z_{25i}$ (44)	$Z_{26i}h_{26i} = Z_{28i}h_{28i} + (Z_2/2)h_2$ (45) $Z_{27i}h_{27i} = Z_{25i}h_{25i}$ (46)
3	High-Pressure Feedwater Heater(HPH_{3i})	$Z_R = Z_{26i} + (Z_3/2)$ (47) $Z_{25i} = Z_{24i}$ (48)	$Z_R h_R = Z_{26i}h_{26i} + (Z_3/2)h_3$ (49) $Z_{25i}h_{25i} = Z_{24i}h_{24i}$ (50)
4	Boiler Feed-pump	$Z_{24i} = Z_{24ii}$ (51) $Z_{22} = Z_{23}$ (52) $Z_{24i} = Z_{24ii} = (Z_{23}/2)$ (53)	$Z_{24i}h_{24i} = Z_{24ii}h_{24ii}$ (54) $Z_{22}h_{22} = Z_{23}h_{23}$ (55) $Z_{24i}h_{24i} = Z_{24ii}h_{24ii} = (Z_{23}h_{23}/2)$ (56)
5	High-Pressure Feedwater Heater(HPH_{1ii})	$Z_{28ii} = (Z_1/2)$ (57) $Z_{29ii} = Z_{27ii}$ (58)	$Z_{28ii}h_{28ii} = (Z_1h_1/2)$ (59) $Z_{29ii}h_{29ii} = Z_{27ii}h_{27ii}$ (60)
6	High-Pressure Feedwater Heater(HPH_{2ii})	$Z_{26ii} = Z_{28ii} + (Z_2/2)$ (61) $Z_{27ii} = Z_{25ii}$ (62)	$Z_{26ii}h_{26ii} = Z_{28ii}h_{28ii} + (Z_2h_2/2)$ (63) $Z_{27ii}h_{27ii} = Z_{25ii}h_{25ii}$ (64)
7	High-Pressure Feedwater Heater(HPH_{3ii})	$Z_R = Z_{26ii} + (Z_3/2)$ (65) $Z_{25i} = Z_{24i}$ (66)	$Z_R h_R = Z_{26ii}h_{26ii} + (Z_3h_3/2)$ (67) $Z_{25i}h_{25i} = Z_{24i}h_{24i}$ (68)
8	Deaerator	$Z_{22} = Z_4 + Z_{21} + (Z_{R+S})$ (69)	$Z_{22}h_{22} = Z_4h_4 + Z_{21}h_{21} + Z_Rh_R + Z_Sh_S$ (70)

9	Low-Pressure Feedwater Heater(LPH_1)	$Z_{21} = Z_{19}$ (71)	$Z_{21}h_{21} = Z_{19}h_{19}$ (72)
10	Low-Pressure Feedwater Heater(LPH_2)	$Z_{17} = Z_{19}$ (73) $Z_{20} = Z_5$ (74)	$Z_{17}h_{17} = Z_{19}h_{19}$ (75) $Z_{20}h_{20} = Z_5h_5$ (76)
11	Low-Pressure Feedwater Heater(LPH_3)	$Z_{15} = Z_{17}$ (77) $Z_{18} = Z_6 + Z_{20}$ (78)	$Z_{15}h_{15} = Z_{17}h_{17}$ (79) $Z_{18}h_{18} = Z_6h_6 + Z_{20}h_{20}$ (80)
12	Low-Pressure Feedwater Heater(LPH_4)	$Z_{13} = Z_{15}$ (81) $Z_{16} = Z_7 + Z_{18}$ (82)	$Z_{13} = Z_{15}$ (83) $Z_{16}h_{16} = Z_7h_7 + Z_{18}h_{18}$ (84)
13	Drain Cooler(DC)	$Z_{12} = Z_{13}$ (85) $Z_{14} = Z_8 + Z_{16}$ (86)	$Z_{12}h_{12} = Z_{13}h_{13}$ (87) $Z_{14}h_{14} = Z_8h_8 + Z_{16}h_{16}$ (87)
14	Gland Steam Condenser (GSC)	$Z_{11} = Z_{12}$ (88) $\sum_{n=1}^{6} Z_{Cn} = Z_I$ (89)	$Z_{11}h_{11} = Z_{12}h_{12}$ (90) $\sum_{n=1}^{6} Z_{Cn}\, h_{Cn} = Z_I h_I$ (91)
15	Condenser(Cond)	$Z_{10} = Z_9 + \sum_{n=1}^{6} Z_{Bn} + Z_F + Z_{(G+H+I+J+T+V+U+X)}$ (92)	$Z_{10}h_{10} = Z_9h_9 + \sum_{n=1}^{6} Z_{Bn}h_n + Z_Fh_F + (Z_{(G+H+I+J+T+V+U+X)}\, h_{(G+H+I+J+T+}$ (93)

16	High-Pressure Expansion Turbine (HPTr)	$Z_{1a} = (\sum_{n=1}^{2} Z_n) + Z_{3in} + \sum_{n=1}^{2} (Z_{Cn} + Z_{Bn})$ (94)	$Z_{1a} h_{1a} = (\sum_{n=1}^{2} Z_n h_n) + Z_{3in} h_n + \sum_{n=1}^{2} (Z_{Cn} h_n + Z_{Bn} h_n)$ (95)
17	Intermediate Pressure Expansion Turbine (IPTr)	$Z_{3out} = \sum_{n=3}^{5} Z_n + \sum_{n=3}^{4} (Z_{Cn} + Z_{Bn})$ (96)	$Z_{3out} h_{3out} = \sum_{n=3}^{5} Z_n h_n + \sum_{n=3}^{4} (Z_{Cn} h_n + Z_{Bn} h_n)$ (97)
18	Low-Pressure Expansion Turbine (LPTr)	$Z_{1b} = \sum_{n=6}^{9} Z_n + \sum_{n=5}^{6} (Z_{Cn} + Z_{Bn})$ (98)	$Z_{1b} h_{1b} = \sum_{n=6}^{9} Z_n h_n + \sum_{n=5}^{6} (Z_{Cn} h_n + Z_{Bn} h_n)$ (99)
19	Reheater	$Z_{3in} = Z_{3out}$ (100)	$Z_{3in} h_{3in} = Z_{3out} h_{3out}$ (101)

3.3 Exergy analysis

Exergy is maximum obtainable work as the systems interact to equilibrium, heat transfer occurs with the environment only(Bejan 1996). In the case of power generation, exergy indicates that the maximum amount of shaft work could be extracted from the process until the properties of steam reach equilibrium with the surrounding environment (Kotas 1985; Dincer et al. 2018). The present study presents the exergy forms of the individual component present in a coal-fired power plant rather than considering the total exergy. There are two forms of exergy, namely physical exergy, and chemical exergy. Specific physical exergy is expressed in enthalpy, entropy at present properties of temperature, and pressure concerning standard temperature and pressure of the surrounding environment. It is expressed as follow

$$e_{xph} = h - h_0 - T_0(s - s_0) \qquad (102)$$

The standard reference condition for exergy analysis is T_0 = 298.15 K and P_0= 101.325 kPa(A. Kumar, K.C. Nikam 2020). The chemical exergy associated with coal containing a fraction of carbon(c), hydrogen(h), oxygen(o), and nitrogen(n) is calculated from (Kotas 1985; A. Kumar, K.C. Nikam 2020) relation. The calculated chemical exergy also considered the fraction of moisture (w) and sulfur(s) in coal. The relation is expressed as follows.

$$exch = [LHV + 2442w](1.0437 + 0.1882\frac{h}{c} + 0.0610\frac{o}{c} + 0.0404\frac{n}{c} + 9417s \qquad (103)$$

The specific enthalpy and specific entropy at the different stream for evaluating physical exergy is calculated according to (Kumar et al. 2019) considering the coefficient (a1,a2,a3,a4,a5,a6, and a7)

$$h_g = -8.29173E-10p^6 + 5.45438E-07p^5 - 0.37544E-04p^4 + 1.66089E-02p^3$$
$$-9.8741E-01p^2 + 2.53297E+01p + 2.60544E+03 \qquad (104)$$

$$h_f = -1.40069E\text{-}09\,p^6 + 9.91868E\text{-}07\,p^5 - 2.68248E\text{-}04\,p^4 + 3.47195\text{-}02\,p^3 - 2.21241\,p^2 + 6.91350E+01\,p + 2.44324E+02 \quad (105)$$

$$s_g = 7.371\,p^{-0.04} \quad (106)$$

$$s_f = 0.257\ \ln(p) + 1.269 \quad (107)$$

$$h_{sup} = a_1 + a_2\,p^{0.25} + a_3\,s^2 + a_4\,ps^{1.5} + a_5\,p^2\,s + a_6\,ps^{2.25} + a_7\,p^{2.05}\,s^{1.05} \quad (108)$$

Exergy analysis is applied to determine the exergetic efficiency of components. Expressions for the exergy flow of fuel and products are represented in table 3.6. Exergetic efficiency is expressed as follows

$$\psi = \frac{E_{xp}}{E_{xf}} \quad (109)$$

Table 3.6: Formulation of total exergy stream of fuel (inlet) and products(outlet) of the components

Components	Exergy stream of Fuel	Exergy stream of Product
Steam Generator	E_{xc}-E_{32} (110)	$(E_{1a}$-$E_{x31})+(E_{x3out}$-$E_{x3in})$ (111)
HPTur.	E_{1a}-E_{x1}-E_{x2}-E_{x3in} (112)	W_{revhpt} (113)
IPTur.	E_{x3out}-E_{x4}-E_{x5i}-E_{x5ii}- E_{x6}-E_{1b} (114)	W_{revipt} (115)
LPTur.	E_{1b}-E_{x7}-E_{x8}-E_{x9}-E_{x10} (116)	W_{revlpt} (117)
Gen.	$W_{hpt}+W_{ipt}+W_{lpt}$ (118)	$mwe + powercep$ (119)
Cond.	E_{1a}-E_{x1}-E_{x2}-E_{x3in} (120)	-
CEPump.	$powercep$ (121)	$E_{x12} - E_{x11}$ (122)
DC	E_{x15}-E_{xh} (123)	$E_{x13} - E_{x14}$ (124)

LPHe-4	$E_{x9}+E_{x17}-E_{x15}$ (125)	$E_{x16}-E_{x14}$ (126)
LPHe-3	$E_{x8}+E_{x19}-E_{x17}$ (127)	$E_{x18}-E_{x16}$ (128)
LPHe-2	$E_{x7}+E_{x21}-E_{x19}$ (129)	$E_{x20}-E_{x18}$ (130)
LPHe-1	$E_{x6}-E_{x21}$ (131)	$E_{x22}-E_{x20}$ (132)
Dear.	$E_{x22}+E_{x5ii}+E_{xR}$ (133)	E_{x23} (134)
PDTur.	$E_{x5i}-E_{xb}$ (135)	*powerbfp* (136)
BFPump.	*powerbfp* (137)	$E_{x24}-E_{x23}$ (138)
HPHe-3	$E_{x4}+E_{x27}-E_{xR}$ (139)	$E_{x26}-E_{x25}$ (140)
HPHe-2	$E_{x2}+E_{x29}-E_{x27}$ (141)	$E_{x28}-E_{x26}$ (142)
HPHe-1	$E_{x1}-E_{x29}$ (143)	$E_{x30}-E_{x28}$ (144)

3.4 Economic Analysis :

In the present work, an economic analysis is performed in terms of Net present value (NPV) of the coal-fired plant. The net present value of the coal-fired plant is evaluated in terms of entire capital investment and total operating cost. The entire capital investment involves the overall direct and indirect costs related to the plant. The cost of each component like steam generator island, turbine island, etc., as well as auxiliary components collectively as BOP mechanical is categorized under total direct cost. The other costs like civil work, ash handling unit, coal handing unit, piping work,and site preparation are added with equipment cost. The installation cost of the plant and initial expenditure is categorized under indirect cost. The latest cost of components is taken into consideration to reduce complexity occur in the analysis (Kumar et al. 2014, 2015; Kumar 2017; Hoon et al. 2019) . The total direct plant cost is expressed as

$$C_{direct} = C_{Eqp} + C_{other} \qquad (145)$$

The cost of equipment, $C_{Eqp,}$ can be expressed as

$$C_{Eqp} = \sum_{i}^{n}(N_iC_i) + C_{piping} + C_{civil} + C_{electrical} + C_{coalhandling} + C_{ashhandlig} \qquad (146)$$

Here, 'N_i' represents the number of spare units of pumps. The available literature indicates that cost of components in term of total load using power law (Kumar et al. 2015) and is given by

$$C_i = a_i MW^{bi} \qquad (147)$$

Where i represent equipment involved plant.
Indirect cost is calculated as follow

$$C_{indirect} = \xi C_{Eqp} \qquad (148)$$

Here, ξ is a factor that considers engineering and plant start-up expenses.
Total capital investment is expressed as

$$C_{tci}=C_{direct}+C_{indirect} \quad (149)$$

The present worth method converts all cash flow to a single sum equivalent at time zero by assuming an interest rate (i). Cost of fuel and Life-time cost can be obtained in terms of present worth factor as follows

$$PWF_k=\frac{1}{(1+i)^k} \quad (150)$$

The cost data of steam generator island, turbine generator island, BOP(Balance of Plant) mechanical, BOP electrical packing, civil works, coal handling unit, ash handling unit, pipe costing are evaluated by curve fitting actual data obtained from the plant with 660MW capacity and a varying number of unit (n)as shown in figures 3.13 to figures 3.20. The number of the capacity unit varies from 1 to 4. The fuel cost is evaluated concerning changing the calorific value of fuel(Tongia and Gross 2019). The cost involved in economic analysis are taken in Indian Rupees(Rs).1$(American Dollar) = 74.555Rs(Indian Rupees). The constants a and b are tabulated in table 3.7. The linear regression curve fitting is shown in Figures 3.14 to figures 3.21. The steam generator BOP electrical packing, coal handling unit, ash handling unit, and ash handling unit shows a linear relationship with variation in plant load from 660MW to 2640MW. The BOP mechanical and Turbine generator island shows power function with variation in plant load. The civil works show exponential rise with variation in plant load.

Table 3.7: Designed thermodynamic properties of points in 660 MW power cycle

Sr.No	Component	a	B	Reference
1	Steam generator island	20000000.00	-3000000000.00	(Dincer and Rosen 2013a; Kumar et al. 2015)
2	Turbine generator island	1000000.00	1.362	(Dincer and Rosen 2013a; Kumar et al. 2015)
3	BOP mechanical work	0.063	3.644	(Dincer and Rosen 2013a; Kumar et al. 2015)
4	BOP electrical packing work	56826.00	4000000000.00	(Dincer and Rosen 2013a; Kumar et al. 2015)
5	Civil work	3000000000.00	0.001	(Dincer and Rosen 2013a; Kumar et al. 2015)
6	Coal handling unit	4000000000.00	7×10^{-5}	(Dincer and Rosen 2013a; Kumar et al. 2015)
7	Ash handling unit	-44162.00	2000000000.00	(Dincer and Rosen 2013a; Kumar et al. 2015)
8	Pipe costing	10928.00	200000000.00	(Dincer and Rosen 2013a; Kumar et al. 2015)
9	Fuel Cost	136.03	0.0005	(Dincer and Rosen 2013a; Kumar et al. 2015)

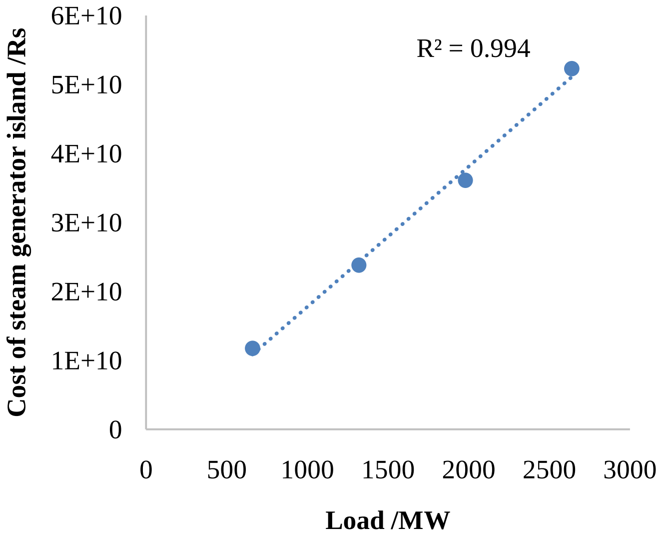


Figure.3.14: Linear regression-curve fitting for the cost of steam Generator Island

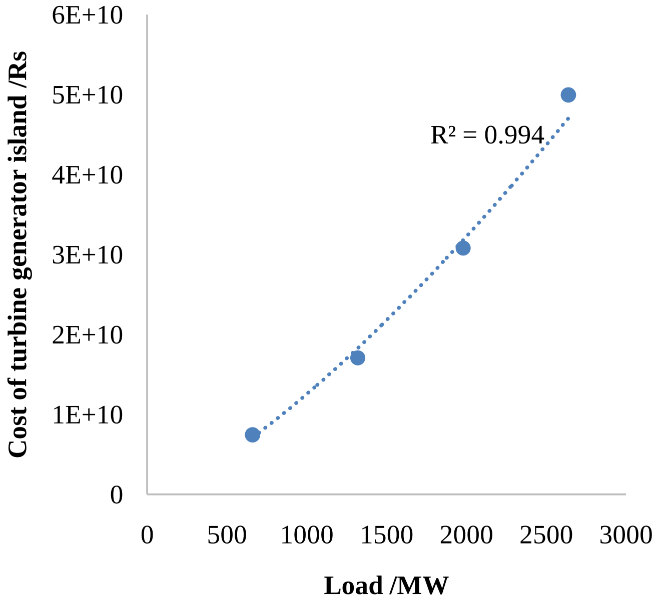


Figure.3.15: Linear regression-curve fitting for turbine generator island

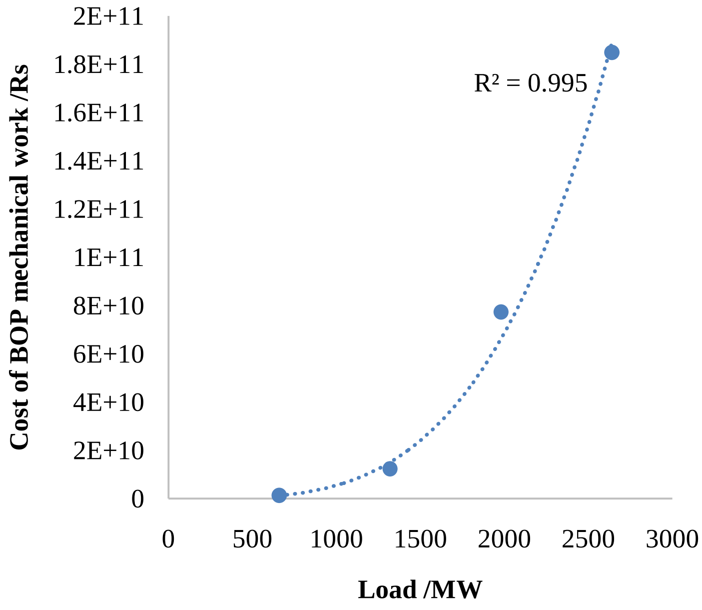


Figure.3.16: Linear regression-curve fitting for BOP mechanical work

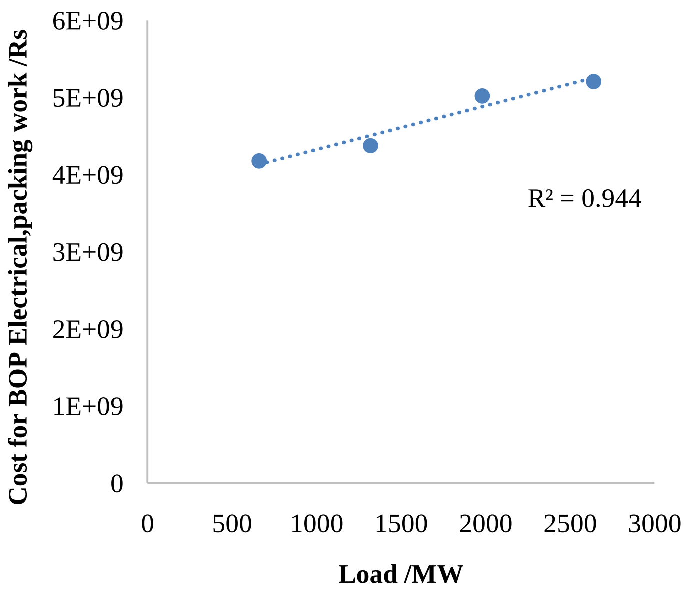


Figure.3.17: Linear regression-curve fitting for BOP Electrical, packing

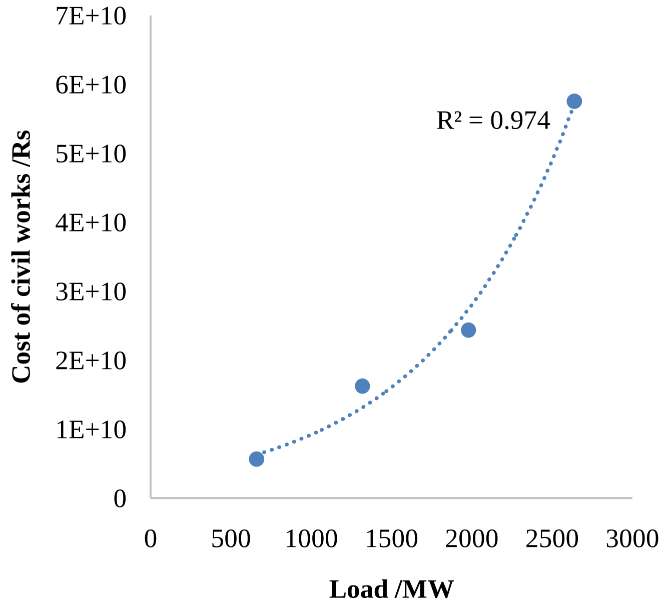


Figure.3.18: Linear regression-curve fitting for civil works

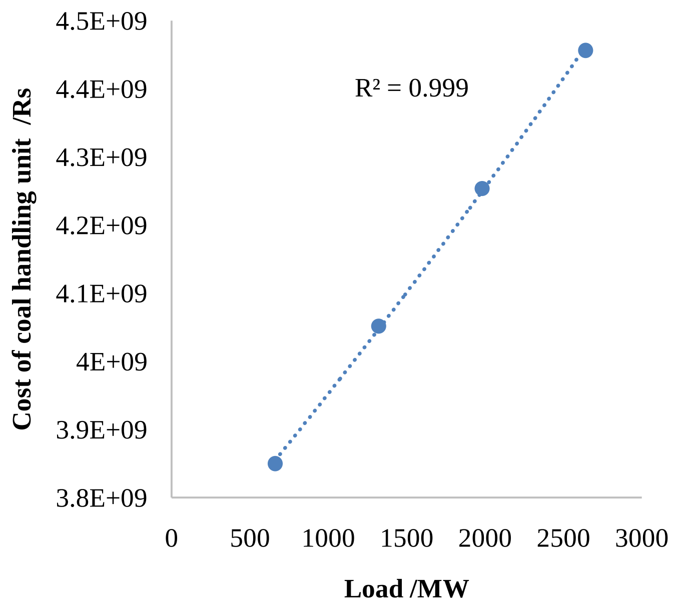


Figure.3.19: Linear regression-curve fitting for coal handling

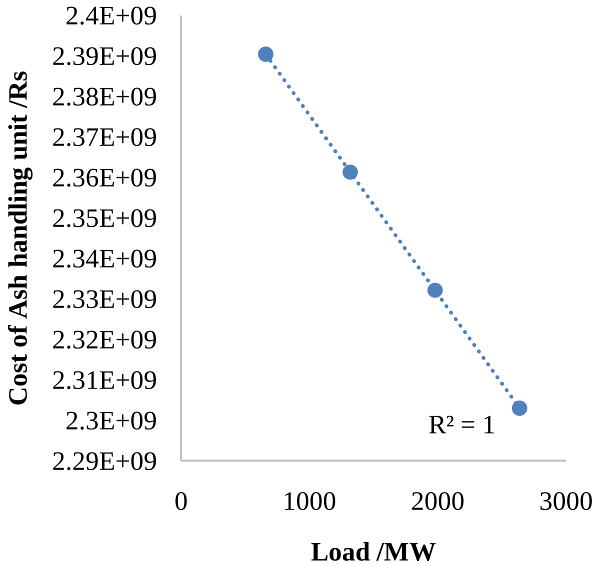


Figure.3.20: Linear regression-curve fitting for ash handling

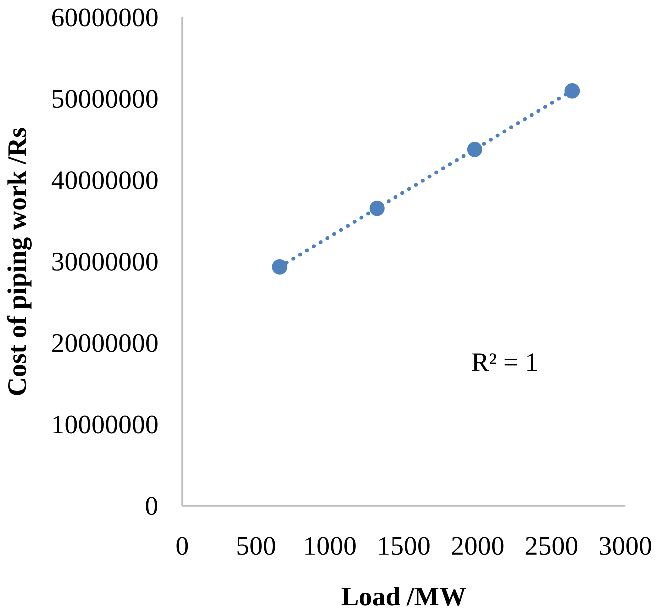


Figure.3.21: Linear regression-curve fitting for pipe costing

The escalation rate value for fuel cost(F), maintenance cost(M), labour cost(L), insurance cost(I), pumping cost (P), number of labour, and their salary component are taken from the literature(Yan et al. 2019, 2020; Kumar et al. 2020).

Fuel Cost

$$C_{coal}=\sum_{k=1}^{pl}(PWF_k \times m_{coal,k}+C_{CC}\ (1+F)^{(k-1)}) \tag{151}$$

Maintenance Cost

$$C_{ma\,\mathrm{int}}=\sum_{k=1}^{pl}(PWF_k \times 0.015 \times C_{tci}\ (1+M)^{(k-1)}) \tag{152}$$

Labour Cost

$$C_{lab}=\sum_{k=1}^{pl}(PWF_k \times n_L \times C_S\ (1+L)^{(k-1)}) \tag{153}$$

Insurance Cost

$$C_{ins}=\sum_{k=1}^{pl}(PWF_k \times 0.01 \times C_{tci}\ (1+I)^{(k-1)}) \tag{154}$$

Pumping Cost

$$C_{ins}=\sum_{k=1}^{pl}(PWF_k \times 8760 Av_{overall} \times [\sum_{j=1}^{N}(\frac{\frac{\Delta P_j\ m_j}{\rho_{water}}}{\eta_{pump,j}})/\ ] \times C_{ep}\ (1+P)^{(k-1)}) \tag{155}$$

Lifetime Cost

$$C_O = C_{coal} + C_{main} + C_{lab} + C_{ins} + C_{pumping} \tag{156}$$

Revenue over the Life span

$$R_{lifetime}=f_{MW}\sum_{k=1}^{pl}(PWFk+MW+8760Av_{overall}\times C_{ep}\ (1+P)^{(k-1)} \quad (157)$$

The sum of all the present values is known as the Net Present Value. This is done by equating each future cash flow to its current value. Net present value is calculated as follow

$$NPV_{lifetime}=R_{lifetime}-(C_o+C_{tci})_{lifetime} \quad (158)$$

3.5 Exergoeconomic Analysis:

The specific exergy costing method (SPECO) approach is performs exergoeconomic analysis(Lazzaretto and Tsatsaronis 2006). The first step in exergoeconomic analysis is to evaluate the exergy of the stream. The reference condition for exergy analysis are T_0 = 298.15 K and P_0= 101.325 kPa(A. Kumar, K.C. Nikam 2020). The individual equipment is classified with the summation of input stream exergy (Fuel) and output stream exergy (Product). Table 3.8 represents the exergy stream of the fuel and product side.

Table 3.8 : Formulation of Exergy Destruction of the components

Components	Exergy Destruction
Steam Generator	E_{xc}-$E_{32}-(E_{1a}$-$E_{x31})+(E_{x3out}$-$E_{x3in})$ (159)
HPTur.	E_{1a}-E_{x1}-E_{x2}-$E_{x3in}-W_{revhpt}$ (160)
IPTur.	E_{x3out}-E_{x4}-E_{x5i}-E_{x5ii}- E_{x6}-$E_{1b}-W_{revipt}$ (161)
LPTur.	E_{1b}-E_{x7}-E_{x8}-E_{x9}-$E_{x10}-W_{revlpt}$ (162)
Gen.	$W_{hpt}+W_{ipt}+W_{lpt}-MW-powercep$ (163)

Cond.	E_{1a}-E_{x1}-E_{x2}-E_{x3in} (164)
CEPump.	$powercep-(E_{x12}-E_{x11})$ (165)
DC	E_{x15}-$E_{xh}-(E_{x13}-E_{x14})$ (166)
LPHe-4	$E_{x9}+E_{x17}$-$E_{x15}-(E_{x16}-E_{x14})$ (167)
LPHe-3	$E_{x8}+E_{x19}$-$E_{x17}-(E_{x18}-E_{x16})$ (168)
LPHe-2	$E_{x7}+E_{x21}$-$E_{x19}-(E_{x20}$-$E_{x18})$ (169)
LPHe-1	E_{x6}-$E_{x21}-(E_{x22}-E_{x20})$ (170)
Dear.	$E_{x22}+E_{x5ii}+E_{xR}-E_{x23}$ (171)
PDTur.	E_{x5i}-$E_{xb}-powerbfp$ (172)
BFPump.	$powerbfp-(E_{x24}-E_{x23})$ (185)
HPHe-3	$E_{x4}+E_{x27}$-$E_{xR}-(E_{x26}-E_{x25})$ (173)
HPHe-2	$E_{x2}+E_{x29}$-$E_{x27}-(E_{x28}-E_{x26})$ (174)
HPHe-1	E_{x1}-$E_{x29}-(E_{x30}-E_{x28})$ (175)

The next step of exergoeconomic starts with the calculation of purchased-equipment cost (PEC) for each component. The PEC's for boiler, heat exchanger, turbine, condenser, deaerator, and generator is being calculated with relation available in the literature (Wang et al. 2014). The capital investment cost (CC) is determined from the purchased-equipment cost.

$$Z_K = \frac{CC+OMC}{N_{aoh}\omega}\frac{PEC_K}{\sum PEC_K} \tag{176}$$

The cost balance of a productive component k is expressed as

$$\sum_{i=1}^{i=n}(E.c)_{in,\,i} + Z_K + C_{aux,\,dc,\,k} = \sum_{i=1}^{nout}(E.c)_{out,\,i} + C_{dif,\,dc,\,k} \quad (177)$$

Where the term $C_{aux,\, dc,k}$ indicates the cost rate of additional working fluids, $C_{diff,\, dc,k}$ are charged to the cost of the final product.

The specific cost of exergy loss is expressed as

$$C_{l,\,j} = c_{F,\,k} \times .E_{l,\,j} \quad (178)$$

The thermo-economic variables, i.e., average unit costs of the fuel $C_{F,k}$, and the product $C_{P,k}$, the cost rate of exergy destruction $C_{D,k}$, the summation $(C_D + Z)_k$, the relative cost difference r_k , and the exergoeconomic factor f_k, are calculated. Table 3.9 represents the formulation of the main exergoeconomic and auxiliary equation to evaluate the cost flow of each stream.

$$c_{F,\,K} = \frac{C_{F,\,K}}{E_{F,\,K}} \quad (179)$$

$$c_{P,\,K} = \frac{C_{P,\,K}}{E_{P,\,K}} \quad (180)$$

$$C_{D,\,k} = c_{F,\,K}.E_{D,\,k} \quad (181)$$

The relative cost difference r_k and exergoeconomic factor f_k are the exergoeconomic variables.

The relative cost difference is expressed in terms of cost per exergy for fuel and product side of components. The exergoeconomic factor f_k is expressed in terms of nonexergy related costs and exergy destruction.

$$r_k = \frac{(c_{p,\,k} - c_{F,\,k})}{c_{F,\,k}} \quad (182)$$

$$f_k = \frac{z_k}{(z + c_D)_k} \quad (183)$$

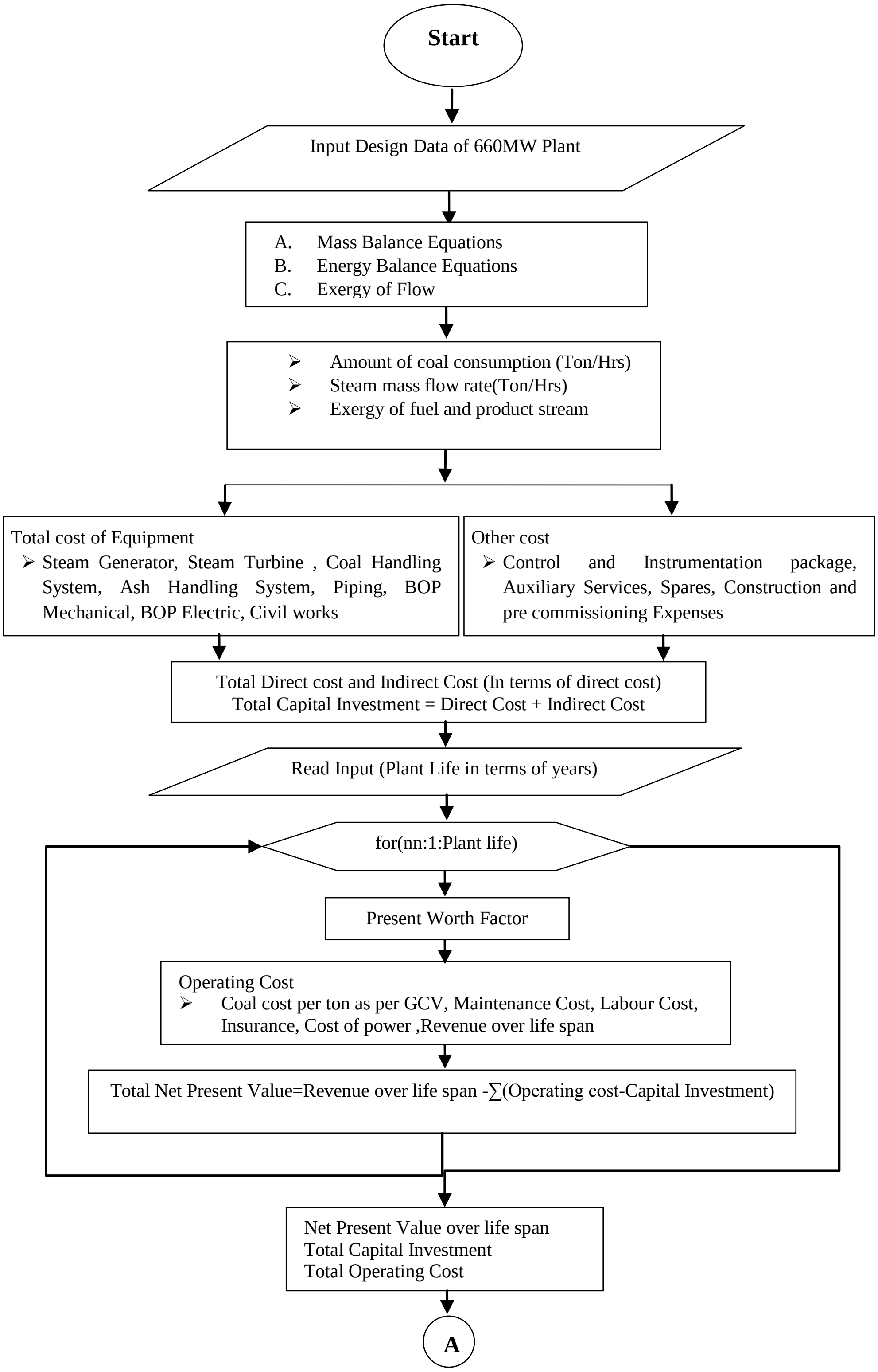
The MATLAB package is used to stimulate economic and exergoeconomic analysis. Figure 3.22 represents the flowcharts of the methodology for economic and exergoeconomic analysis. The economic and exergoeconomic analysis is carried out by using the present worth method and SPECO approach.

Table 3.9 : Exergoeconomic Equations

Component	**Main Equations**	**Auxiliary Equations**
Steam Generator	$C_c + C_{30} + C_{3in} - C_{1a} - C_{3out} - C_{31} = -Z_{comb}$ (184)	$C_{1a} - C_{30} = \frac{(E_{1a} - E_{x30})}{(E_{3out} - E_{3in})}(C_{3out} - C3_{in})$ (185) $C_c = \frac{(E_c)}{(E_{31})} C_{x31}$ (186)
HPTur.	$C_{1a} - C_{x1} - C_{x2} - C_{x3in} - C_{hpt} = -Z_{hptur.}$ (187)	$C_{1a} = \frac{(E_{1a})}{(E_1)} C_{x1}$ (188) , $C_{1a} = \frac{(E_{1a})}{(E_2)} C_{x2}$ (189) $C_{1a} = \frac{(E_{1a})}{(E_{3in})} C_{x3in}$ (190)
IPTur.	$C_{x3out} - C_{x4} - C_{x5i} - C_{x5ii} - C_{x6} - C_{1b} - C_{ipt} = -Z_{iptur.}$ (191)	$C_{3out} = \frac{(E_{3out})}{(E_4)} C_{x4}$ (192) , $C_{3out} = \frac{(E_{3out})}{(E_{5i}} C_{x5i}$ (193) $C_{3out} = \frac{(E_{3out})}{(E_{5ii})} C_{5ii}$ (194) , $C_{3out} = \frac{(E_{3out})}{(E_{5ii})} C_{x1b}$ (195)

		$C_{3out} = \frac{(E_{3out})}{(E_6)} C_{x6}$ (196)
LPTur.	$C_{1b} - C_{x7} - C_{x8} - C_{x9} - C_{x10} - C_{lpt} = -Z_{lptur.}$ (197)	$C_{1b} = \frac{(E_{1b})}{(E_7)} C_{x7}$ (198) , $C_{1b} = \frac{(E_{1b})}{(E_8)} C_{x8}$ (199) $C_{1b} = \frac{(E_{1b})}{(E_9)} C_{x9}$ (200) , $C_{1b} = \frac{(E_{1b})}{(E_{10})} C_{x10}$ (201)
Gen.	$C_{hpt} + C_{ipt} + C_{lpt} - C_{PE} - C_{PB} = -Z_{gen.}$ (202)	$C_{PE} = \frac{(E_{PE})}{(E_{PB})} C_{PB}$ (203)
Cond.	$C_{xb} + C_{x10} + C_{xh} - C_{x11} - C_{waterout} = -Z_{cond.}$ (204)	$C_{x11} = \frac{(E_{11})}{(E_{xb} + E_{x10} + E_{xh})} (C_{xb} + C_{x10} + C_{xh})$ (205)
CE Pump	$C_{x11} + C_{PB} - C_{x12} = -Z_{cepump}$ (206)	-
LPHe-4	$C_{x14} + C_{x9} + C_{x17} - C_{x15} - C_{x16} = -Z_{lphe\text{-}4}$ (207)	$C_{x15} = \frac{(E_{15})}{(E_9 + E_{17})} (C_{x9} + C_{x17})$ (208)
LPHe-3	$C_{x16} + C_{x8} + C_{x19} - C_{x17} - C_{x18} = -Z_{lphe\text{-}3}$ (209)	$C_{x17} = \frac{(E_{17})}{(E_8 + E_{19})} (C_{x8} + C_{x19})$ (210)
LPHe-2	$C_{x7} + C_{x18} + C_{x21} - C_{x20} - C_{x19} = -Z_{lphe\text{-}2}$ (211)	$C_{x19} = \frac{(E_{19})}{(E_7 + E_{21})} (C_{x7} + C_{x21})$ (212)

LPHe-1	$C_{x6} + C_{x20} - C_{x22} - C_{x21} = -Z_{lphe1}$ (213)	$C_{x21} = \frac{(E_{21})}{(E_6)}(C_{x6})$ (214)
Dear.	$C_{x5ii} + C_{x22} + C_{xR} - C_{x23} = -Z_{dear}$ (215)	-
BFPump.	$C_{x23} - C_{x24} + C_{PF} = -Z_{bfpump}$ (216)	-
PDTur.	$C_{x5i} - C_{xb} - C_{PF} = -Z_{pdtur.}$ (217)	$C_{x5i} = \frac{(E_{5i})}{(E_{xb})}(C_{xb})$ (218)
HPHe-3	$C_{x24} + C_{x27} - C_{x26} - C_{xR} = -Z_{hphe3}$ (219)	$C_{xR} = \frac{(E_R)}{(E_4 + E_{27})}(C_{x4} + C_{x27})$ (220)
HPHe-2	$C_{x2i} + C_{x26} + C_{x29} - C_{x28} - C_{x27} = -Z_{hphe2}$ (221)	$C_{x27} = \frac{(E_{27})}{(E_2 + E_{29})}(C_{x2} + C_{x29})$ (222)
HPHe-1	$C_{x28} + C_{x1} - C_{x29} - C_{x30} = -Z_{hphe1}$ (223)	$C_{x29} = \frac{(E_{29})}{(E_1)}(C_{x1})$ (224)
DC	$C_{x15} + C_{x12} - C_{xh} - C_{x14} = -Z_{DC}$ (225)	$C_{xh} = \frac{(E_{xh})}{(E_{15})}(C_{x1})$ (226)
Combustion	$C_c = Z_{comb}$ (227)	-


Start
Input Design Data of 660MW Plant
A. Mass Balance Equations
B. Energy Balance Equations
C. Exergy of Flow
Amount of coal consumption (Ton/Hrs)
Steam mass flow rate(Ton/Hrs)
Exergy of fuel and product stream
Total cost of Equipment
Steam Generator, Steam Turbine , Coal Handling System, Ash Handling System, Piping, BOP Mechanical, BOP Electric, Civil works
Other cost
Control and Instrumentation package, Auxiliary Services, Spares, Construction and pre commissioning Expenses
Total Direct cost and Indirect Cost (In terms of direct cost)
Total Capital Investment = Direct Cost + Indirect Cost
Read Input (Plant Life in terms of years)
for(nn:1:Plant life)
Present Worth Factor
Operating Cost
Coal cost per ton as per GCV, Maintenance Cost, Labour Cost, Insurance, Cost of power ,Revenue over life span
Total Net Present Value=Revenue over life span -∑(Operating cost-Capital Investment)
Net Present Value over life span
Total Capital Investment
Total Operating Cost
A

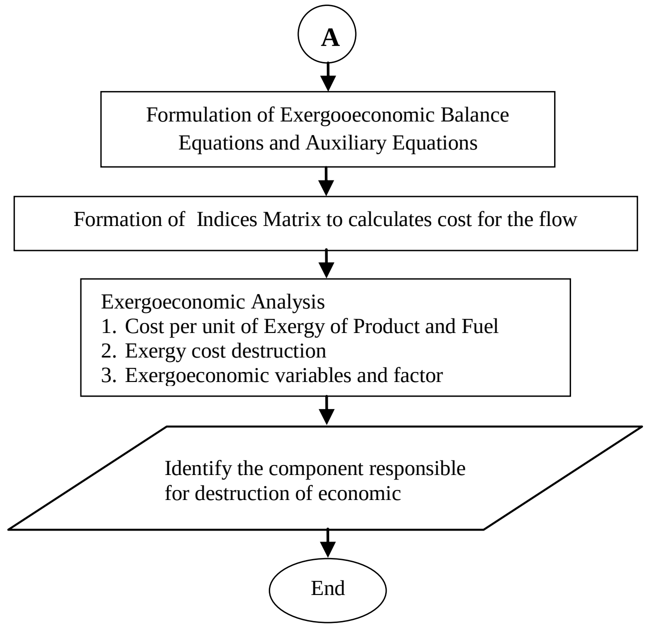


Figure. 3.22. Flowchart for Economic and Exergoeconomic Analysis

3.6 Exergo-environmental analysis

3.6.1 Life cycle assessment

The trend in over-exploitation of non-renewable and finite energy sources leads engineers to think of product performance from an environmental point of view. Now a day, pollution prevention technology is a significant concern for the components in use. LCA is the most preferred tool to assess the environmental impact of components based upon its manufacturing, operation, maintenance, and final disposal. LCA reveals information on the unsustainable consumption of fuel. LCA assesses the life cycle of the components from their existence to their destruction. Eco-indicator 99 is widely preferred to analyze an environmental load of components. Eco-indicators are represented in the unit of point(Pt) or milipoint(mPts). The various damage factor based upon human health, ecosystem quality, resources were prepared by Goedkoop(Goedkoop and Spriensma 2001). The hierarchies' perspective with the average weighting approach is considered in the present study. Due to limited data available, most of the consideration and assumptions are been used to figure out the contribution to the environmental impact of each component(Cavalcanti 2017). The environmental impact rate is calculated considering the power plant life of operation as 25 years with a time of operation of the plant per year in Hours as 6900 and an availability factor of 0.8.

The exergo-environmental analysis is performed in the same manner as that of exergoeconomic analysis by allocating cost to the exergy flow of components by the SPECO method proposed by (Lazzaretto and Tsatsaronis 2006). The environmental impact factor(B_i) of i^{th} flow in terms of mPts s^{-1} is calculated as a product of specific environmental impact factor b_i and corresponding exergy flow of that particular stream(Meyer et al. 2009). It is expressed as follows:

$$B_i = b_i E_{xi} \tag{228}$$

The environmental impact balance for the j^{th} components equation is expressed in terms of the summation of environmental impact on the inlet and outlet of components. It is expressed as follows

$$\sum_{i=1}^{n} \dot{B}_{i,j,in} + \dot{Y}_j + \dot{B}^{PF}_{j,k,in} = \sum_{i=1}^{m} \dot{B}_{i,j,out} \tag{229}$$

where , $\dot{Y}_j$ is the environmental impact of the j^{th} component obtained from the life cycle assessment tool. It is the summation of the environmental effects associated with construction, operation, maintenance, and disposal life phases and is expressed as follows

$$\dot{Y}_j = Y^{CON}_j + Y^{OMe}_j + Y^{DIP}_j \tag{230}$$

and $\dot{B}^{PF}_{j,k,in}$ is the factor related to pollutants produced in the components during the operation. It is considered as zero when no chemical reaction takes place in the component. It is expressed as

$$\dot{B}^{PF}_{j,k,in} = \sum_k b^{PF}_k (\dot{m}_{k,out} - \dot{m}_{k,in}) \tag{231}$$

The environmental impact of product and fuel is expressed as follows

$$b_{i,f} = \frac{B_{i,f}}{E_{i,f}} \tag{232}$$

$$b_{i,p} = \frac{B_{i,p}}{E_{i,p}} \tag{233}$$

The environmental impact with the exergy destruction for the j^{th} component in the system is expressed as follows

$$B_{D,J} = b_{f,j}.E_{D,j} \tag{234}$$

To obtain environmental impact rates for flows (mPts s^{-1}), an incidence matrix based on environmental impact balance equations and supporting equations have been constructed. The environmental impacts brought from the LCA of the fuel and the plant's components are considered as input. The environmental impact rate of the equipment is obtained based on the estimated weight (kg) of this equipment(Cavalcanti 2017), and corresponding Eco-indicator values are considered from the life cycle impact assessment methodology(Goedkoop and Spriensma 2001). The auxiliary equations for condensate extraction pump, reheater, deaerator, and boiler feed pump are not formed since a single output flow is coming out from these components (Rocha and Silva 2019).

The exergo-environmental variable r_b is expressed as a ratio of the relative difference of specific environmental impact of product, and fuel to the specific environmental impact of fuel. The variable r_b represents the impact of the component based on the environment. The lower value of the exergo-environmental variable indicates maximum measures are to be taken to reduce the environmental impact of components. It is expressed as follows.

$$r_b = \frac{b_{i,p} - b_{i,f}}{b_{i,f}} \tag{235}$$

One more factor is vital for exergo-environmental analysis i.e., Exergo-environmental factor f_b. The exergo-environmental factor indicates whether exergy destruction is dominant over component related environmental impact. It is expressed as follows.

$$f_b = \frac{Y_j + B_{j,k}^{PF}}{Y_j + B_{j,k}^{PF} + B_{D,j}} \tag{236}$$

3.7 Multi-Objective Optimization

3.7.1 Objective Function

The present complex synthesis problem involves three objective functions, Energetic Efficiency (%), Exergetic efficiency (%), and Cost of electricity (Rs/Unit). The first law efficiency for a thermal power plant is formulated as follow

$$\eta = \frac{mwe \times 1000 \times 100}{CVcoal \times mcoal} \tag{237}$$

Where, mwe is the power generated (MW), CVcoal is the calorific value of coal, η is the plant efficiency (%), and mcoal is the amount of coal consumed (Kg/sec)

The present study involved certain assumptions as Isentropic efficiency of turbine 91%, Isentropic mechanical efficiency of turbine 99.63%, and Generator, and transformation efficiency 98.32%(Dincer and Rosen 2013b). The exergetic efficiency (%) is formulated as follow

$$\psi = \frac{mwe \times 956.5584 - 15.06}{CVcoal \times mcoal} \times 100 \tag{238}$$

The expression for the cost of electricity (COE) in terms of the operating cost for lifetime, power output (mwe), annual time of operation of the plant per years in Hrs (No), and annual capacity factor (ωc) is estimated as

$$COE = \frac{Operating\ \cos t\ \ for\ lifetime}{mwe \times No \times \omega c} \tag{239}$$

3.7.2 Decision variables

The power demand always varies with the requirement of the customer for the electricity. So it becomes complicated for plant engineers to make the power generation plan as per customer demand. Because of this, power output (mwe), the calorific value of coal (CVcoal), and the amount of coal consumed (mcoal) are taken as direct decision variables. The indirect decision variables are pressure and temperature conditions at the inlet of high-pressure turbine, intermediate pressure turbine, and low-pressure turbine. The inlet pressure, and temperature conditions of HPTu, IPTu and LPTu play a vital role in exergy analysis of supercritical coal-fired power plant(Nikam et al. 2020b). The upper and lower bounds of decision variables have been taken from the design manual of the supercritical power plant and are shown in Table3.10.

Table 3.10: Decision variables lower and upper bounds

Decision Variables	Lower bounds	Upper bounds
Power output	198 MW	660MW
Calorific value of coal	3400 Kcal/Kg	7000 Kcal/Kg
Amount of coal consumed.	18.2296 Kg/sec	124.6524
Pressure at inlet of High-Pressure turbine	92.3061bar	247 bar
Temperature at inlet of High-Pressure turbine	565 °C	565 °C
Pressure at inlet of Intermediate-Pressure turbine	15.8330 bar	50.5292 bar
Temperature at inlet of Intermediate-Pressure turbine	593 °C	593 °C
Pressure at inlet of Low-	2.0873 bar	5.8221 bar

Pressure turbine		
Temperature at inlet of Low-Pressure turbine	267.5344 °C	298.3528 °C

3.7.3 Optimization technique

The present study employs the particle swarm optimization technique for multi-objective optimization. The particle swarm optimization technique is inspired by flying birds' change positions. The murmuration phenomenon of flying birds changes position by changing the velocity based upon neighbor birds and past experience searching for food. So, this searching process have been utilized for the optimization problems (Prakash et al. 2018). Each bird is considered as a particle with a fitness value. The individual particle fitness value is PBest value, and group particle fitness values are GBest value. The outcome of PSO is to determine fitness value. The initial velocity and position for j^{th} particle with population size of n are expressed by Vj = (V(j,1)+ V(j,2) + ...+ V(j,n)) and Sj = (S(j,1) + S(j,2) + ...+ S(j,n)), respectively. The flowchart for multi-objective particle swarm optimization is as shown in the figure.3.23. The position and velocity of particles are updated by the following relation:

$$Vj = w \times Vj + cj \times r1 \times (PBest, j - Sj) + c2 \times r2 \times (GBest, j - Sj) \qquad (240)$$

Where, w,r1,r2,c1,c2 are the inertia factor to impose the effect of old velocity on latest velocity, random numbers with an interval of 0 to 1, positive constants and coefficient respectively.

The present study focuses on optimizing the thermodynamic and economic parameters of coal-fired supercritical coal fired power plant by using multi-objective particle swarm optimization. The objective of the optimization study is to maximize energy efficiency, maximize exergy efficiency, and minimize cost of electricity. The equal weights are assigned to all input variables of

0.33, and their sum is approximated to 1. The common objective value (*Xmax*) is formed with the following relation

$$X\max = \frac{w1 \times X1}{X1\max} + \frac{w2 \times X2}{X2\max} - \frac{w3 \times X3}{X3\min} \tag{241}$$

Where, *X1max* is the maximum value of energy efficiency, *X2max* is the maximum value of exergy efficiency, and *X3min* is the minimum value of cost of electricity and the terms '*w1*', '*w2*', '*w3*' are the weights assigned to the responses.

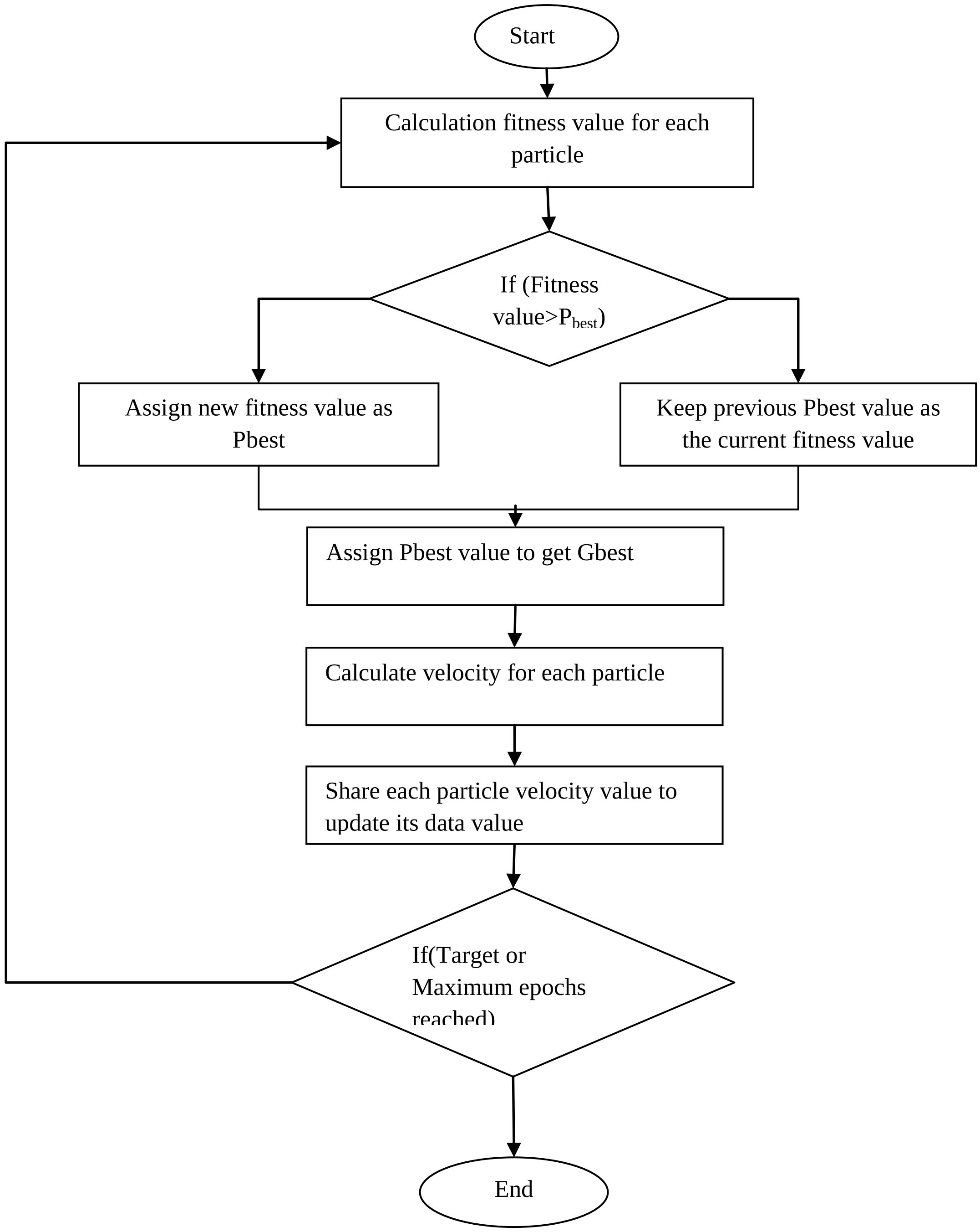


Figure 3.23: Flowchart for MOPSO

CHAPTER 4

4. RESULTS AND DISCUSSION

This chapter presents the results obtained from energy, exergy, economic, exergoeconomic, and exergoenvironmental analysis of SUPP of capacity 660MW. The chapter also includes the validation of results with suitable references.

4.1 Energy Analysis

The plant performance parameters were determined by the model, and validated with actual operating data. The attempt is made to draw the Sankey diagram of 660MW coal-fired SUPP. The previous effort to construct a Sankey diagram for a conventional power plant for energy analysis was made (Soundararajan, Ho, and Su 2014). Figure 4.1 represents the amount of heat energy involved in different equipment types of 660MW coal-fired power plants. The amount of heat released by burning coal in the boiler section contributes to 2050060kJ/s. The effect of re-heater is seen in the intermediate pressure turbine as steam is allowed to re-heater section. The condenser contributes to 36.42% of energy rejected to cooling water.

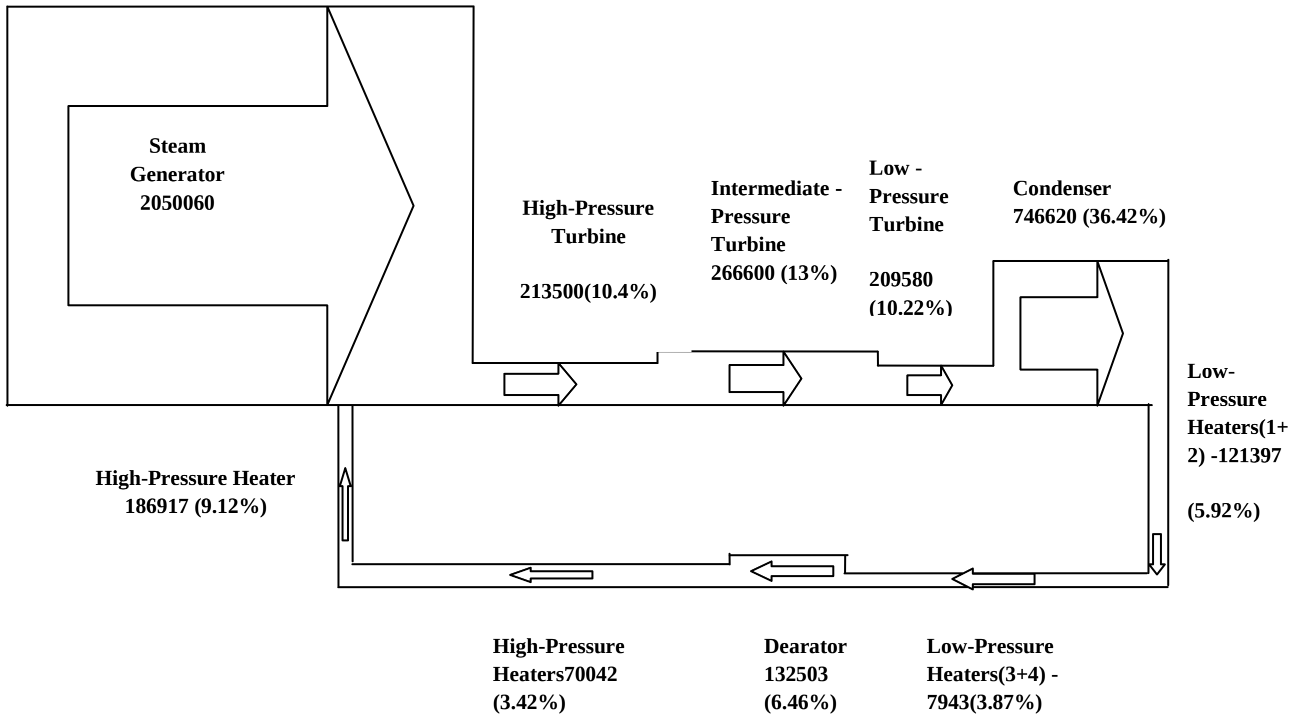


Figure 4.1: Sankey diagram of 660MW plant

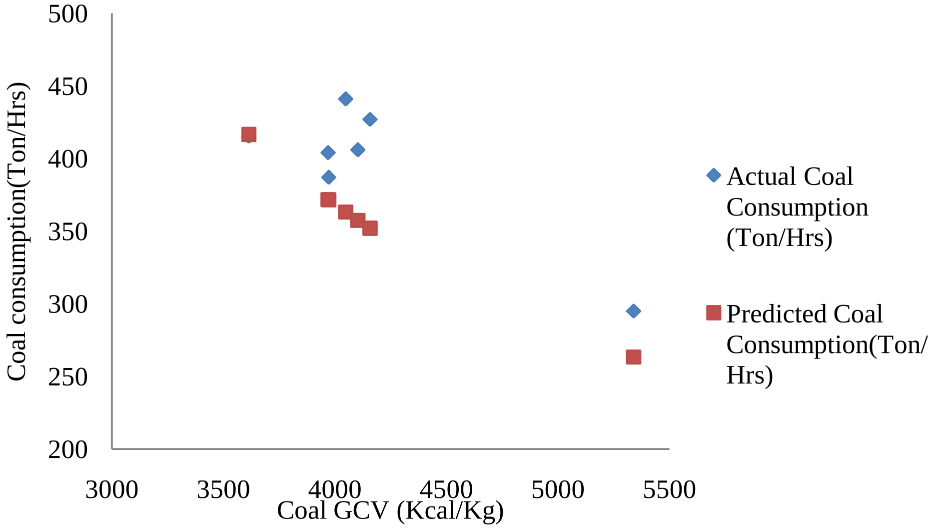


Figure 4.2: Coal Gross Calorific Value (GCV) vs. Mass of coal consumption

Coal is available in different grades and classified according to gross calorific values(Xue 2016). The coal consumption with various coal grades was monitored for a 660MW SUPP. The semi-empirical model determines the predicted coal consumption, and results were validated with actual fuel consumption. The trend of coal consumption decreases with an increase in the fuel quality, as shown in Figure 4.2. The predicted 415 TPH (ton per hour) coal consumption is matched to actual coal consumption, with coal having a grade of 3613 Kcal/kg.

The present study also compares actual and predicted steam generator efficiency with varying plant loads of SUPP, as shown in figure 4.3. Many times situation comes where the demand load is low for electricity; the plant needs to run at a different load. Steam generator operating efficiency was found to be approximately in a range of 84% to 87% during the plant visit. Operational steam generator efficiency was validated with the output obtained from the simulated model's output (see fig. 4.3). The variation of predicted and actual steam generator efficiency is majorly seen due to varying moisture content in coal, varying feedwater temperature recorded during monitoring.

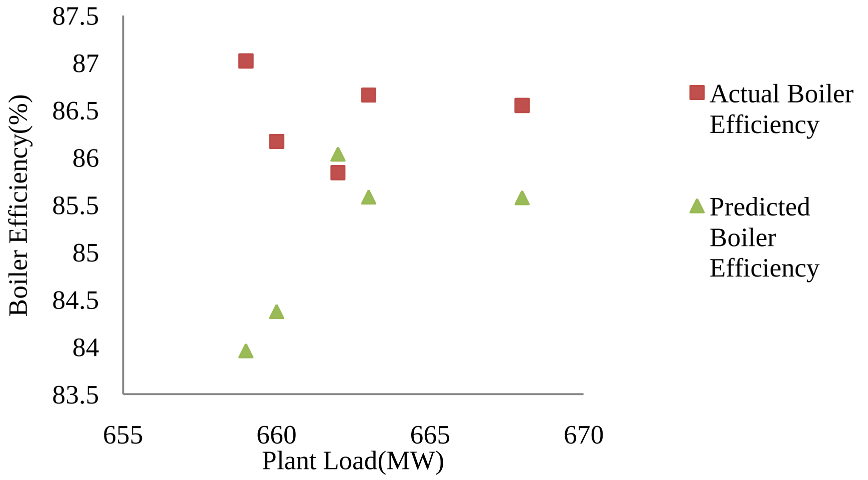


Figure 4.3: Plant load vs. Boiler Efficiency

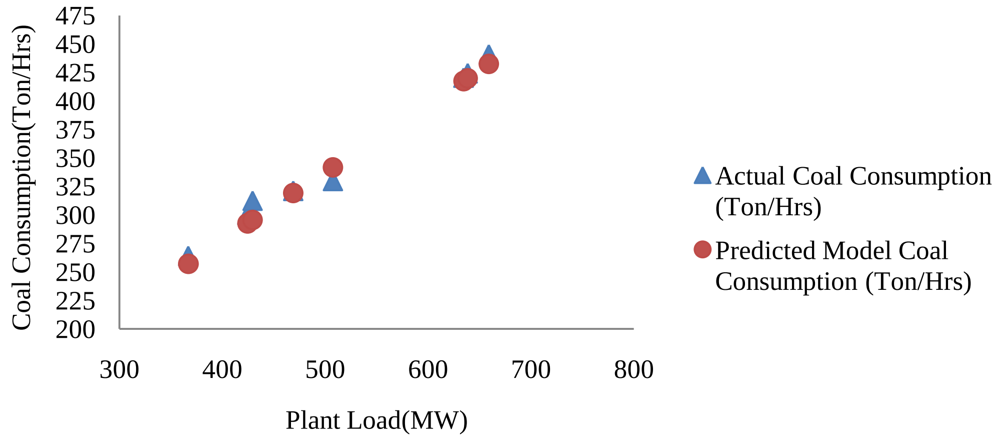


Figure 4.4: Plant load vs. Coal consumption

The coal consumption is a decision parameter to predict the duration of the plant working and planning of fuel for electricity generation(D. P. Hanak et al. 2015; Kumar, Kshitij Ojha, Ahmadi, Raj, et al. 2019). While visiting the 660MW SUPP, it was observed that coal with an average GCV of 3600kcal/kg was used. Coal consumption rate in Ton/Hrs at different loads was recorded, and the same was used for validation of the semi-imperial module, as shown in figure 4.4. The average percentage error concerning the actual coal consumption of the predicted model was found to be 1.39%. This variation in the result is due to the presence of varying moisture content. Figure 4.4, confirms that the coal consumption rate increases with an increase in plant load for a fixed capacity of SUPP(Surywanshi et al. 2019). At plant load 634.45MW, predicated coal consumption was found to be 417.4487 Ton/hrs, and the true exact value was recorded as 420.37 Ton/hrs. The minimum percentage error of 0.694935 has been evaluated.

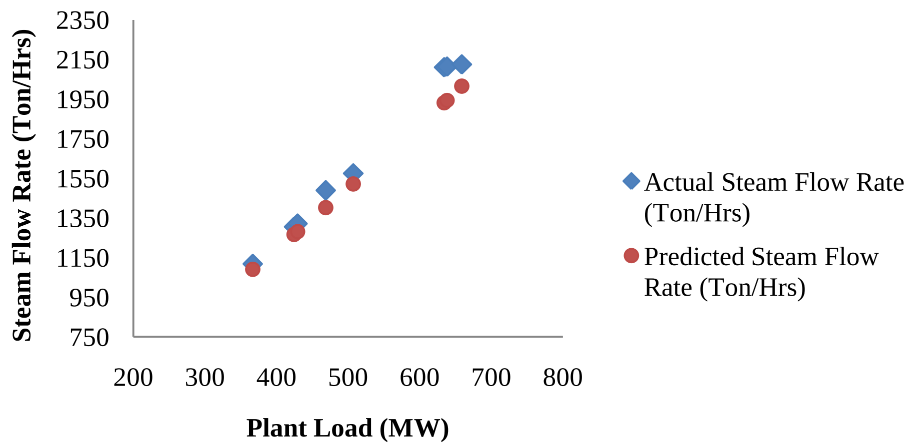


Figure 4.5: Plant Load vs. Steam flow rate

The steam flow rate follows the linear relationship with the plant load. As the plant load increases, the steam flow rate also increases. The validation of increment in steam flow rate with actual readings is shown in figure 4.5. It is clear from the figure 4.5, that the steam flow rate increases from 1120 Ton/hrs to 2085 Ton/hrs with a varying load of 366.9 MWe to 649.7MWe.

4.2 Exergetic Efficiency

The operating parameters, such as steam mass flow rate, temperature, pressure have been considered from the 660MW power plant. The exergy of fuel, product, and exergetic efficiency are tabulated in Table 4.1. It is seen from table 4.1, that the steam generator contributes the lowest exergetic efficiency of 51% among all the components. The previous investigation was confirmed that the boiler is a significant contributor to exergy destruction(Adibhatla and Kaushik 2014; Ameri et al. 2016; Mohammadi et al. 2015; Noroozian et al. 2017). As can be seen from Table 4.1 that the exergy destruction is not dominant for the component such as turbines set, generator, heaters set. Besides, the boiler, deaerator, and condensate extraction pump contribute to lower exergetic efficiency in a range of 70% to 80%. The overall exergetic efficiency of the plant is evaluated as 35.54%. Exergetic efficiency always indicates how components approach with the flawless operation. Table 4.1

also compares the results obtained from the semi-empirical model with available literature. Figure 4.7 represents the exergetic efficiency of the components. It is clear from figure 4.7 that the lowest exergetic efficiency is seen in the Steam generator of 51%, followed by condenser 54%, deaerator 70%, and condensate extraction pump 78%. The turbine set and high-pressure heater set contribute to the maximum exergy efficiency of the system. Figure 4.6 represents the Grassman diagram of components exergy destruction as a percentage of total input exergy.

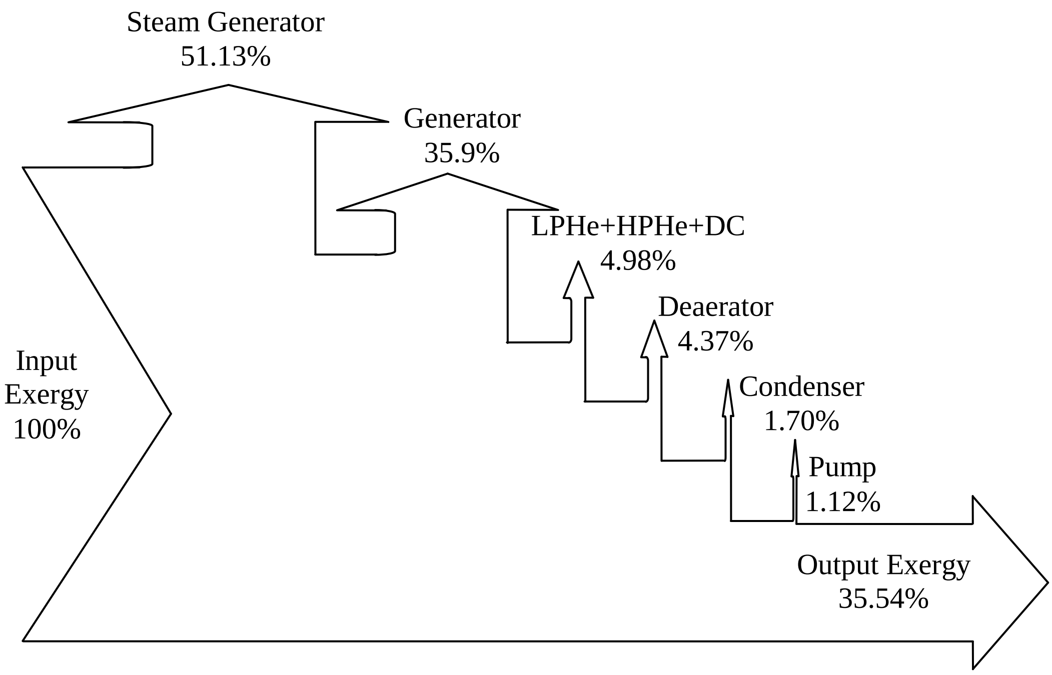


Figure 4.6: Grassman Diagram of components exergy destruction as percentage of total input exergy

Table 4.1: Exergetic efficiency of plant (components wise)

Components	Exergy of Fuel (kW)	Exergy of Product (kW)	Exergy Destruction (kW)	Exergetic Efficiency (%)			
				Present Study	Ref. (Kumar, Nikam, and Jilte 2020)	Ref. (Adibhatla and Kaushik 2014)	Ref. (Topal et al. 2017)
Steam Generator	1843158	942590	900568	51	-	52.30	43.19
HPTur.	227210	213500	13710	94	95.04	93.64	90.15
IPTur.	266600	253850	12750	95	94.8	95.11	-
LPTur.	217180	209580	7600	96	68.77	90.18	-
Gen.	689670	661700	27970	96	-	90.18	-
Cond.	58045	31430	26615	-	-	-	-
CEPump	1698	1333	365	78	67.18	71.77	75.51
DC	765	708	57	93	-	-	-
LPHe-4	4798	4110	688	86	85.93	87.62	84.07
LPHe-3	8155	6920	1235	85	86.91	80.03	89.77
LPHe-2	10200	8903	1297	87	86.94	79.84	87.19
LPHe-1	22656	19577	3079	86	89.99	65.64	-
Dear	114760	80622	34138	70	-	90.94	98.63
PDTur.	23877	21773	2104	91	-		-
BFPump	21773	19423	2350	89	88.83	90.81	-
HPHe-3	13809	13234	575	96	95.9	94.03	98.90
HPHe-2	25637	23391	2246	91	92.9	92.18	-
HPHe-1	15310	15080	230	98	-	92.51	-
Plant	1843158	655157		35.54	39.23	35.56	31.26

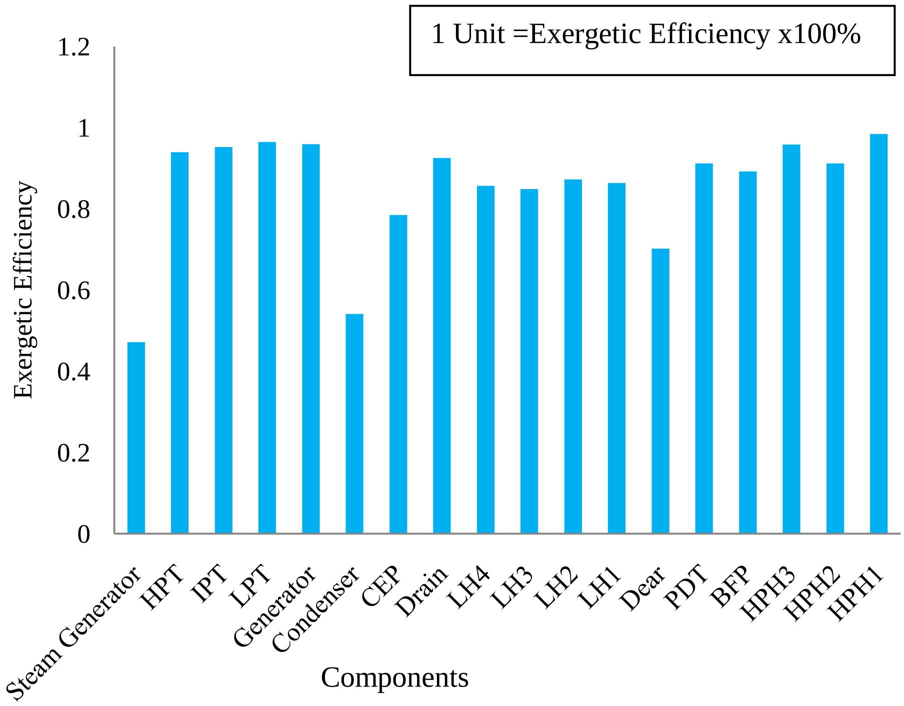


Figure .4.7: Exergetic efficiency of components

The variation of exergetic efficiency of the turbine set, pumps, deaerator, and steam generator to inlet pressure of high-pressure turbine is represented by figures 4.8 to figures 4.11. The high-pressure turbine shows maximum variation as compared with low and intermediate pressure turbines. The exergetic efficiency of high, intermediate, and low-pressure turbine is maximum at full load capacity at a pressure of 247bar as represented in figure 4.8. The condensate extraction pump shows less variation with an increase in the inlet pressure of high-pressure turbine. The boiler feed pump shows a significant growth in exergetic efficiency from 87.50% to 89.20%, with an increment in pressure from 127.90bar to 247bar, as shown in figure 4.9. It is clear from figure 4.10 that with an increase in the inlet pressure of a high-pressure turbine, the exergetic efficiency decreases from 85.36% to 70.25%. The trend of steam generator exergetic efficiency shows increment from 49.72% to 51.11 % up to a pressure of 202.89bar and then remains nearly constant at a higher pressure of 247bar, as shown in figure 4.11.

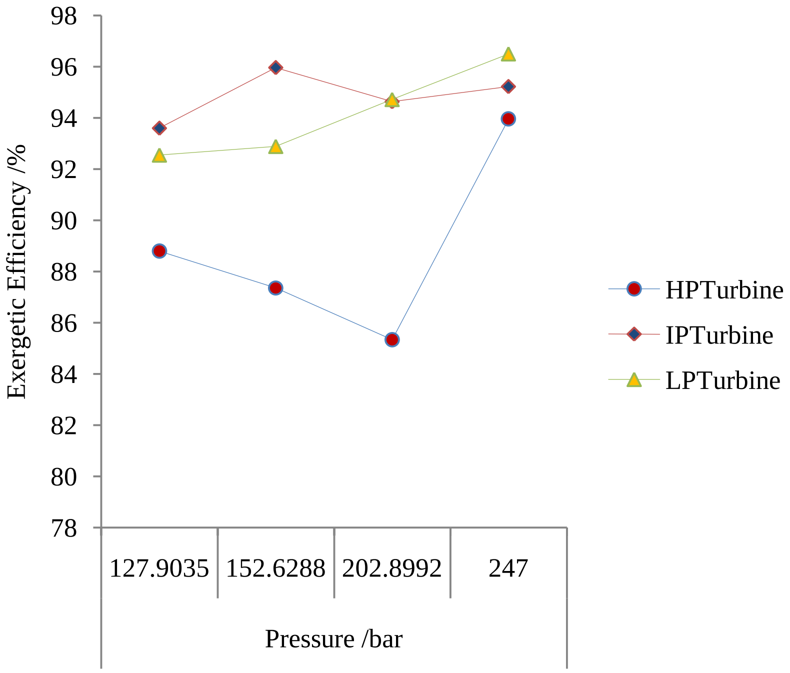


Figure.4.8 Variation of Exergetic Efficiency of Turbine set with inlet pressure

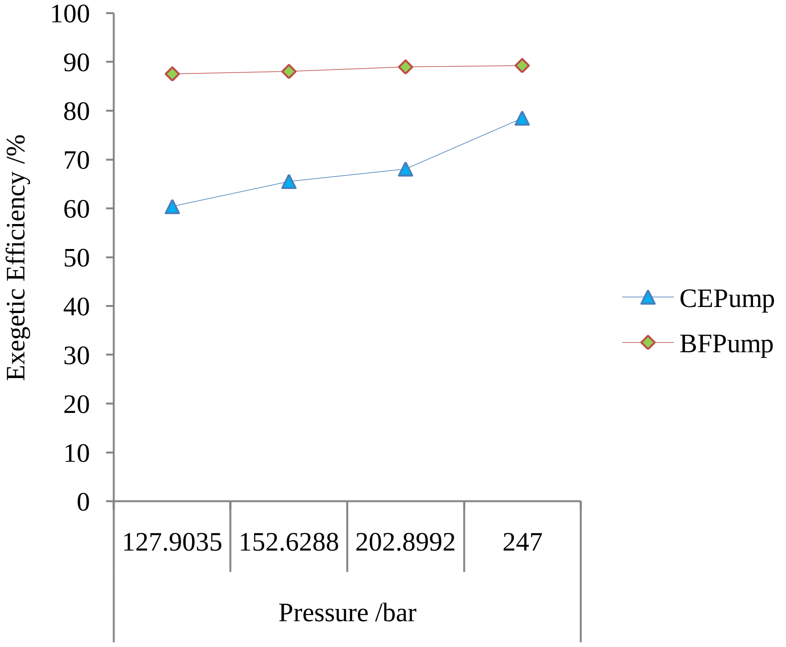


Figure.4.9 Variation of Exergetic Efficiency of Pump set with inlet pressure

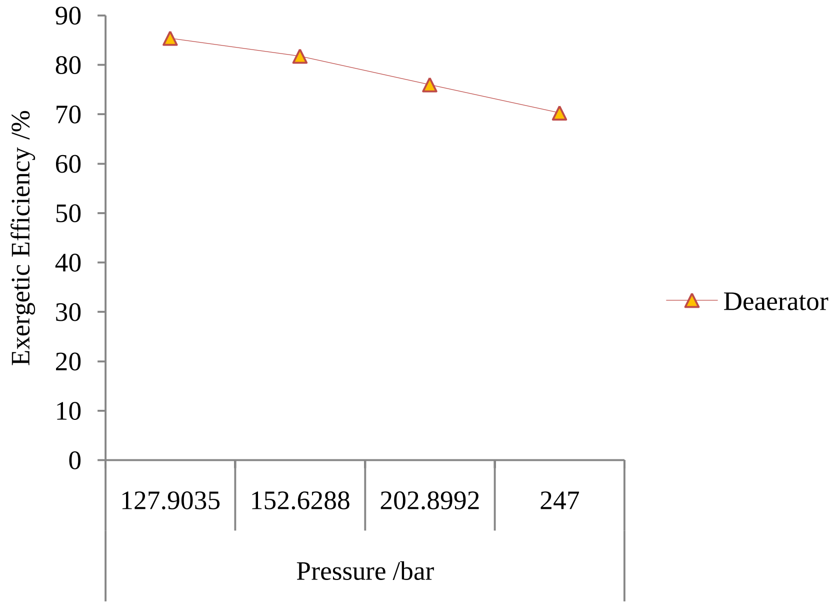


Figure.4.10 Variation of Exergetic Efficiency of Deaerator with inlet pressure

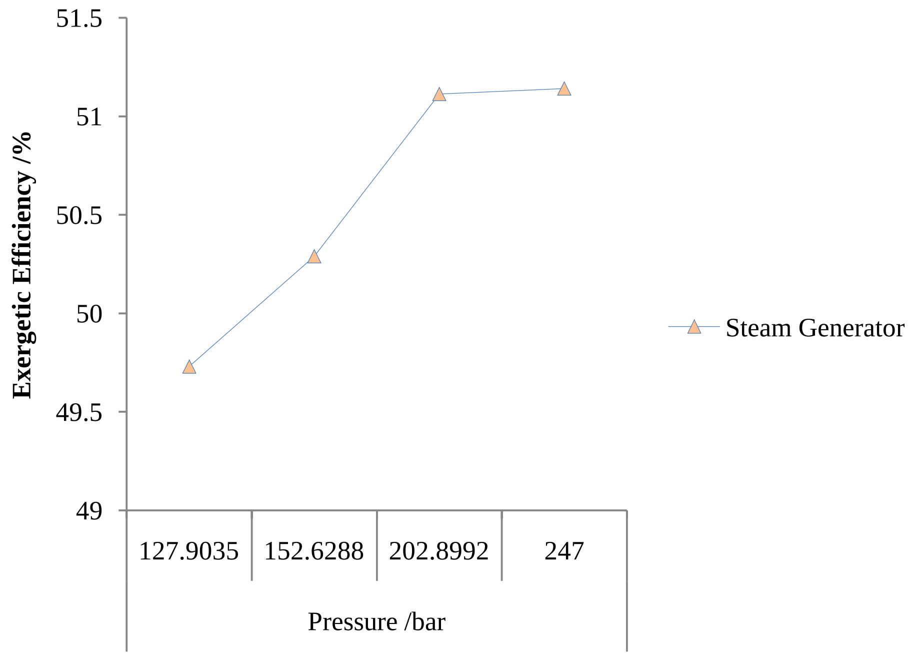


Figure.4.11 Variation of Exergetic Efficiency of Steam Generator with inlet pressure

4.3 Economic Analysis

The economic analysis of the 660MW Plant is carried out to reveal the behavior of the lifetime cost of necessary components. The plant life of 30 years and present interest rate of 9% is taken into account for this analysis(Kumar, Ahmadi, et al. 2020). The lifetime cost increases with plant life as, shown in figure 4.12. The cost related to pumping and labour shows the least increment as compared with other lifetime costs. The fuel cost increases from 1171.6crores to 5169.26crores with 30 years of life span.

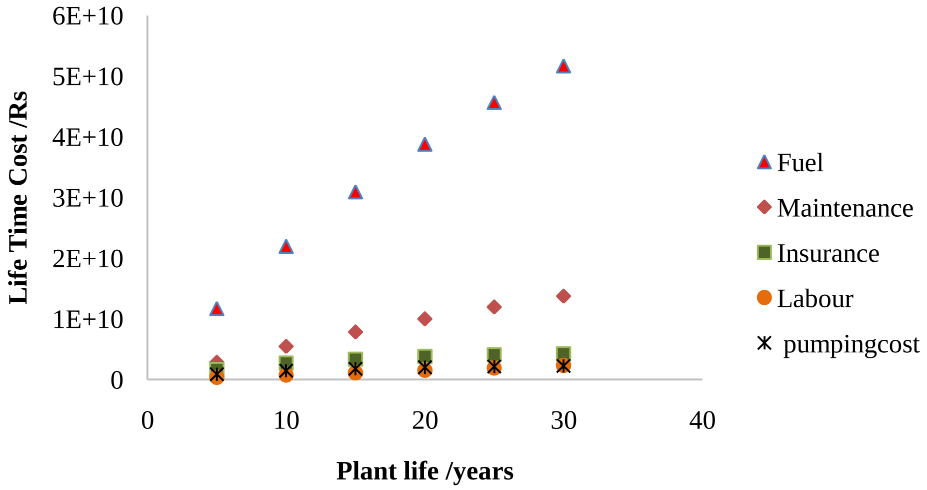


Figure.4.12: Plant life (Years) v/s Life Time cost (Rs.)

A previous similar study was conducted on a subcritical power plant of 250MW capacity, which results in the payback period of 10 years(Kumar, Ahmadi, et al. 2020). The current research of supercritical proved to be more feasible as payback period reduces to 4.5 years, as shown in figure 4.13. Total revenue increases up to 31640 INR Corers over 30 years. The total capital cost remains nearly steady as compared with operating costs. The supercritical plant generates revenue and gives the profit after 4.5 years of commencement.

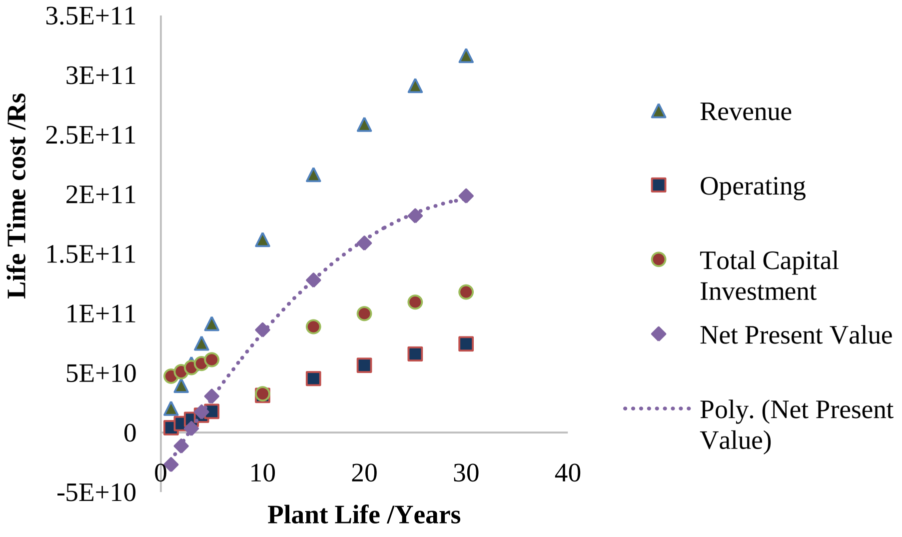


Figure.4.13: Plant life (Years) v/s Life Time cost (Rs.)

The economic study was extended to lifetime cost plotted concerning varying the plant load from 198MW to 660MW. The situation occurs where plant needs to run under capacity for a long-duration depends upon the demand requirement. It is necessary to study the behavior of the lifetime cost of the supercritical plant with varying loads. Figure 4.14 shows that, except labour and pumping cost, all other costs improve with plant load varying from 198MW to 660MW. Figure 4.15 represents revenue goes on increasing as the plant operates to its maximum capacity. The revenue generated varying plant load increased from 8736.54crores to 29121.8crores. The revenue generated is 2.92 times greater for the supercritical power plant than the subcritical power plant of capacity 210MW(Kumar et al. 2015).

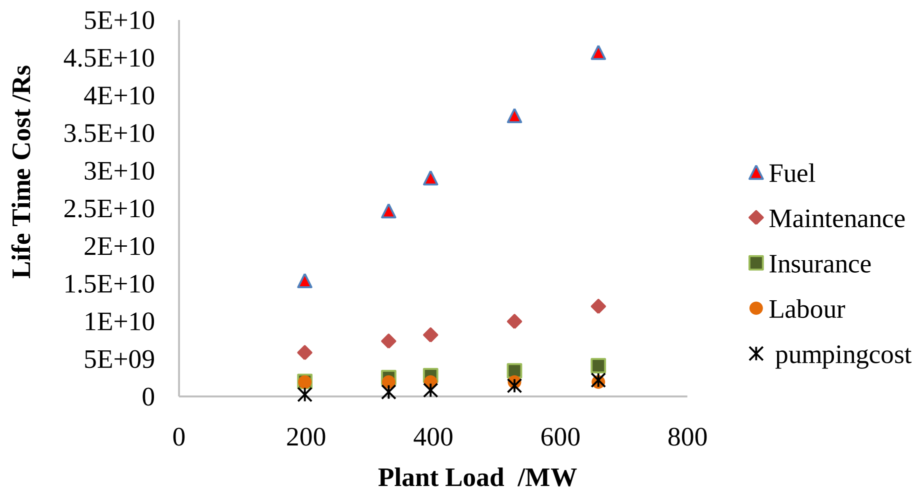


Figure.4.14: Plant load (MW) v/s Life Time cost (Rs.)

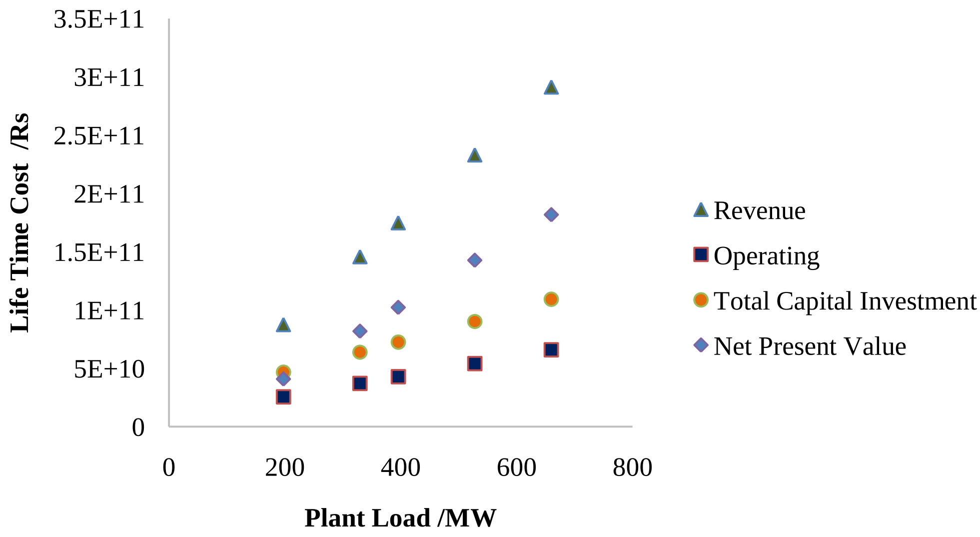


Figure .4.15: Plant load (MW) v/s Life Time cost (Rs.)

The prediction of lifetime cost concerning the varying interest rate is performed in the present study. The increase in the interest rate causes a decrease in lifetime cost, specifically for fuel cost and maintenance cost. The other cost shows the least decrement for varying interest rates. The annual interest rate from 9% to 15 % is considered for the study, as shown in figure 4.16. Also, the revenue generated from the plant shows the decrement curve for an increase in the interest rate, as shown in figure 4.17.

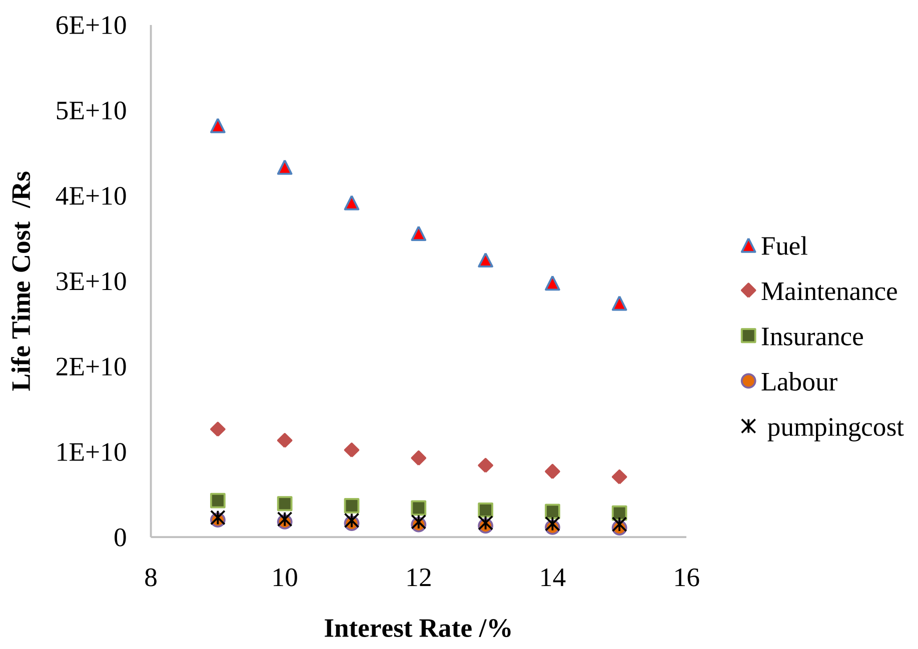


Figure.4.16: Interest Rate (%) v/s Life Time cost (Rs.)

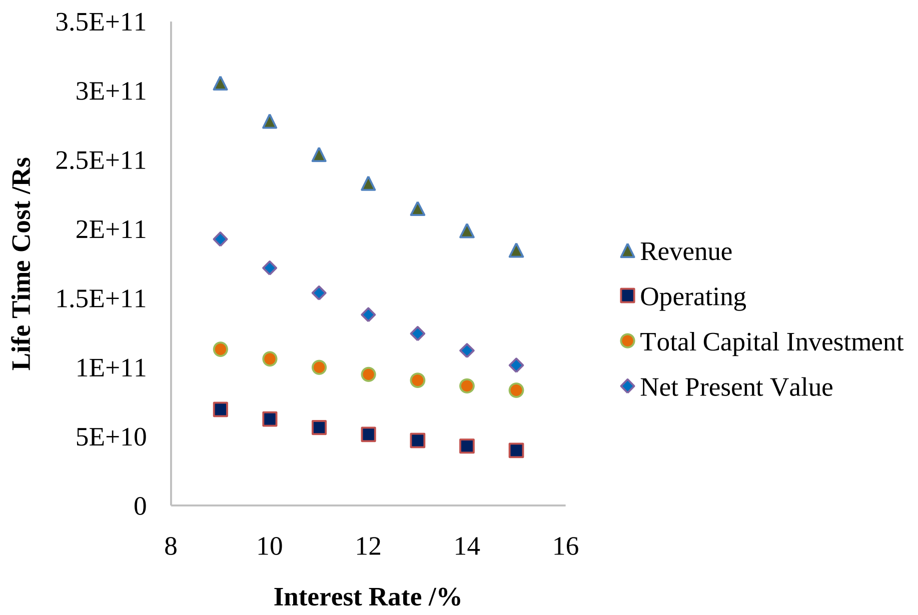


Figure.4.17: Interest Rate (%) v/s Life Time cost (Rs.)

The payback period obtained in this study of the 660MW supercritical unit can be compared with results from other power generation systems, as presented in table 4.2. The supercritical power plant remains dominant over the subcritical power plant concerning the payback period. The lesser the payback period, the more will be the revenue generated throughout plant life.

Table 4.2: Comparison of the present study with available literature

Plant type	Fuel used	Capacity	Interest Rate (%)	Payback period (Years)	Reference
Supercritical power plant	Coal	660MW	9	4.5	Present Study
Subcritical power plant	Coal	250MW	9	10	(Kumar, Ahmadi, et al. 2020)
Subcritical power plant	Coal	210MW	9	10	(Kumar et al. 2015)
Subcritical power plant integrated with solar technology	Natural Gas	250MW	10.5	6	(Mehrpooya, Taromi, and Ghorbani 2019)
Ultra supercritical power plant	Coal	500MW 400MW 430MW	10.9 6.7 7.7	7.4 11.1 9.9	(Vu et al. 2020)
Supercritical power plant	Coal	1000MW	10	2.92	(Y. Liu et al. 2018)
Ultra-supercritical coal-fired power plant	Coal	670MW	0	25.13	(Gai et al. 2016)

4.4 Exergoeconomic Analysis

The present study also includes an exergoeconomic analysis of a 660MW supercritical power plant. The purchased equipment cost evaluated during the economic analysis was considered as the external attributes. The square matrix of [42,42] was constructed by considering the main and auxiliary equations to find the cost flow at the various stream of the plant. The fuel and product side cost flow was computed for major equipment present in the 660MW Plant. The first step involves in exergoeconomic analysis is to evaluate the exergy of fuel, and product side of each equipment present in the plant. Table 4.3 represents the exergy of the fuel and product side of components. Table 4.4 gives the values of the cost of equipment per unit exergy for the product, fuel flows, and respective cost of destruction of components. The steam generator contributes to a major cost destructive component followed by generator.

Table 4.3: Exergy flow at inlet and outlet of components

Components	Fuel side Exergy (kW)	Product side Exergy (kW)
Steam Generator	1997400	942590
HPTur.	227210	213500
IPTur.	266600	253850
LPTur.	217180	209580
Gen.	689670	661700
Cond.	58045	31430
CEPump	1698	1333
DC	765	708
LPHe-4	4798	4110
LPHe-3	8155	6920
LPHe-2	10200	8903
LPHe-1	22656	19577
Dear.	114760	80622
PDTur.	23877	21773
BFPump	21773	19423
HPHe-3	13809	13234
HPHe-2	25637	23391
HPHe-1	15310	15080

Table 4.4: Cost per exergy for product and fuel side of components

Components	**cf /$ GJ^{-1}**	**Cp /$ GJ^{-1}**	**Cd /$ s^{-1}**
Steam Generator	475.3	1066.8	501.4
HPTur.	1148.9	1223.1	15.8
IPTur.	1070.7	1124.1	13.6
LPTur.	10378.	10756.0	8.5
Gen.	1146.7	1195.2	32.1
Cond.	990.3	1830.5	26.4
CEPump	1195.2	1525.1	0.4
DC	1124.1	1216.1	0.1
LPHe-4	1124.1	1312.6	0.8
LPHe-3	1124.1	1324.8	1.4
LPHe-2	1124.1	1288.0	1.5
LPHe-1	971.4	1124.1	3.0
Dear.	1144.9	1630.1	39.1
PDTur.	1124.1	1238.0	2.4
BFPump	1238.0	1387.9	2.9
HPHe-3	1125.9	1174.9	1.3
HPHe-2	1030.0	1128.9	4.6
HPHe-1	1128.9	1146.2	0.5

The purchased equipment cost(PEC) of components is evaluated from the available literature relations(Fu et al. 2016; Wang et al. 2014). Table 4.5 represents the PEC of the various components. The capital recovery factor of 0.09733 has been evaluated by considering the interest rate of 9% and the number of years as 30. Assuming 6900 annual plant operating hours and a factor αq = 1.06 is considered in the account of maintenance cost for each plant component(Singh and Kaushik 2014), the cost rate has been evaluated shown in table 4.5. The cost rate of all sets of turbines contributes to maximum as compared with other components. The largest capital cost rate is observed in intermediate pressure turbine (1530$ H^{-1}) followed by high (1310.09$ H^{-1}) and low (1293.21$ H^{-1}) pressure turbine.

Table 4.5: Purchased Equipment Cost of various components

Components	C_0 /$	C /$ Year^{-1}	Z /$ H^{-1}
Steam Generator	59465000	5787728.45	889.129298
Gen.	11191000	1089220.03	167.329454
HPTur.	87619000	8527957.27	1310.09199
IPTur.	102360000	9962698.8	1530.50155
LPTur.	86490000	8418071.7	1293.21101
Cond.	11550000	1124161.5	172.697274
CEPump	115560	11247.4548	1.72786987
LPHe-4	77874	7579.47642	1.16438333
LPHe-3	88293	8593.55769	1.32016973
LPHe-2	91495	8905.20835	1.3680465
LPHe-1	142400	13859.792	2.12918544
Dear.	6377100	620683.143	95.3513234
BFPump	707050	68817.1765	10.5719141
HPHe-3	271760	26450.4008	4.06339491
HPHe-2	495850	48261.0805	7.41402106
HPHe-1	308040	29981.5332	4.60585872

The relative cost difference and exergoeconomic factor are presented in figures 4.18 and 4.19.The maximum relative cost difference in boiler(124.4%) followed by condenser(84.8%) and deaerator (42.4%).The steam generator contributes to maximum exergy destruction and lower capital cost rate while the high-pressure heater and turbine contribute lower exergy destruction but high capital cost rate. The trend of relative cost difference decreases as it moves from the boiler to high-pressure heaters. The component having work as the product shows lower relative cost difference ranging from 3.5% to 6.5%. The component having work as the fuel shows a higher relative cost difference as compared with turbines ranging from 12% to 27%. The exergoeconomic factor signifies the performance of components. The exergoeconomic factor for turbines (above 90%), condenser (64%), and high-pressure heater 1(71%) are maximum, which implies to decrease investment cost of these components at the expense of exergetic efficiency. A high exergoeconomic factor (71%) and lower relative cost difference (1.5%) indicate that the performance of high-pressure heater 1 can be improved by reducing the exergy destruction rate. The components such as boiler feed pump (50%), condensate extraction pump (54%) exhibit lower exergoeconomic factor, which indicates that cost saving of the overall plant can be achieved by reducing their exergy destruction rate. The remaining components, such as a steam generator, low-pressure heaters, deaerator, and generator, have exergoeconomic factors within the permissible range.

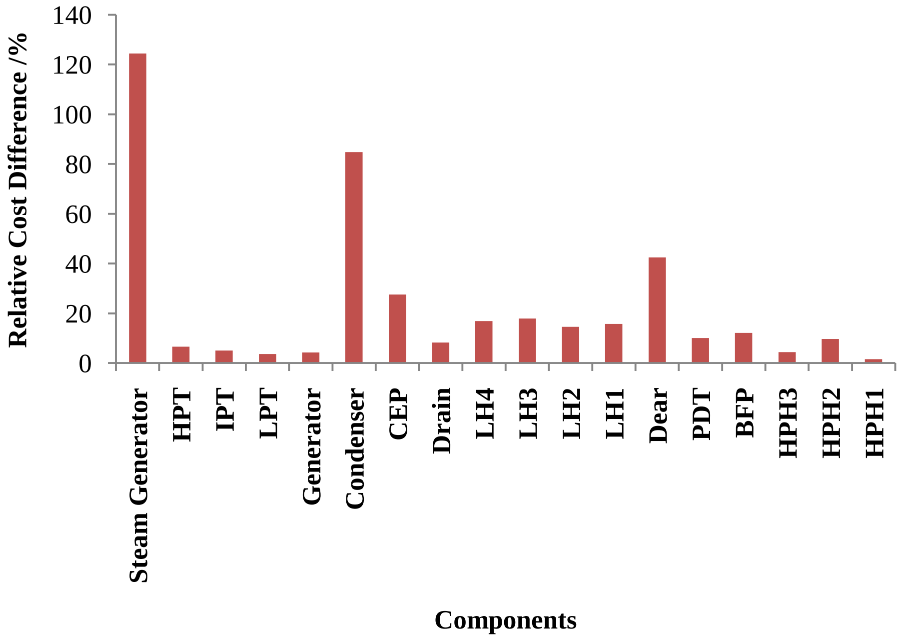


Figure.4.18: Relative cost difference of components

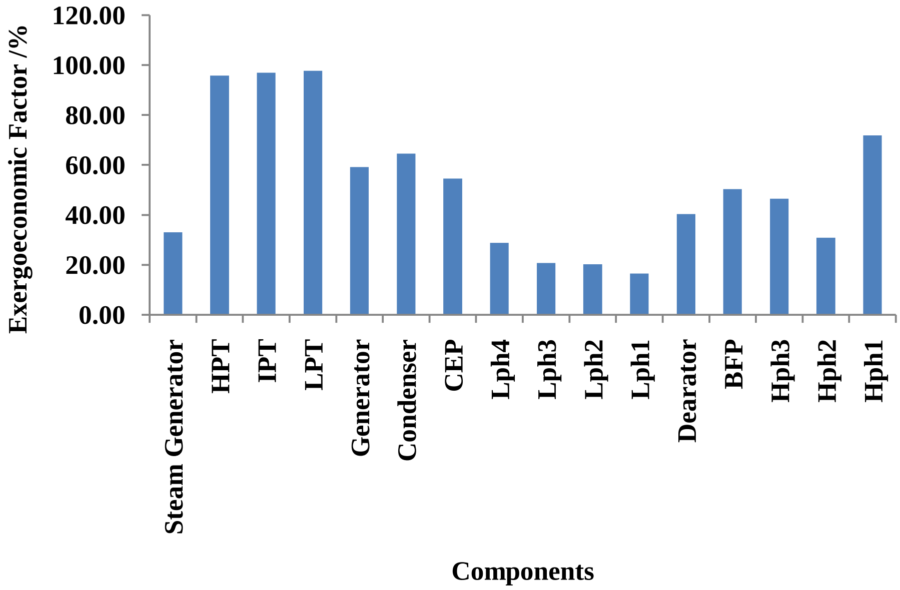


Figure. 4.19: Exergoeconomic Factor of components

4.5 Exergo-environmental analysis

The external attribution of environmental impact for the fuel input was performed based on the damage factors of the Eco-indicators-99. The respective fuel consumption values and emission factors for each pollutant are considered (Goedkoop and Spriensma 2001). The external environmental impact attribution for the fuel is represented in table 4.6

Table 4.6: Environmental Impact of coal for the supercritical unit

Contents	Specific Consumption (kg sec^{-1})	Emission Factor (kg sec^{-1})	Ecoindicator 99[mPts s^{-1}]
Coal	59.6966	-	357.567
CO_2	-	166.9726	910.751
SO_2	-	0.3737	591.245
$MP_{2.5}$	-	0.02	369.315
$MP_{1.0}$	-	0.438	4263.266
TSP	-	0.4482	1283.292
NO_X	-	0.3582	982.467
Total			8757.904

The environmental impact rates of the flow are listed in table 4.7. These values are obtained from the indices matrix consist of [44,44] rows and columns. The environmental impact rates of 8237.81 mPts s^{-1} go on reducing as the steam passed through a high-pressure turbine with an impact rate of 2266.92 mPts s^{-1}due to work output. While environmental impact per unit exergy increases in case of steam bled. To improve the quality of steam, 449.2982 kg sec^{-1} of steam is allowed to pass through the re-heater section. In re-heater, the environmental impact rate increases from 4999.01 mPts $s^{-1}$to 6672.33 mPts s^{-1} as heat is involved in the process. This effect is significantly seen for the increased environmental impact rate of intermediate pressure turbine compared to the high-pressure turbine. The gain of 251.34 mPts s^{-1} is seen in an intermediate turbine due to the reheating process. The environmental impact rate significantly reduces as steam passes through the low-pressure turbine and condenser. The cooling water used in the condenser shows a remarkable environmental impact rate of 507.173 mPts s^{-1}which contributes to 2.89 mPts kWh^{-1} of electricity generated. There is the scope of reducing the environmental impact rate of cooling water by varying flow rates. The low-pressure heaters section contributes to the overall lowest environmental impact rate. The exhaust flue gases contribute to the environmental impact rate of 676.29 mPts s^{-1}corresponds to 3.689 mPts kWh^{-1} of electricity. The environmental impact per unit of electricity generated for the 660 MW supercritical power plant was evaluated as 46.29 mPts kWh^{-1}. The validation of the present semi-empirical model is done with other power plants presented in table 4.8. It is seen from Table 4.8 that the environmental impact per unit of electricity generated is low in the case of an ultra-supercritical power plant of capacity 800MW. The present study shows that the environmental impact per unit of electricity generated for the supercritical power plant is more significant as coal is used as a major fuel. The limited literature is available for comparison of supercritical coal-fired power plant with subcritical coal-fired power plant. Also, the previous studies show that the integration of the solar system with a conventional system contributes to the lowest environmental impact per unit of electricity generated(Javadi et al. 2019).

Table 4.7: Environmental Impact Rates per unit of Energy of the flows for the supercritical power plant

Stream	E*(kW)	B(mPts s^{-1})	e(mPt GJ^{-1})
1a	825760	8237.81	9976.038
1	40741	406.432	9975.995
2	52678.00	565.695	10738.73
3_{in}	501100	4999.01	9976.075
B_{hpt}	213500	2266.92	10617.91
3_{out}	672690	6672.33	9918.878
4	27165	269.449	9918.977
5i	29519	292.797	9918.934
5ii	54728	542.838	9918.835
6	20995	208.242	9918.647
B_{ipt}	253850	2518.26	9920.276
1b	286430	2841.07	9918.881
7	10190	101.07	9918.548
8	7685.8	76.234	9918.811
9	4968.7	49.284	9918.892
B_{lpt}	209580	2154.42	10279.71
10	46404	460.273	9918.822
11	1257.8	12.475	9918.111
B_{cwout}	39244	507.173	12923.58
12	2590.5	30.287	11691.57
14	1882.6	37.875	20118.45
15	1108.5	10.995	9918.809
16	5992.3	85.471	14263.47
17	938.1196	9.305	9918.778
18	12912	166.358	12883.98

19	1407.2	13.958	9918.988
20	21815	267.535	12263.81
21	1417.8	14.063	9918.888
22	44472	461.714	10382.13
23	80701	1162.97	14410.8
24	100046	1399.87	13992.22
26	126514	1411.5	11156.84
27	16016.8	170.032	10615.85
28	177788	1908.12	10732.55
29	10120.2	100.959	9975.989
30	207940	2213.59	10645.35
31	154241.3	643.298	4170.725
B_C	1997400	8330.63	4170.737
B_{PE}	660000	6921.8	10487.58
B_{cep}	1698	17.808	10487.63
b	5642.3	55.965	9918.827
h	343.5658	3.408	9919.497
R	15564.4	158.403	10177.26
B_{bfp}	21773	236.882	10879.62

Table 4.8: Environmental impact rate of electricity for power plant

References	Type of power plant	The Capacity of the plant(MW)	Environment Impact Factor(mPts kWh^{-1})
Present study	Supercritical coal-fired power plant	660	46.29
(Rocha and Silva 2019)	Ultra supercritical coal-fired power plant	800	40.78
(Cavalcanti 2017)	Integrated solar combined gas/steam turbine system	400	20
(Petrakopoulou et al. 2011)	Natural gas-fired, combined cycle power plant with CO_2 capture	-	23
(Petrakopoulou et al. 2011)	Natural gas-fired, combined cycle power plant without CO_2 capture	-	32

The exergo-environmental variables and factors for each component are tabulated in table 4.9. As can be seen from table 4.9, the exergo-environmental impact concerning unit exergy of fuel(mPts GJ^{-1}) for component boiler feed pump and condensate extraction pump contributes to maximum value above 11000 mPts GJ^{-1} as the work is considered as input. While on the product side, condenser and deaerator have maximum value above 15000 mPts GJ^{-1} of the exergo-environmental impact concerning unit exergy of product. The exergo-environmental destruction rate of the steam generator contributes a maximum of 4625 mPts s^{-1} followed by deaerator and condenser.

Table 4.9: Exergo-environmental variables and factors

Components	***bf (mPts GJ⁻¹)***	***bp(mPts GJ⁻¹)***	***Bd(mPts s⁻¹)***	***rb(%)***	***Y(mPts s⁻¹)***	***fb***
Steam Generator	4384.6	9846.9	4625	124.5782	10.16732	65.46722
HPT	10606	11288	145.4787	6.4365	0.261	0.179086
IPT	9882.9	10378	125.9268	5.0071	0.3069	0.24312
LPT	10378	10756	78.948	3.6418	0.2575	0.325104
Generator	10583	11031	296.0166	4.2271	0.00056	0.000189
Condenser	9141.8	16884	243.3134	84.6853	0.0066	0.002712
CEP	11031	14055	4.0294	27.4192	0.0015	0.037213
Drain	10378	11215	0.5915	8.0654	0.001	0.168776
LH4	10378	12117	7.1466	16.7592	0.0012	0.016788
LH3	10378	12230	12.8153	17.8472	0.0014	0.010923
LH2	10378	11890	13.4619	14.5715	0.0014	0.010399
LH1	8967.3	10378	27.6136	15.7281	0.0026	0.009415
Dear	10569	15044	360.8356	42.3496	0.0109	0.003021
PDT	10378	11383	21.836	9.6857	0.0493	0.225265
BFP	11383	12761	26.7456	12.1047	0.0171	0.063895
HPH3	10394	10846	11.9479	4.3488	0.0086	0.071927
HPH2	9507.9	10421	42.7195	9.608	0.0161	0.037674
HPH1	10421	10581	9.6045	1.5305	0.008	0.083225

It is seen from figure 4.20 that the exergo-environmental variable (r_b) for steam generator represents 124.57 %, which relatively offers high potential to reduce environmental impact by small efforts. The previous attempts were made to reduce the environmental impact of the boiler by introducing secondary fuel along with coal, implementing carbon capture technology of post-combustion (Kumar, Jilte, and Nikam 2019; Restrepo and Bazzo 2016). The components condenser, deaerator, and condensate extraction pump also show the lower scope of improvement from the environmental point of view (Cavalcanti 2017; Hong et al. 2018). The condenser and deaerator are critical components for increment in efficiency to reduce environmental impact. Other components such as turbine set, high and low-pressure heater could be neglected as they represent a lower potential towards environmental impact.

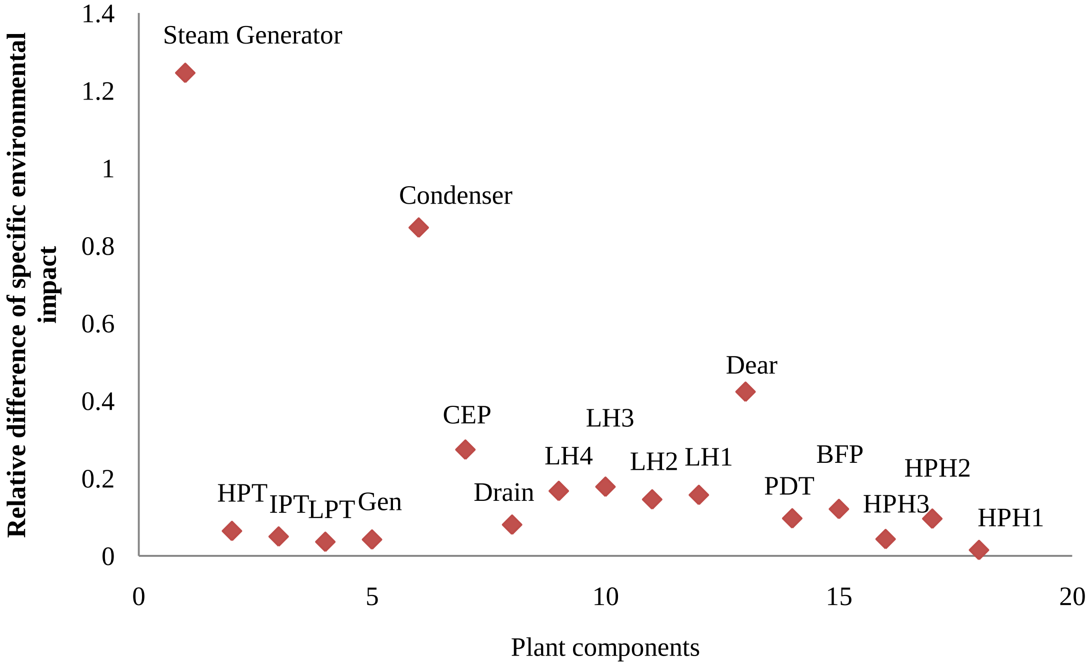


Figure.4.20: **Relative difference of specific environmental impact of components**

Figure 4.21 shows that the exergo-environmental factor of various components. The exergo-environmental factor of the boiler seen above 50% indicates that its environmental impact is dominant over its exergy destruction. In contrast, for other components, exergy destruction is the leading cause of the environmental impact.

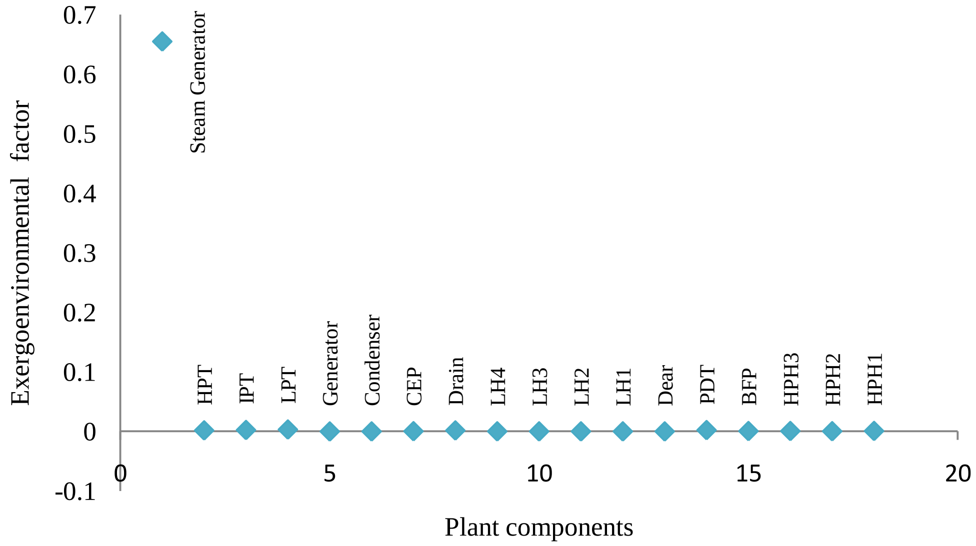


Figure.4.21: Exergo-environmental Factor

4.6 Multi-Objective Optimization

The MATLAB code was executed for a different numbers of particle sizes ranging from 10 to 180. It is observed from figure 4.22 that the group fitness value of 0.1402096 remains the same after 150 particle sizes. Hence, the 150 particle size was selected for finding an optimum solution. In continuation with the above context, the group best fitness value remains constant at 0.1402096 after 131 iterations, as shown in figure 4.23.

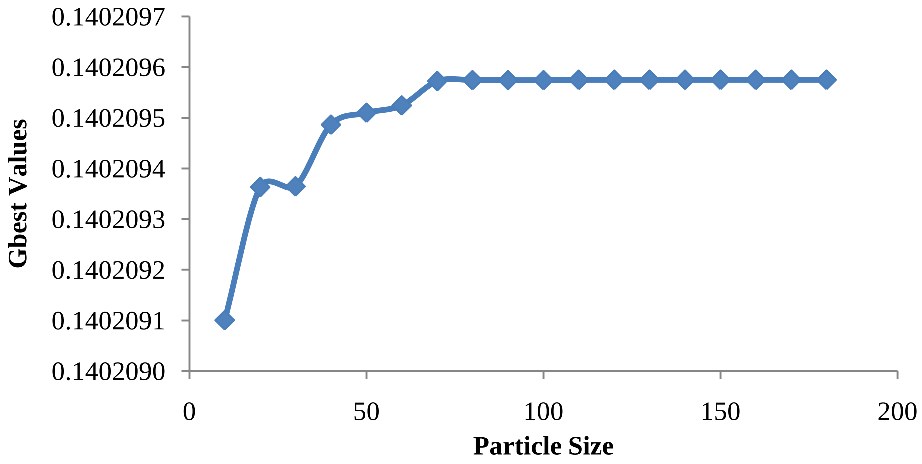


Figure.4.22.Variation of Particle Size on GBest values

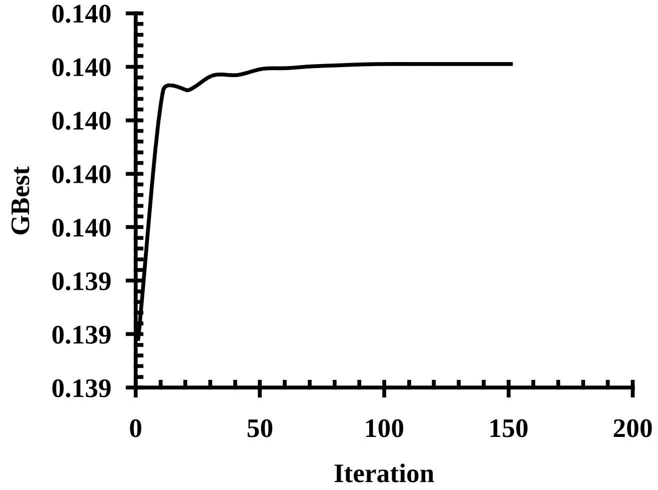


Figure.4.23. Propagation of GBest value with iteration

Figures 4.24, 4.25 give an idea about the propagation of overall plant efficiency, exergy efficiency with iteration. Moreover, it is observed that the propagation of plant efficiency and exergy efficiency are of a similar kind. The maximum overall plant efficiency of 41.643% and exergy efficiency of 39.8347% was been observed after 21iteration. At 291 iterations, the value of overall plant efficiency and exergy efficiency were evaluated as 41.479% and 39.8328%, respectively. The propagation of cost of electricity with iteration is expressed in figure 4.26. It is observed that cost of electricity decreases to 3.1309 Rs/Unit at 61iteration and further increases to the optimum value of 3.1456 Rs/Unit at 131iteration.

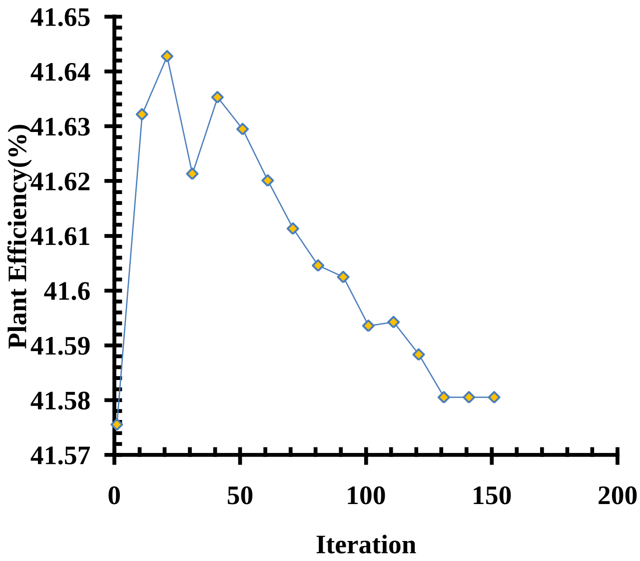


Figure.4.24.Propagation of Plant Efficiency with Iteration

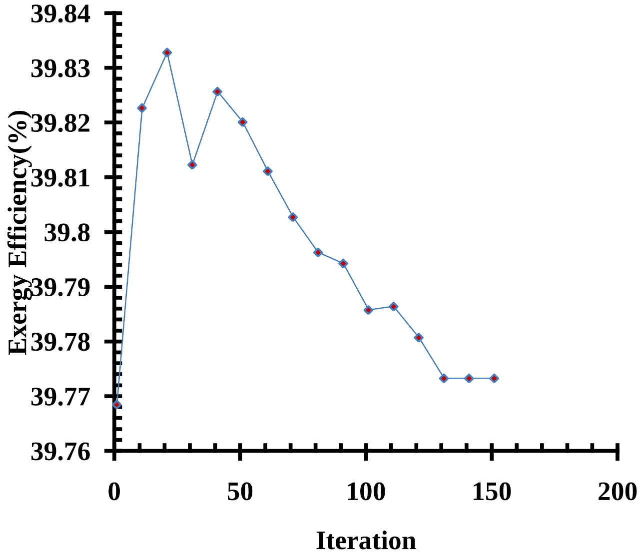


Figure.4.25.Propagation of Exergy Efficiency with Iteration

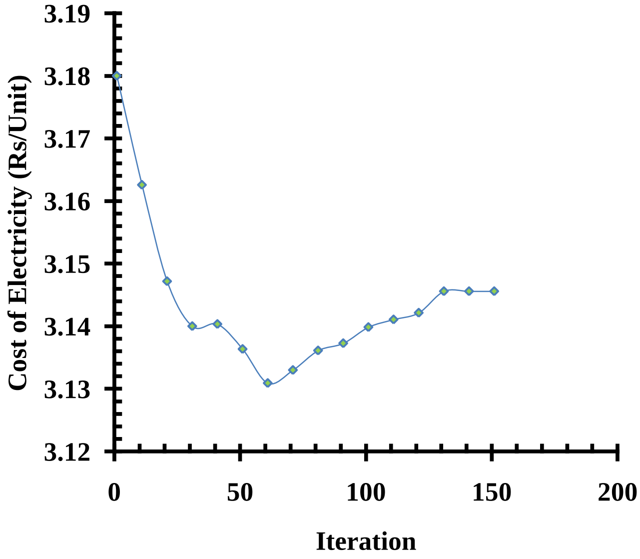


Figure.4.26. Propagation of Cost of Electricity with Iteration

At each iteration, the global optimized function best value is determined using PSO. The input response of plant efficiency, exergetic efficiency, and cost of electricity has been calculated for each of the iterations, and the variation is plotted in figures 4.27, 4.28, and 4.29 respectively. Figure 4.27 expresses the best the Pareto curve between plant efficiency and exergy efficiency. The trend of Pareto curve is linear between plant efficiency and exergetic efficiency. The increase in plant efficiency resulted in an increase in increased exergetic efficiency. The optimized coal calorific value and power output are evaluated to maximize objective function are 3667 Kcal/Kg and 659.12 MW, respectively. The remaining optimized values are represented in Table 4.11.

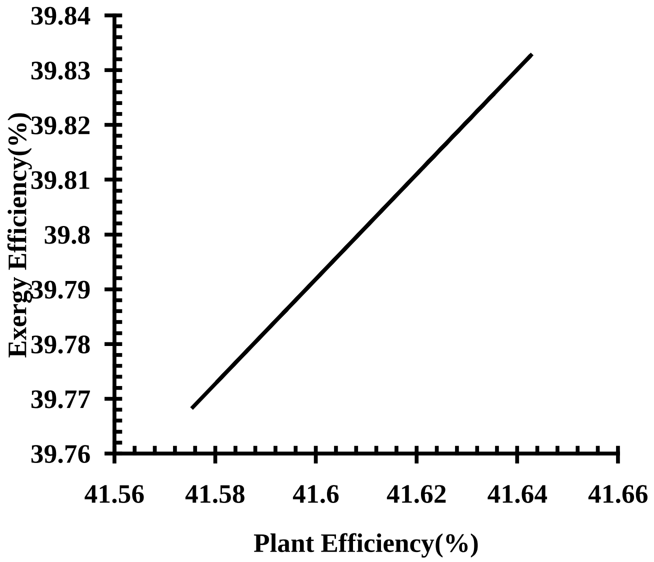


Figure.4.27.Pareto curve based on Plant Efficiency and Exergy Efficiency

Also, the optimization has been done based on the plant efficiency and cost of electricity. As Figure 4.28 shows, the best Pareto curve of between plant efficiency and cost of electricity. The increase in plant efficiency reduces the cost of electricity and indirectly reduces the dependency of high-grade coal. The maximum value of plant efficiency of 41.620% and exergetic efficiency of 39.81% with minimum cost of electricity 3.1309 Rs/Unit is evaluated at 131iteration. A similar trend of the Pareto curve is observed between exegetic efficiency and cost of electricity, as shown in figure 4.29. The 3D Pareto curve of cost of electricity vs. plant efficiency and exergy efficiency is represented in the figure 4.30.The present study also compares the previous studies of using PSO for multi-objective optimization in the thermal power plant, as indicated in Table 4.10. The table indicates that the present study shows the different approaches to employing PSO for energy, exergy, and cost analysis of supercritical power plant.

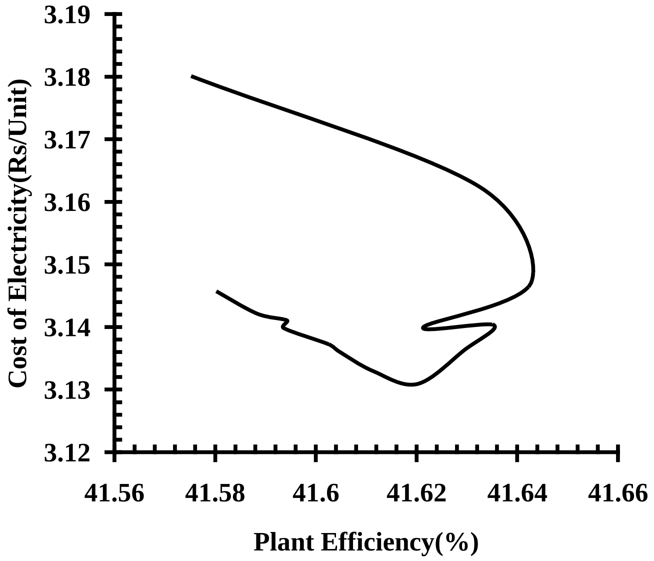


Figure.4.28. Pareto curve based on Plant Efficiency and Cost of Electricity

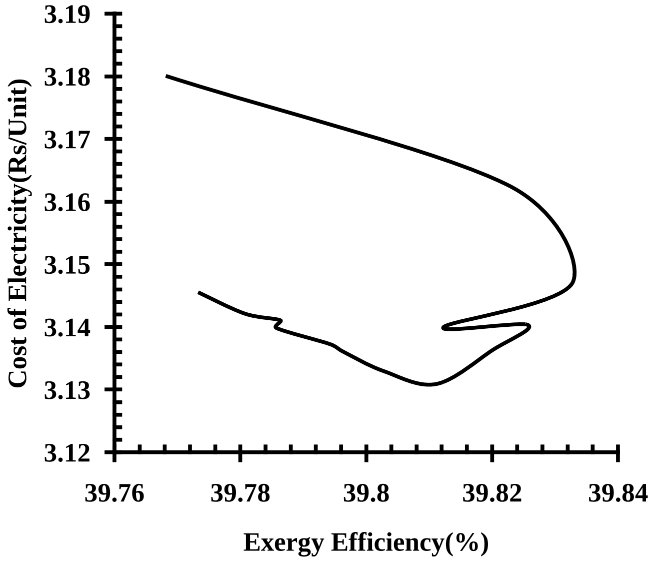


Figure.4.29. Pareto curve based on Exergy Efficiency and Cost of Electricity

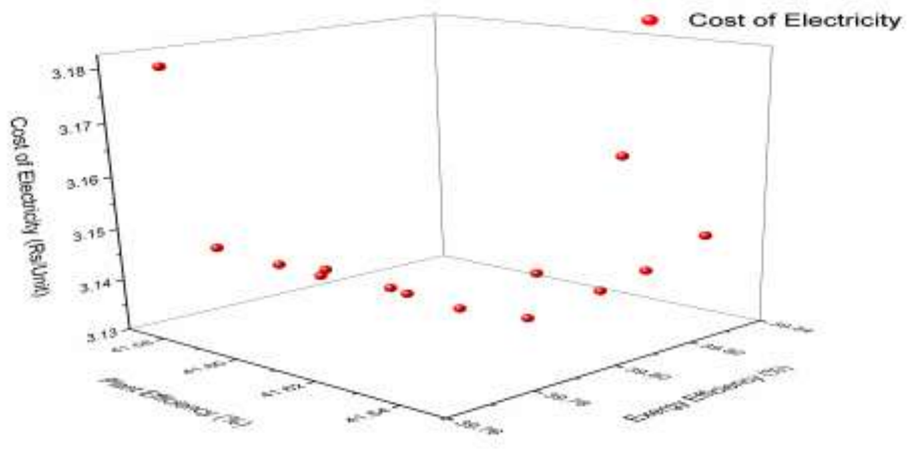


Figure.4.30. Pareto curve based on Cost of Electricity vs. Plant Efficiency and Exergy Efficiency

Table 4.10 Multi-objective optimization using PSO in thermal power plant

Reference	Type of Plant	Objectives	Variables	Technique
Present Study	660MW SUPP	Overall plant efficiency, exergetic efficiency, cost of electricity	Mass of coal consumption, Calorific value of coal, Power output, Temperature and Pressure at inlet of high, intermediate and low pressure turbine	PSO
(Biao et al. 2014)	600MW coal fired thermal power plant ,1200MW coal fired thermal power	Generation profit	Power balance, System spinning reserve requirement, Output power, Thermal power generator, Minimum up time and down time constraints,	PSO

	plant,			
(Groniewsky 2013)	10 MW thermal power plant is	Total cost	Pressure and Temperature	PSO
(Jagtap et al. 2020)	500MW Coal fired power plant	Maximize availability parameters,	Inertia Weight	PSO
(Kheshti and Ding 2018)	-	Power outputs, fuel cost	Operation constraints	PSO
(Mahmoodabadi, Ghavimi, and Mahmoudi 2015)	30MW Cogeneration Plant	Exergetic efficiency, Total cost rate	Compressor pressure ratio, efficiency of the air preheater , and temperature of the combustion products entering the gas turbine have	CGAM-GA+PSO
(Malik and Tewari 2020)	-	Performability level for Coal Handling System, Failure and Repair Rates	inertia weight, cognitive parameter, social parameter, random numbers	PSO
(Panahizadeh et al. 2020)	single-effect absorption chillers	Power factor, COP, Annual cost of plant	Cooling water inlet temperature of network, Solution heat exchanger efficiency, Opening percentage of inlet steam control valve, Inlet steam temperature of network, Chilled water outlet temperature of network	PSO

Table 4.11 Optimized values of the decision variables

Sr.No	Variables	Optimized values
1	Power output	659.12 MW
2	Calorific value of coal	3667 Kcal/Kg
3	Amount of coal consumed	113.62 kg/sec
4	Pressure at inlet of High Pressure turbine	247 bar
5	Temperature at inlet of High Pressure turbine	565°C
6	Pressure at inlet of Intermediate Pressure turbine	50.5292 bar
7	Temperature at inlet of Intermediate Pressure turbine	593°C
8	Pressure at inlet of Low Pressure turbine	5.8221 bar
9	Temperature at inlet of Low Pressure turbine	267.5344°C

The present study carryout Energy,Exergy, Economic and Exergoeconomic and Exergoenvironmental analysis components oriented with a semi-empirical simulation model of a supercritical power plant of 660 MW capacity. The thermal performance analysis of a 660 MW unit has been done using mass and energy balance with pure sliding pressure operation. The plant efficiency, coal consumption rate, steam mass flow rate is evaluated and validated. The economic analysis of a 660 MW unit had been done using present worth method followed by exergoeconomic analysis with specific exergy costing method. The payback period, relative cost difference and exergoeconomic factor are evaluated. The Environmental impact rate for the electricity generated by the 660MW coal-fired supercritical power plant is evaluated. The exergoenvironmental variable and factors for components are investigated. The multi-objective optimization is carried out by keeping Energy efficiency, Exergy Efficiency and Cost of Electricity as objective functions. The metaheuristic approach of particle swarm optimization is used for multi-objective optimization. The semi-imperial model of energy, exergy and economic is considered as input for multi-objective optimization.

CHAPTER 5

CONCLUSION

The thermodynamic analysis is performed on a SUPP of capacity 660MW. The semi-empirical relations are developed based on mass and energy balance equations with pure sliding pressure operation. The Sankey diagram is constructed with energy involved in various thermal devices present in the system. 36.42% of maximum heat is included in the condenser section. The predicted steam generator efficiency of 86.04% is being validated with actual efficiency. It is concluded that as plant load increases, the coal consumption rate also increases with the same coal proportion for the fixed capacity of SUPP. The predicted overall plant efficiency was found to 37.71%. The high grades quality coal can increases the overall efficiency of the plant for fixed capacity. Finally, the SUPP has better flexibility with varying plant loads and pure sliding pressure operation. The results of the simulated model have been validated with operational data of 660MW SUPP. In this study, the economic and exergoeconomic semi-empirical model of a 660MW coal-fired power plant was established. The economic analysis reveals that the lifetime cost decreases with an increase in the annual interest rate. The revenue generated from the 660MW supercritical coal-fired power plant is 2.92 times higher than the subcritical coal-fired power plant of capacity 210MW. The fuel cost is found to be one of the independent variables which get affected by the grade of coal used. The economic analysis indicates the payback period for a supercritical power plant is 4.5 years. The specific exergy costing method is used to perform an exergoeconomic analysis of the 660MW power plant. The relative cost difference for the steam generator was evaluated to be 124%, which implies that the maximum exergy destruction rate and capital cost rate occur in the steam generator. Following conclusions have been drawn from exergoeconomic analysis

- The capital cost of the components such as turbine set and condenser set can decrease in the expense of exergetic efficiency.

- The higher exergoeconomic factor and lower relative cost difference indicate that high-pressure heater-1 performance can be increase by reducing the exergy destruction rate.
- The condensate extraction pump and boiler feed boiler includes work as fuel show a significantly higher relative cost difference.

The results of the economic and exergoeconomic analysis can be implemented as input for the overall economic optimization of the supercritical power plant. It is shown that the exergo-environmental methodology is applied to supercritical coal-fired power plants to evaluate the improvement of the environmental performance of the components. The results of the exergetic analysis established that the boiler is the major source of destruction in the exergy of the system with exegetic efficiency of 51 %, respectively. The Grassman diagram of components exergy destruction as a percentage of total input exergy indicates the exergetic efficiency of the plant is 35.54%. Following conclusions are drawn from exergy and exergoenvironmental analysis.

- The exergetic efficiency of the deaerator shows a 15.11% decrement with an increase in the inlet pressure of a high-pressure turbine.
- The exergetic efficiency of low, intermediate, and high-pressure turbine is maximum at high pressure of 247 bar.
- The cooling water and exhaust emission gases represent the environmental impact rate of 507.173 mPts s^{-1} and 676.29 mPts s^{-1}
- The estimated environmental impact per unit of electricity generated is 46.29 mPts kWh^{-1} by combining electricity, wastewater in the condenser, exhaust gas.
- The steam generator of the supercritical power plant got the highest potential to reduce environmental impact. The components such as turbine set, high and low-pressure heater could not represent lower potential towards environmental influence. Hence it is concluded that further improvement in environmental impact can be achieved by clubbing carbon capture and solar technology with the newly commenced 660MW supercritical power plant.

The exergo-environmental analysis tool proves to be a better option for decision-makers from environmental aspects in the power generation sector.

In this study, multi-objective optimization of a 660MW coal-fired power plant using particle swarm was performed. The plant operating parameters are optimized to fulfill the demand for variation in power generation. The increase in plant efficiency and exergetic efficiency reduces the cost of electricity. Hence, the optimization reveals that the improvement in overall efficiency and exergy efficiency minimizes the dependency on high-grade coal. The optimized value of power output and coal calorific value is evaluated as 659 MW and 3667 Kcal/Kg with 150 particle size. The maximum value of plant efficiency 41.643% and exergy efficiency 39.8347%, with a minimum cost of electricity of 3.1456 Rs/Unit are evaluated from the present study. It is also concluded that Particle Swarm Optimization has proven suitable techniques for integrating energy, exergy, and economic analysis to perform multi-objective optimization of the supercritical power plant.

FUTURE SCOPE OF WORK

The 5 E analysis can be carried out on the Ultra Supercritical and Combined heat and power system along with carbon capture technology. The exergoeconomic and exergoenvironmental analysis can be carried out on the different coal composition used in the steam generator section. The economic analysis for conversion of conventional Subcritical power plant to Ultra Supercritical power plant in developing countries can be studied. Emergy analysis can be performed on supercritical power plant to integrate existing power plant with the Solar system.

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APPENDIX [A] Designed thermodynamic properties of points in 660 MW power cycle

Stream	m (kgs^{-1})	T(°C)	p (bar)	h ($kJkg^{-1}$)	s ($kJkg^{-1}K^{-1}$)
1a	539.4	565.0	247	3395.51	6.26
1b	348.9	280.8	5.89	3022.73	7.32
1	33.2	385.0	80.14	3099.65	6.31
2	56.8	335.6	55.87	3016.95	6.33
3in	447.3	335.6	55.87	3016.95	6.33
3out	447.3	593.0	50.27	3651.16	7.25
3	10.9	479.7	23.65	3419.57	7.30
4	23.2	384.0	11.98	3227.37	7.34
5	25.5	280.2	5.67	3022.10	7.34
6	15.5	171.1	2.04	2812.33	7.38
7	16.4	101.1	0.957	2678.88	7.40
8	15.4	73.5	0.3691	2539.03	7.43
9	301.9	46.3	0.1047	2393.53	7.54
10	420.7	46.3	0.1047	193.87	0.66
11	420.7	46.6	30.68	197.73	0.66
12	420.7	46.9	1.0132	196.46	0.66
13	420.7	50.8	1.0132	212.76	0.71
14	72.8	51.8	1.0132	216.94	0.73
15	420.7	70.6	1.0132	295.59	0.96
16	57.4	75.5	1.0132	316.12	1.02
17	420.7	94.9	1.0132	397.61	1.25
18	41.1	99.8	1.0132	418.26	1.30
19	420.7	117.3	1.0132	2711.01	7.45
20	25.5	122.2	1.0132	2720.91	7.47
21	420.7	152.9	1.0132	2782.25	7.62
22	552.0	186.5	11.83	2782.76	6.53
23	552.0	192.0	300.96	830.15	2.22
24i	552.0	192.0	300.96	830.15	2.22
25i	276.0	219.8	300.96	951.90	2.47
26i	43.2	224.8	1.0132	2924.55	7.94
27i	276.0	266.0	300.96	1162.68	2.88
28i	16.6	271.0	1.0132	3016.36	8.11
29i	276.0	270.0	300.96	1181.62	2.91
24ii	552.0	192.0	300.96	830.15	2.22
25ii	276.0	219.8	300.96	951.90	2.47
26ii	43.2	224.8	1.0132	2924.47	7.93
27ii	276.0	266.0	300.96	1162.68	2.88
28ii	16.6	271.0	1.0132	3016.42	8.12

29ii	276.0	270.0	300.96	1181.62	2.91
30	552.0	289.7	296.14	1277.27	3.09
31	552.0	289.7	291.02	1277.40	3.09
32	-	125	-	-	-

APPENDIX [B] LIST OF PUBLICATIONS ARISE OUT OF PRESENT WORK

1. Keval Chandrakant Nikam, Ravinder Kumar, Ravindra Jilte**,“Economic and exergoeconomic investigation of 660 MW coal-fired power plant”**, Journal of Thermal Analysis and Calorimetry, **(SCI and Scopus Indexed), (Impact factor 2.731)**, **Springer International Publishing** , 2020.
2. Keval Chandrakant Nikam, Ravinder Kumar, Ravindra Jilte**, “Exergy and exergo-environmental analysis of a 660 MW supercritical coal-fired power plant”**, Journal of Thermal Analysis and Calorimetry, **(SCI and Scopus Indexed), (Impact factor 2.731)**, **Springer International Publishing** , 2020.
3. Keval Chandrakant Nikam, Ravinder Kumar, Ravindra Jilte, **“Thermodynamic modeling and performance evaluation of a supercritical coal-fired power plant situated in Western India”**, Energy Sources,Part A: Recovery, Utilization, and Environmental Effects, **(SCI and Scopus Indexed), (Impact factor 1.184)**, **TAYLOR & FRANCIS INC,** Vol.42, 2020.
4. Ravinder Kumar, Keval Chandrakant Nikam, Ravindra Jilte,“**A Simulation Model to Predict Coal-Fired Power Plant Production Rate Using Artificial Neural Network Tool**”, Advances in Intelligent Systems and Computing**,(Scopus Indexed)**,**Springer publication** ,Vol.1155, 2020.
5. Ravinder Kumar, Keval Chandrakant Nikam, Ravindra Jilte, **“Exergy analysis of a 660MW thermal power plant”**, International Conference on Advances in Sustainable Technologies (ICAST - 2020), Lovely Professional University, 2020.