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Economic and exergoeconomic investigation of 660 MW coal-fired power plant

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Abstract

This paper presents the economic and exergoeconomic analysis of the 660 MW coal-fired supercritical unit. The economic analysis is carried out using 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 supercritical power plant is evaluated to 4.5 years for 9% of interest rate and plant life of 30 years. The relative cost difference and exergoeconomic factor are studied for various components available in plant. This study reveals that 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 significant decrease in exergy destruction rate. The components with work as a input parameters show higher relative cost difference. The analysis is performed using the MATLAB programming environment. The outcomes of this study will help the researcher to develop the optimize economic analysis model of the upcoming power plants.

Keywords Economic · Exergoeconomic · Lifetime cost · Payback period · Coal-fired supercritical unit

Abbreviations

HPTur.	High-pressure turbine
IPTur.	Intermediate-pressure turbine
LPTur.	Low-pressure turbine
Gen.	Generator
Cond.	Condenser
CEPump	Condensate extraction pump
BFPump	Boiler feed pump
LPHe	Low-pressure heater
Dear.	Dearator
PDTur.	Pump drive turbine
DC	Drain cooler
SG	Steam generator
RH	Reheater
LCA	Life cycle assessment
SPECO	Specific exergy costing
F and P	Fuel and product
IAPWS	International association for the properties of water and steam
W_{revhpt}, W_{revipt}, W_{revlpt}	Work output from high, intermediate and low-pressure turbine
BOP	Balance of plant

List of symbols

C	Cost
h	Specific enthalpy (kJ kg^{-1})
s	Specific entropy (kJ kg^{-1} K^{-1})
E_{x}	Exergy flow of stream
r_{k}	Relative cost difference
f_{k}	Exergoeconomic factor
ξ	Engineering and plant start-up expenses
NPV	Net present value
PWF	Present worth factor
PEC	Purchased equipment cost
C_{x}	Specific cost of exergy
Z_{x}	Levelized cost rates

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Introduction

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 [1]. 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 [2, 3]. 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. Some approaches based on the literature are discussed in this section. Some researchers optimized condenser design parameters by taking into account condenser cost, energy generation cost and developed numerical approach in fluent code [4]. Few technologists developed real structural optimization procedures and use it for large-scale thermal power plant by taking into account the objective of minimization of total operating cost flow during installation [5]. Others compared the existing supercritical plant with an economically design plant, which suggested that the cost of electricity can be lowered by 2% to 4% by considering temperature at various stages. In comparison, efficiency can be increased by 2% [6]. Also, some researchers suggested a multi-objective multi-constraint nonlinear programming approach to study the exergoeconomic parameters considering heat, mass and pressure as parameters [7]. The results were validated by the MATLAB code. Some of the researchers modified and developed a globally accepted relation between thermodynamic losses and capital cost for newly installed coal-fired power plant [8]. The 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 [9]. The investigator also 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 [10]. The thermodynamic and exergoeconomic modeling indicates that maximum exergy destruction occurs 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 [11]. The discussion on 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 [12–15]. The specific cost of the product and the fuel found to be evaluating parameters in exergoeconomics analysis of various systems [16]. Ahmadi et al. reviewed economic analysis of different fuel thermal power plants and identified that economical optimization is complicated for coal-fired power plant [17]. The analysis 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 [18] [19]. The harmony Search optimization technique was used by taking into account economic, and emission as a minimization objective function, and result was compared with the PSO algorithm on the basis of minimum parameters, less computational steps and easiness of implementation [20]. The integration of exergetic principles with economic concepts determined the cost related to thermodynamic inefficiencies of an energy system. The 4 E analyses were done using city gas station to ensure vapor generator as key parameters the responsible components for exergy destructor. The unit cost and CO_2 emission cost were estimated involved in the production plant of hydrogen [21]. In hydrogen liquefaction plant, exergoeconomic analysis was performed to check the feasibility of components from economic perspectives [22]. The exergoeconomic analysis also found popularity in evaluation of specific cost of blended diesel fueled direction injection engine system [23]. The SPECO approach was also seen to carry out exergoenvironmental analysis of traditional sugarcane bagasses cogeneration plant [24]. The investigator 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 favorable way for heat recovery. The payback period was estimated by performing economic analysis of the waste recovery system involved in coal-fired power plant [25]. Hofman et al. performed a comparative study of exergoeconomic and proposed a idea about secondary Rankine cycle that helped to reduce fuel dependency, reduction in emission and reduction in the cost of electricity to end-users [26]. The effect of coal cost and 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 literatures have been studied in multidisciplinary directions and is also included in the following section. The multi-objective optimization was carried out considering generation cost produced from the desalination unit integrated with the thermal power unit [27]. The economic analysis was carried out to evaluate the capital cost involved in proposing a power plant operating with natural gas as a fuel [28]. The price of electricity generated from the combined cycle power plant was taking into account as an objective function to carry out an economic analysis of power generating plant [29, 30]. The incremental variation of air temperature found significantly increasing impact on specific cost rate of steam and electricity produced from natural gas-fired cogeneration system [31]. The product cost ratio was taken into account 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 [32, 33]. The modern thermal power plant operating above a critical point of water was analyzed economically on the basis of fuel tax and biomass combustion. The feasibility of plant was cross-verified by evaluating Net Present Value (NPV), the benefit to cost ratio and internal rate of return (IRR) [34]. The financial hurdles of carbon capture technology involving initial investment and penalty charges were analyzed, and incentive-based approach was proposed by some of the researchers in the literature [35, 36]. The exergoeconomic analysis was performed on 660 MW coal-fired subcritical power plant to reveal the effect of the flue gas temperature on payback period of plant. The resulted payback period was 5.02 years. The research also evaluated the exergoeconomic factor and relative cost difference for the collective system components of subcritical power plant [37]. From the literature review, it is concluded that limited work was found on economic analysis of supercritical coal-fired plant, and it is hard to manage different cash flow by any relevant empirical relations. The present study deals with economic analysis of supercritical power plant of capacity 660 MW in the form of capital cost, present worth value and net present value over a span of 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 MATLAB package. The study was extended to reveal the exergoeconomic variables for 660 MW supercritical power plant by SPECO analysis [38].

Layout and description of 660 MW supercritical coal-fired power plant

The supercritical coal-fired thermal power plant of 660 MW capacity situated in western India has been chosen for economic analysis. The schematic diagram of the 660 MW supercritical power plant is shown in Fig. 1. It consists of high-pressure, intermediate-pressure and low-pressure turbine set operating at 247 bar, 50.5292 bar and 5.8221 bar, respectively. The steam bled is extracted from each turbine section and allowed to pass through series of high-pressure and low-pressure heaters, as shown in Fig. 1B1 to B6 and C1 to C6 represents the loss occurred during the expansion of steam in turbine set. These losses are collected and allowed to pass through the condenser section. The increase in temperature from 335.6 °C to 593 °C observed in the re-heater placed between high and intermediate-pressure turbines. The wet steam coming out from a low-pressure turbine is pass through the condenser 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 and high-pressure heaters before entering the once-through steam generator section. A pump drive turbine is used to drive the boiler feed pump. The values of specific enthalpy and specific entropy were formulated as per the IAPWS IF97 standard [39] and tabulated in Table 1.

Economic analysis

In the present work, an economic analysis is performed in terms of Net present value (NPV) of 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 along with site preparation are added with equipment cost. The installation cost of plant and initial expenditure is categorized under indirect cost. The latest cost of components are taken into consideration to reduce complexity occur in analysis [9, 13, 34, 40]. The total direct plant cost is expressed as

$$C_{\mathrm{direct}} = C_{\mathrm{Eqp}} + C_{\mathrm{other}} \tag{1}$$

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

$$C_{\mathrm{Eqp}} = \sum_{i}^{n} (N_{\mathrm{i}} C_{\mathrm{i}}) + C_{\mathrm{piping}} + C_{\mathrm{civil}} + C_{\mathrm{electrical}} + C_{\mathrm{coalhandling}} + C_{\mathrm{ashhandling}} \tag{2}$$

Here, ‘N_{i}’ represents the number of spare units of pumps. The available literature indicates that cost of components in terms of total load using power law [40] and is given by

$$C_{\mathrm{i}} = a_{\mathrm{i}} \mathrm{MW}^{\mathrm{bi}} \tag{3}$$

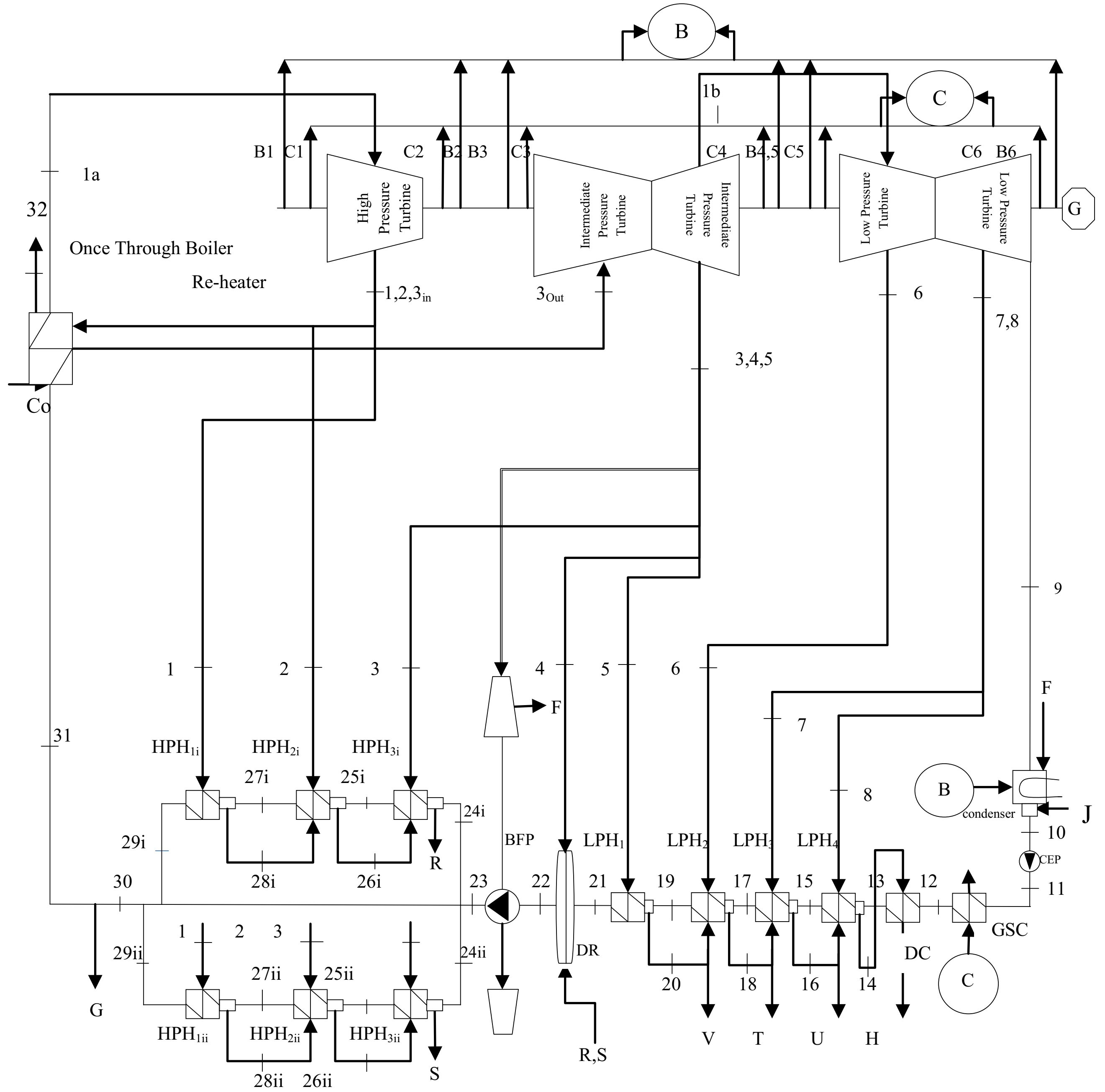


Fig. 1 Schematic diagram of 660 MW supercritical power plant

where i represent equipment involved plant.

Indirect cost is calculated as follows

$$C_{\text{indirect}} = \xi C_{\text{Eqp}} \tag{4}$$

Here, ξ is a factor which considers engineering and plant start-up expenses.

Total capital investment is expressed as

$$C_{\text{tci}} = C_{\text{direct}} + C_{\text{indirect}} \tag{5}$$

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 Lifetime cost can be obtained in terms of present worth factor as follows

$$\text{PWF}_{\text{k}} = \frac{1}{(1+i)^{\text{k}}} \tag{6}$$

The cost data of steam generator island, turbine generator island, BOP (Balance of Plant) mechanical, BOP

Table 1 Designed thermodynamic properties of points in 660 MW power cycle

Stream	m/kg s^{-1}	T/°C	p/bar	h/kJ kg^{-1}	s/kJ kg^{-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	–	–	–

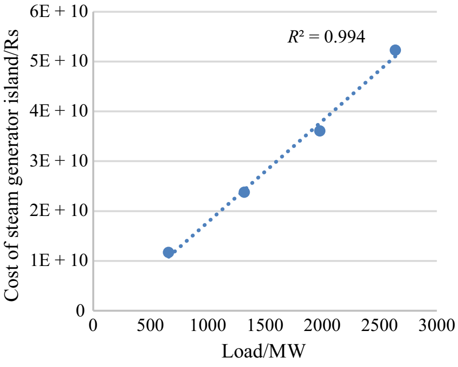


Fig. 2 Linear regression-curve fitting for cost of steam generator island

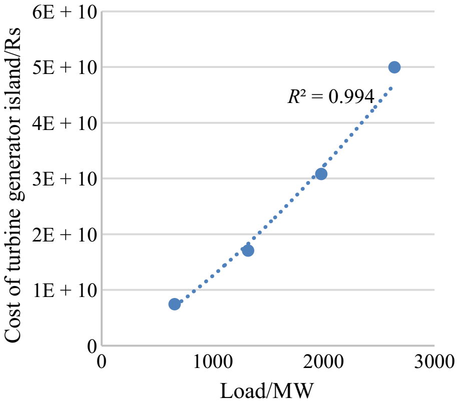


Fig. 3 Linear regression-curve fitting for turbine generator island

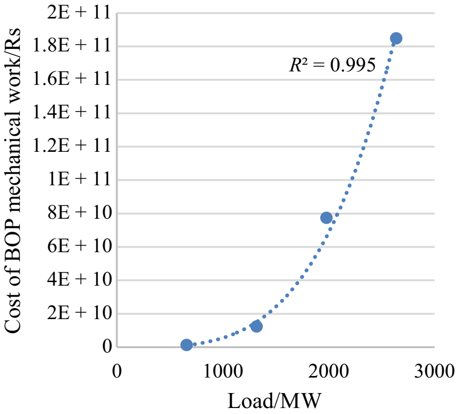


Fig. 4 Linear regression-curve fitting for BOP mechanical work

electrical packing, civil works, coal handling unit, ash handling unit, pipe costing are evaluated by curve fitting actual data obtained from the plant with 660 MW capacity and a varying number of unit (n) as shown in Figs. 2–9. The number of capacity unit varies from 1 to 4. The fuel cost is evaluated with respect to changing calorific value of fuel [41]. 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 2. The linear regression-curve fitting is shown in

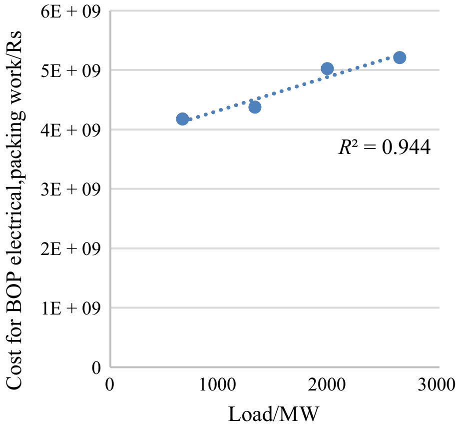


Fig. 5 Linear regression-curve fitting for BOP Electrical, packing

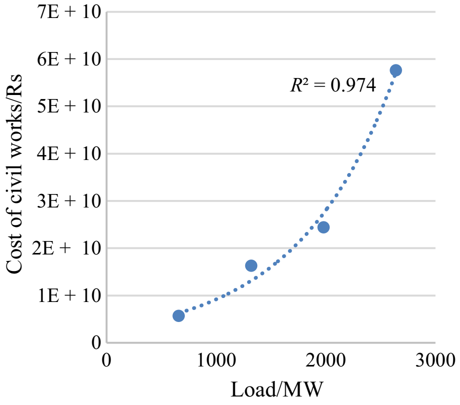


Fig. 6 Linear regression-curve fitting for civil works

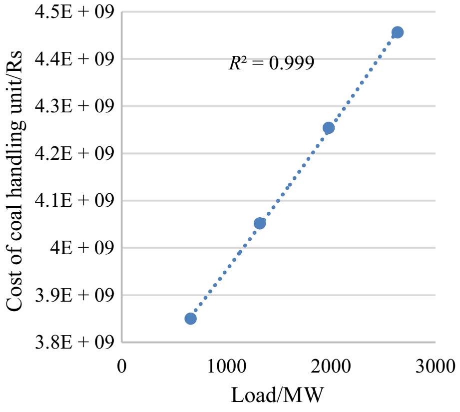


Fig. 7 Linear regression-curve fitting for coal handling

Figs. 2–9. The steam generator BOP electrical packing, coal handling unit, ash handling unit and ash handling unit shows linear relationship with variation in plant load

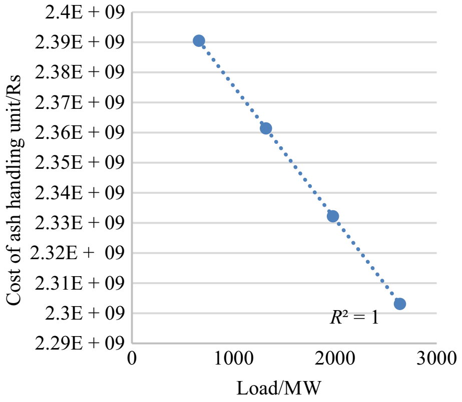


Fig. 8 Linear regression-curve fitting for ash handling

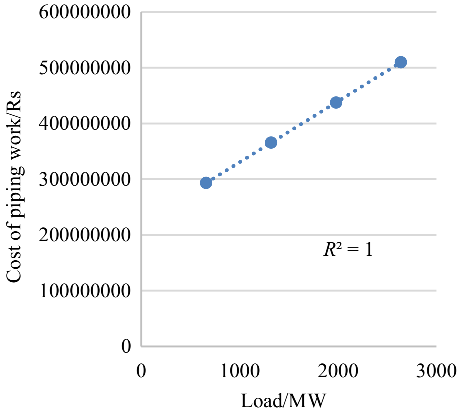


Fig. 9 Linear regression-curve fitting for pipe costing

from 660 to 2640 MW. 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.

The escalation rate value for fuel cost (F), maintenance cost (M), labor cost (L), insurance cost (I), pumping cost (P), number of labor and their salary component are taken from the literature [3, 43, 44].

Fuel Cost

$$C_{\mathrm{coal}} = \sum_{\mathrm{k}=1}^{\mathrm{pl}} \left(\mathrm{PWF}_{\mathrm{k}} \times m_{\mathrm{coal,k}} + C_{\mathrm{CC}}(1+F)^{(\mathrm{k}-1)}\right) \tag{7}$$

Maintenance Cost

$$C_{\mathrm{maint}} = \sum_{\mathrm{k}=1}^{\mathrm{pl}} \left(\mathrm{PWF}_{\mathrm{k}} \times 0.015 \times C_{tci}(1+M)^{(\mathrm{k}-1)}\right) \tag{8}$$

Table 2 Designed thermodynamic properties of points in 660 MW power cycle

S. no.	Component	*a*	*b*	References
1	Steam generator island	20000000.00	−300000000.00	[40, 42]
2	Turbine generator island	1000000.00	1.362	[40, 42]
3	BOP mechanical work	0.063	3.644	[40, 42]
4	BOP electrical packing work	56826.00	4000000000.00	[40, 42]
5	Civil work	3000000000.00	0.001	[40, 42]
6	Coal handling unit	4000000000.00	7×10^{-5}	[40, 42]
7	Ash handling unit	−44162.00	2000000000.00	[40, 42]
8	Pipe costing	10928.00	200000000.00	[40, 42]
9	Fuel Cost	136.03	0.0005	[40, 42]

Labor Cost

$$C_{\text{lab}} = \sum_{k=1}^{\text{pl}} \left(\text{PWF}_{\text{k}} \times n_{\text{L}} \times C_{\text{S}}(1+L)^{(\text{k}-1)}\right) \tag{9}$$

Insurance Cost

$$C_{\text{ins}} = \sum_{k=1}^{\text{pl}} \left(\text{PWF}_{\text{k}} \times 0.01 \times C_{\text{tci}}(1+I)^{(\text{k}-1)}\right) \tag{10}$$

Pumping Cost

$$C_{\text{ins}} = \sum_{k=1}^{\text{pl}} \left(\text{PWF}_{\text{k}} \times 8760\ \text{Av}_{\text{overall}} \times \left[\sum_{j=1}^{N} \left(\frac{\frac{\Delta Pjm_j}{\rho_{\text{water}}}}{\eta_{\text{pump,j}}}\right) / \right] \times C_{\text{ep}}(1+P)^{(\text{k}-1)}\right) \tag{11}$$

Lifetime Cost

$$C_{\text{O}} = C\text{coal} + C\text{main} + C\text{lab} + C\text{ins} + C\text{pumping} \tag{12}$$

Revenue over Life span

$$R_{\text{lifetime}} = f_{\text{MW}} \sum_{k=1}^{\text{pl}} (\text{PWFk} + \text{MW} + 8760\ \text{Av}_{\text{overall}} \times C_{\text{ep}}(1+P)^{(\text{k}-1)} \tag{13}$$

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

$$\text{NPV}_{\text{lifetime}} = R_{\text{lifetime}} - (C_{\text{o}} + C_{\text{tci}})_{\text{lifetime}} \tag{14}$$

Exergoeconomic analysis

The specific exergy costing method (SPECO) approach is used to perform exergoeconomic analysis [38]. The first step in exergoeconomic analysis is to evaluate the exergy of the stream. The reference condition for exergy analysis is $T_0 = 298.15$ K and $P_0 = 101.325$ kPa [45]. The individual equipment is classified with the summation of input stream exergy (Fuel) and output stream exergy (Product). Table 3 represents the exergy stream of the fuel and product side.

The next step of exergoeconomic starts with the calculation of purchased equipment cost (PEC) for each component. The PECs for boiler, heat exchanger, turbine, condenser, deaerator and generator have been calculated with relation available in the literature [46]. The capital investment cost (CC) is determined from purchased equipment cost.

$$Z_{\text{K}} = \frac{\text{CC} + \text{OMC}}{N_{\text{aoh}\omega}} \frac{\text{PEC}_{\text{K}}}{\sum \text{PEC}_{\text{K}}} \tag{15}$$

The cost balance of a productive component k is expressed as

$$\sum_{i=1}^{i=n} (E.c)_{\text{in,i}} + Z_{\text{K}} + C_{\text{aux,dc,k}} = \sum_{i=1}^{\text{nout}} (E.c)_{\text{out,i}} + C_{\text{dif,dc,k}} \tag{16}$$

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

The specific cost of exergy loss is expressed as

$$C_{\text{l,j}} = c_{\text{F,k}} \times .E_{\text{l,j}} \tag{17}$$

The thermo-economic variables, i.e., average unit costs of the fuel $C_{\text{F,k}}$ and the product $C_{\text{P,k}}$, the cost rate of exergy destruction $C_{\text{D,k}}$, the summation $(C_{\text{D}}+Z)_{\text{k}}$, the relative cost difference r_{k} and the exergoeconomic factor f_{k}, are calculated. Table 4 represents the formulation of main exergoeconomic and auxiliary equation to the evaluate cost flow of each stream.

$$C_{\text{F,K}} = \frac{C_{\text{F,K}}}{E_{\text{F,K}}} \tag{18}$$

$$C_{\text{P,K}} = \frac{C_{\text{P,K}}}{E_{\text{P,K}}} \tag{19}$$

$$C_{\text{D,k}} = c_{\text{F,K}}.E_{\text{D,k}} \tag{20}$$

Table 3 Formulation of total exergy stream of fuel (inlet) and product (outlet) of the components

Components	Exergy stream of fuel	Exergy stream of product
Steam generator	$E_{xc} - E_{32}$	$(E_{1a} - E_{x31}) + (E_{x3out} - E_{x3in})$
HPTur.	$E_{1a} - E_{x1} - E_{x2} - E_{x3in}$	W_{revhpt}
IPTur.	$E_{x3out} - E_{x4} - E_{x5i} - E_{x5ii} - E_{x6} - E_{1b}$	W_{revipt}
LPTur.	$E_{1b} - E_{x7} - E_{x8} - E_{x9} - E_{x10}$	W_{revlpt}
Gen.	$W_{hpt} + W_{ipt} + W_{lpt}$	MW + powercep
Cond.	$E_{1a} - E_{x1} - E_{x2} - E_{x3in}$	–
CEPump.	powercep	$E_{x12} - E_{x11}$
DC	$E_{x15} - E_{xh}$	$E_{x13} - E_{x14}$
LPHe-4	$E_{x9} + E_{x17} - E_{x15}$	$E_{x16} - E_{x14}$
LPHe-3	$E_{x8} + E_{x19} - E_{x17}$	$E_{x18} - E_{x16}$
LPHe-2	$E_{x7} + E_{x21} - E_{x19}$	$E_{x20} - E_{x18}$
LPHe-1	$E_{x6} - E_{x21}$	$E_{x22} - E_{x20}$
Dear.	$E_{x22} + E_{x5ii} + E_{xR}$	E_{x23}
PDTur.	$E_{x5i} - E_{xb}$	powerbfp
BFPump.	powerbfp	$E_{x24} - E_{x23}$
HPHe-3	$E_{x4} + E_{x27} - E_{xR}$	$E_{x26} - E_{x25}$
HPHe-2	$E_{x2} + E_{x29} - E_{x27}$	$E_{x28} - E_{x26}$
HPHe-1	$E_{x1} - E_{x29}$	$E_{x30} - E_{x28}$

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.

$$r_k = \frac{(c_{p,k} - c_{F,k})}{c_{F,k}} \tag{21}$$

$$f_k = \frac{z_k}{(z + c_D)k} \tag{22}$$

The MATLAB package is used to simulate economic and exergoeconomic analysis. Figure 10 represents the flowcharts of the methodology for economic and exergoeconomic analysis. The economic and exergoeconomic analysis is carried out by using present worth method and SPECO approach.

Results and discussion

Economic analysis

The economic analysis of 660 MW 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 [3]. The lifetime cost increases with plant life as, shown in Fig. 11. The cost related to pumping and labor shows the least increment as compared with other lifetime costs. The fuel cost increases from 1171.6 crores to 5169.26 crores with 30 years of life span.

The previous similar study was conducted on subcritical power plant of 250 MW capacity, which results in a payback period of 10 years [3]. The current research of supercritical proved to be more feasible as payback period reduces to 4.5 years, as shown in Fig. 12. Total revenue increases up to 31,640 INR crores over a span of 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.

The economic study was extended to lifetime cost plotted with respect to varying plant load from 198 to 660 MW. The situation occurs where plant need to run under capacity for 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 13 shows that, except labor and pumping cost, all other costs improve with plant load varying from 198 MW to 660 MW. Figure 14 represents revenue goes on increasing as the plant operates to its maximum capacity. The revenue generated varying plant load increased from 8736.54 crores to 29,121.8 crores. The revenue generated is 2.92 times greater for supercritical power plant than the subcritical power plant of capacity 210 MW [40].

Table 4 Exergoeconomic equations

Component	Main equations	Auxiliary equations
Steam Generator	$C_{c} + C_{30} + C_{3in} - C_{1a} - C_{3out} - C_{31} = -Z_{comb}$	$C_{1a} - C_{30} = \frac{(E_{1a}-E_{x30})}{(E_{3out}-E_{3in})}(C_{3out} - C_{3in})$ $C_{c} = \frac{(E_{c})}{(E_{31})} C_{x31}$
HPTur.	$C_{1a} - C_{x1} - C_{x2} - C_{x3in} - C_{hpt} = -Z_{hptur.}$	$C_{1a} = \frac{(E_{1a})}{(E_{1})} C_{x1},\ C_{1a} = \frac{(E_{1a})}{(E_{2})} C_{x2}$ $C_{1a} = \frac{(E_{3out})}{(E_{3in})} C_{x3in}$
IPTur.	$C_{x3out} - C_{x4} - C_{x5i} - C_{x5ii} - C_{x6} - C_{1b} - C_{ipt} = -Z_{iptur.}$	$C_{3out} = \frac{(E_{3out})}{(E_{4})} C_{x4}, C_{3out} = \frac{(E_{3out})}{(E_{5i}} C_{x5i}$ $C_{3out} = \frac{(E_{3out})}{(E_{5ii})} C_{5ii}, C_{3out} = \frac{(E_{3out})}{(E_{5ii})} C_{x1b}$ $C_{3out} = \frac{(E_{3out})}{(E_{6})} C_{x6}$
LPTur.	$C_{1b} - C_{x7} - C_{x8} - C_{x9} - C_{x10} - C_{lpt} = -Z_{lptur.}$	$C_{1b} = \frac{(E_{1b})}{(E_{7})} C_{x7}, C_{1b}=\frac{(E_{1b})}{(E_{8})} C_{x8}$ $C_{1b} = \frac{(E_{1b})}{(E_{9})} C_{x9}, C_{1b} = \frac{(E_{1b})}{(E_{10})} C_{x10}$
Gen.	$C_{hpt} + C_{ipt} + C_{lpt} - C_{PE} - C_{PB} = -Z_{gen.}$	$C_{PE} = \frac{(E_{PE})}{(E_{PB})} C_{PB}$
Cond.	$C_{xb} + C_{x10} + C_{xh} - C_{x11} - C_{waterout} = -Z_{cond.}$	$C_{x11} = \frac{(E_{11})}{(E_{xb}+E_{x10}+E_{xh})}(C_{xb} + C_{x10} + C_{xh})$
CE Pump	$C_{x11} + C_{PB} - C_{x12} = -Z_{cepump}$	–
LPHe-4	$C_{x14} + C_{x9} + C_{x17} - C_{x15} - C_{x16} = -Z_{lphe - 4}$	$C_{x15} = \frac{(E_{15})}{(E_{9}+E_{17})}(C_{x9} + C_{x17})$
LPHe-3	$C_{x16} + C_{x8} + C_{x19} - C_{x17} - C_{x18} = -Z_{lphe - 3}$	$C_{x17} = \frac{(E_{17})}{(E_{8}+E_{19})}(C_{x8} + C_{x19})$
LPHe-2	$C_{x7} + C_{x18} + C_{x21} - C_{x20} - C_{x19} = -Z_{lphe - 2}$	$C_{x19} = \frac{(E_{19})}{(E_{7}+E_{21})}(C_{x7} + C_{x21})$
LPHe-1	$C_{x6} + C_{x20} - C_{x22} - C_{x21} = -Z_{lphe - 1}$	$C_{x21}=\frac{(E_{21})}{(E_{6})}(C_{x6})$ S
Dear.	$C_{x5ii} + C_{x22} + C_{xR} - C_{x23} = -Z_{dear}$	–
BFPump.	$C_{x23} - C_{x24} + C_{PF} = -Z_{bfpump}$	–
PDTur.	$C_{x5i} - C_{xb} - C_{PF} = -Z_{pdtur.}$	$C_{x5i} = \frac{(E_{5i})}{(E_{xb})}(C_{xb})$
HPHe-3	$C_{x24} + C_{x27} - C_{x26} - C_{xR} = -Z_{hphe - 3}$	$C_{xR}=\frac{(E_{R})}{(E_{4}+E_{27})}(C_{x4} + C_{x27})$
HPHe-2	$C_{x2i} + C_{x26} + C_{x29} - C_{x28} - C_{x27} = -Z_{hphe - 2}$	$C_{x27} = \frac{(E_{27})}{(E_{2}+E_{29})}(C_{x2} + C_{x29})$
HPHe-1	$C_{x28} + C_{x1} - C_{x29} - C_{x30} = -Z_{hphe - 1}$	$C_{x29} = \frac{(E_{29})}{(E_{1})}(C_{x1})$
DC	$C_{x15} + C_{x12} - C_{xh} - C_{x14} = -Z_{DC}$	$C_{xh} = \frac{(E_{xh})}{(E_{15})}(C_{x1})$
Combustion	$C_{c} = Z_{comb}$	–

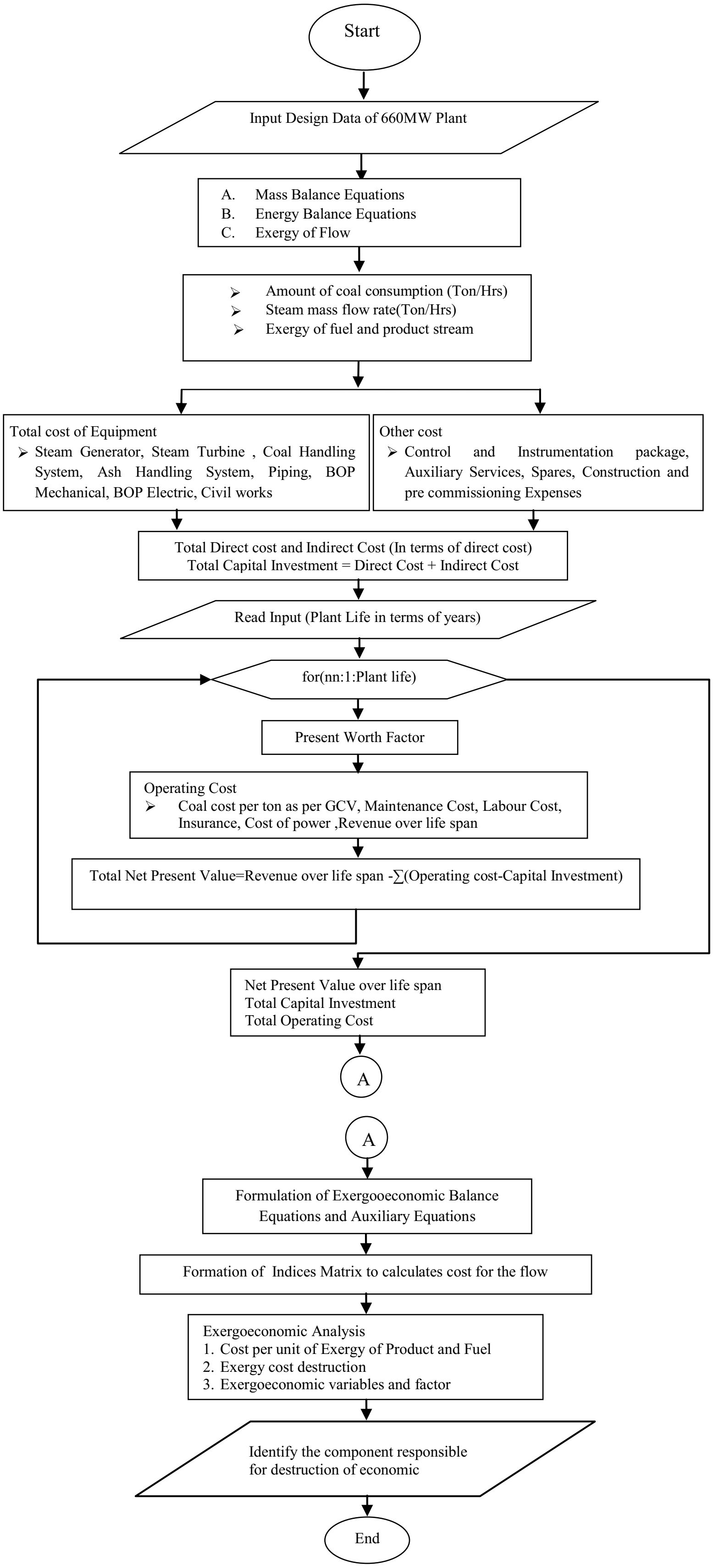
The prediction of lifetime cost with respect to the varying interest rate is performed in the present study. The increase in interest rate causes a decrease in lifetime cost specifically for fuel cost and maintenance cost. The other cost shows the least decrement for varying interest rate. The annual interest rate from 9 to 15% is considered for the study, as shown in Fig. 15. Also, the revenue generated from the plant shows the decrement curve for an increase in the interest rate, as shown in Fig. 16.

The payback period obtained in this study of 660 MW supercritical unit can be compared with results from other power generation systems, as presented in Table 5. The supercritical power plant remains dominant over subcritical power plant with respect to the payback period. Lesser the payback period, more will be the revenue generated throughout plant life.

Exergoeconomic analysis

The present study also includes exergoeconomic analysis of 660 MW supercritical power plant. The purchased equipment cost evaluated during the economic analysis was considered as the external attributes. The square matrix of [41] was constructed by considering the main and auxiliary equations in order to find the cost flow at the various streams of the plant. The fuel and product side cost flow was computed for major equipment present in the 660 MW Plant. The first

Fig. 10 Flowchart for economic and exergoeconomic analysis



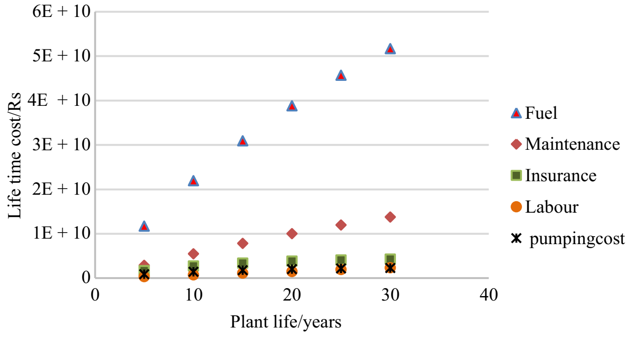


Fig. 11 Plant life (Years) versus Life Time cost (Rs.)

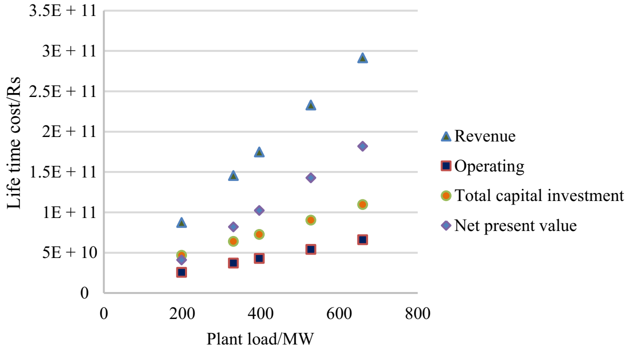


Fig. 14 Plant load (MW) versus Life Time cost (Rs.)

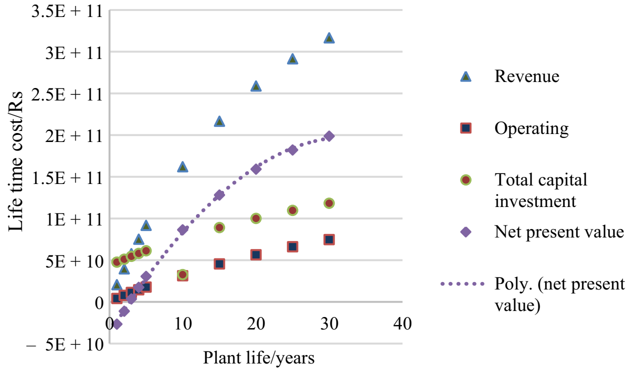


Fig. 12 Plant life (Years) versus Life Time cost (Rs.)

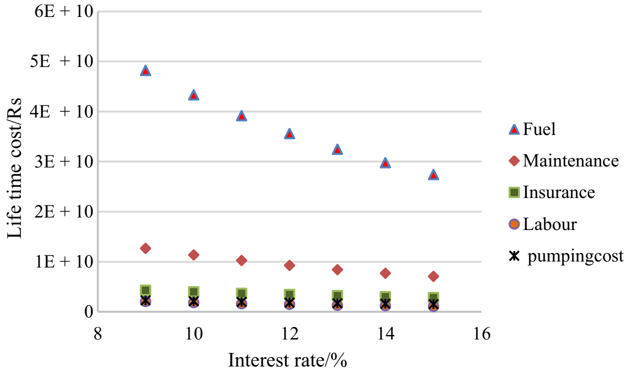


Fig. 15 Interest rate (%) versus Life Time cost (Rs.)

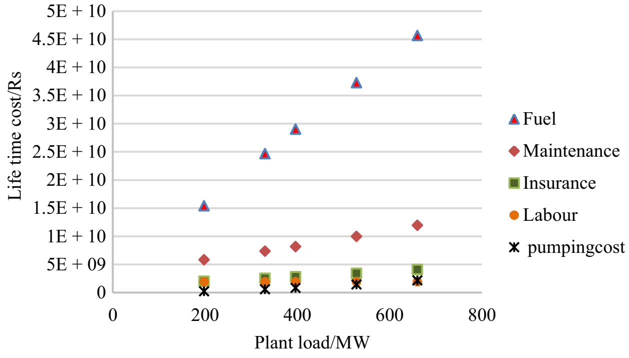


Fig. 13 Plant load (MW) v/s Life Time cost (Rs.)

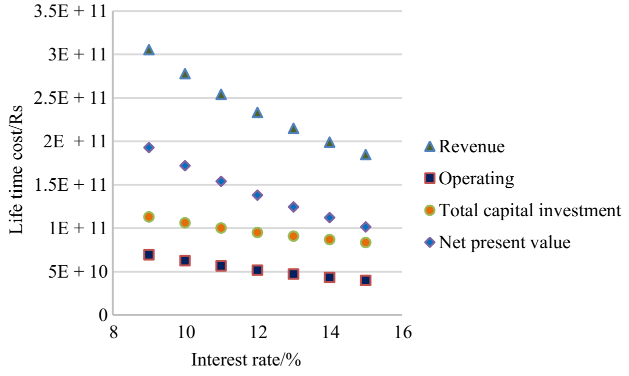


Fig. 16 Interest Rate (%) versus Life Time cost (Rs.)

step involved in exergoeconomic analysis is to evaluate the exergy of fuel and product side of each equipment present in the plant. Table 6 represents the exergy of the fuel and product side of components. Table 7 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 major cost destructive component followed by generator.

The purchased equipment cost (PEC) of components are evaluated from the available literature relations [46, 51]. Table 8 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 $\alpha q = 1.06$ is considered in the account of maintenance cost for each plant component [52], the cost rate has been evaluated as, shown in Table 8. The cost rate of all set

Table 5 Comparison of the present study with available literature

Plant type	Fuel used	Capacity	Interest rate (%)	Payback period (years)	References
Supercritical power plant	Coal	660 MW	9	4.5	Present Study
Subcritical power plant	Coal	250 MW	9	10	[3]
Subcritical power plant	Coal	210 MW	9	10	[40]
Subcritical power plant integrated with solar technology	Natural Gas	250 MW	10.5	6	[47]
Ultra-supercritical power plant	Coal	500 MW 400 MW 430 MW	10.9 6.7 7.7	7.4 11.1 9.9	[48]
Supercritical power plant	Coal	1000 MW	10	2.92	[49]
Ultra-supercritical coal-fired power plant	Coal	670 MW	0	25.13	[50]

Table 6 Exergy flow at inlet and outlet of components

Components	Fuel side exergy (KW)	Product side exergy (KW)
Steam generator	1,997,400	942,590
HPTur.	227,210	213,500
IPTur.	266,600	253,850
LPTur.	217,180	209,580
Gen.	689,670	661,700
Cond.	58,045	31,430
CEPump	1698	1333
DC	765	708
LPHe-4	4798	4110
LPHe-3	8155	6920
LPHe-2	10,200	8903
LPHe-1	22,656	19,577
Dear.	114,760	80,622
PDTur.	23,877	21,773
BFPump	21,773	19,423
HPHe-3	13,809	13,234
HPHe-2	25,637	23,391
HPHe-1	15,310	15,080

Table 7 Cost per exergy for product and fuel side of components

Components	$cf/\$\ \mathrm{GJ}^{-1}$	$Cp/\$\ \mathrm{GJ}^{-1}$	$Cd/\$\ \mathrm{s}^{-1}$
Steam Generator	475.3	1066.8	501.4
HPTur.	1148.9	1223.1	15.8
IPTur.	1070.7	1124.1	13.6
LPTur.	10378.0	10,756.0	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

of turbines contributes to be maximum as compared with other components. The largest capital cost rate is observed in intermediate-pressure turbine ($1530\$\ \mathrm{H}^{-1}$) followed by high ($1310.09\$\ \mathrm{H}^{-1}$) and low ($1293.21\$\ \mathrm{H}^{-1}$) pressure turbine.

The relative cost difference and exergoeconomic factor are presented in Figs. 17,18. The maximum relative cost difference in boiler (124.4%) followed by condenser (84.8%) and dearator (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 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 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%) is 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%) indicates that performance of high-pressure heater 1 can be improved by reducing exergy destruction rate. The components such as boiler feed

Table 8 Purchased equipment cost of various components

Components	C_0/$	C/$ Year^{-1}	Z/$ H^{-1}
Steam Generator	59,465,000	5,787,728.45	889.129,298
Gen.	11,191,000	1,089,220.03	167.329,454
HPTur.	87,619,000	8,527,957.27	1310.09,199
IPTur.	102,360,000	9,962,698.8	1530.50,155
LPTur.	86,490,000	8,418,071.7	1293.21,101
Cond.	11,550,000	1,124,161.5	172.697,274
CEPump	115,560	11,247.4548	1.72,786,987
LPHe-4	77,874	7579.47,642	1.16,438,333
LPHe-3	88,293	8593.55,769	1.32,016,973
LPHe-2	91,495	8905.20,835	1.3,680,465
LPHe-1	142,400	13,859.792	2.12,918,544
Dear.	6,377,100	620,683.143	95.3,513,234
BFPump	707,050	68,817.1765	10.5,719,141
HPHe-3	271,760	26,450.4008	4.06,339,491
HPHe-2	495,850	48,261.0805	7.41,402,106
HPHe-1	308,040	29,981.5332	4.60,585,872

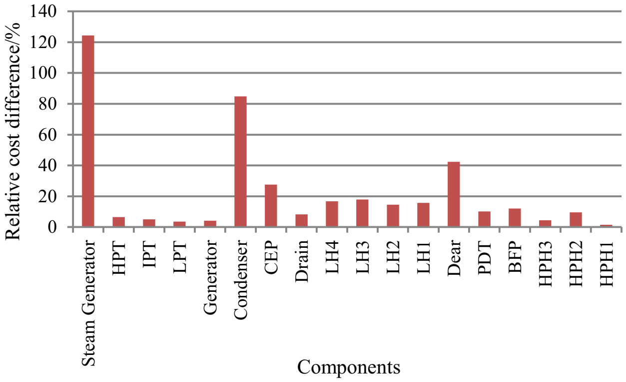


Fig. 17 Relative cost difference of components

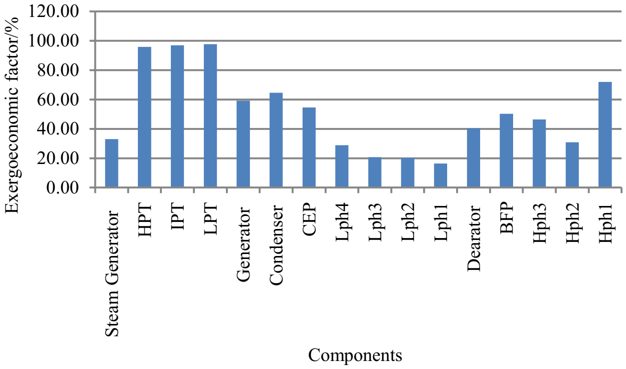


Fig. 18 Exergoeconomic factor of components

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, dearator, and generator, have exergoeconomic factors within the permissible range.

Conclusions

In this paper, the economic and exergoeconomic semi-empirical model of a 660 MW coal-fired power plant was established. The economic analysis reveals that the lifetime cost of decreases with an increase in annual interest rate. The revenue generated from the 660 MW supercritical coal-fired power plant is 2.92 times higher than the subcritical coal-fired power plant of capacity 210 MW. The fuel cost is found to be one of the independent variable which gets 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 exergoeconomic analysis of the 660 MW power plant. The relative cost difference for the steam generator 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 be decrease in expense of exergetic efficiency.
- The higher exergoeconomic factor and lower relative cost difference indicates that high-pressure heater 1 performance can be increase by reducing exergy destruction rate.
- The condensate extraction pump and boiler feed boiler having work as fuel shows significant higher relative cost difference.

The results of the economic and exergoeconomic analysis can be implemented as input for overall economical optimization of supercritical power plant.

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