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Thermoeconomic Analysis with Regression Modelling and Optimization of Steam Coal Power Plant

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There are no conflicts to declare.

ABSTRACT

In this study, exergy and economic analyses with regression of a 50MWunit of Lakhra steam power plant, situated near Jamshoro Pakistan is presented. Firstly, a thermodynamic model is developed using Engineering Equation Solver (EES) software and validated, followed by an economic assessment parametric analysis to show the impacts of various operating parameters on the levelized cost and finally regression along with optimization is carried out. The condenser pressure, main steam pressure, temperature and interest rate are selected as operating parameters while levelized cost, net power output, energy and exergy efficiencies are selected as performance parameters. Furthermore, in order to know about the effects of predictor and response variables with each other and to correlate the performance parameters with the operating parameters the multiple polynomial regression analysis has been prepared. In economic analysis, levelized cost of electricity is estimated under various operating and economic conditions. Under designed parameters, the plant is simulated yielding 53.5 MW power output with 31.02% and 26.24% energy and exergy efficiencies, respectively with levelized cost of US$0.0654/kWh. According to the optimization results, maximum power, energy and exergy efficiencies are obtained as 53.786 MW, 31.25% and 26.43%, respectively, whereas minimum levelized cost is obtained as US$0.04856/kWh under given optimal conditions.

Keywords: Exergy, Operating parameters, Economic assessment, Optimization, Levelized cost

1. Introduction

Generally, the world's electricity demands are met by fossil fuels. Although much progress has been done on inexhaustible sources of energy like power of wind and solar power to name a few, still the dominance of fossil fuels is anticipated to prolong for many decades to come. In Pakistan, by source electricity generation comes as Oil 35.2%, Gas 29.0%, Hydel 29.9% and Nuclear and imported 5.8% [1]. Power production Industry of Pakistan chiefly comprises of thermal and hydropower plants with fixed capacity of 12442 and

6481 MW respectively [1]. Moreover, these thermal power plants are operated with very low efficiencies due to many technical and management inefficiencies. For such reasons, the electricity supply and demand gap is get widening, which is leading the country's social and economic growth near to standstill. Recently, Pakistan is experiencing worst energy crisis in history. The gap between electricity demand and supply keeps widening; a maximum shortfall of higher than 6000 MW was recorded in year 2010 [2]. The scenario has yet to be better as country witnesses currently massive protests. Many businesses have to be shut off owing to severe power crisis. Many factors contribute to the acute shortage of dwindling of energy in Pakistan involving absence of Integrated Energy Planning and Demand Forecasting and nonappearance of central and concentrated entity answerable for the sector of energy, unevenness energy mix with greater interdependence on gas and oil and their exorbitant import. Nonutilization of enormous local coal of Thar and hydro proficiency, dearth of efficacious project structuring, planning and implementation of known and feasible projects are leading causes of crisis of power. Country has tremendous hydro and coal energy potential (185 billion tones) [2] that could be put into action in order to overcome the electricity crisis. Global generation of electricity is offered 40% through coal. On the other hand, regardless of having massive stockpile of lignite, Pakistan brings about only 0.1% electricity from Lakhra FBC power plant. The performance assessment of power plants is mostly performed on the basis of energy concepts, whereas exergy concepts are being widely used nowadays for more elaborative investigation. The exergetic performance assessment is more beneficial in designing, evaluation, and optimization of various energy conversion processes than using energy principles alone [3].

Various researchers have conducted exergy based analysis of different types of power plants worldwide. For instance, Rajper, et.al. [4] Performed the energy and exergy analysis of 210 MW Jamshoro thermal power plant regression and optimization analysis where major destructing region was found to be boiler yielding 82.11% of the total destruction of exergy. Memon et.al. [5] did analyzed the simple gas turbine cycle in perspective of thermodynamic analysis with multiple regression modelling and optimization and also conducted the parametric based study by setting compressor inlet temperature , pressure ratio and turbine inlet temperature as the operating parameters and fuel consumption, energy efficiency ,net power output and exergy efficiency as the performance parameters. Vosough, et.al. [6] analyzed power plant constituents and identified and quantified areas of greatest energy and exergy destructions and found boiler as a site which generates maximum irreversibilities with nearly 86% exergy destruction of total followed by stack with 13%. Dai,et.al [7] applied the exergy concepts to analyze a cogeneration system and concluded that turbine, condenser and heat recovery steam generator (HRSG) are the major contributors towards exergy destruction. Kotas [8] illustrated the importance of exergy methods for performance evaluation of the thermal plants. Ganapathy,et.al. [9] performed exergy analysis on 50 MW lignite coal plan in India that optimum energy losses of 39% happens in condenser, whereas maximum losses of 42.73% accrue in combustor. Sengupata et.al. [10] and Regulagada et.al. [11] investigated actual steam power plants by exergy methods under

designed and off-designed conditions. They reported that plant performance is highly affected by the load variations and highest exergy destruction occurs in boilers followed by turbines. Aljundi et. al. [12] provided a comprehensive energy and exergy based analysis of a steam power plant located in Jordan. They have shown that exergy methods should be widely employed to evaluate the performance of power plants for effective and efficient utilization of energy resources. Memon et. al. [13] has performed the thermodynamic, environmental and economic analyses of simple and regenerative gas turbine cycles. The authors have developed various regression models to show correlation of response variables with predictor variables and finally optimization was carried out. Jamali,et al [14] carried out the energy and exergy analyses of the boiler and its parts furnace, economizer and superheaters and results showed maximum destruction in furnace. Then another study was conducted in which the unit #2 of 50 MW Lakhra coal power plant (FBC) was comprehensively analyzed and study found that the relatively least exergy destruction happens in condenser (0.306%) but it has the highest energy loss (68.19%) and the highest exergy destruction happens in boiler (93.84%) [15]. Carried out parametric based exergy analysis of cooling towers of the thermal and the lakhra coal power plant Jamshoro in which it was investigated that the lowest exergy destruction occurs in condenser along with cooling tower [16].

Keeping in view the current energy scenario of Pakistan and importance of exergy methods for power plant evaluation, this paper presents exergy-based analysis of Lakhra Coal Power Plant situated in Lakhra 187 km from major city Karachi. A 50 MW capacity unit of the power plant is selected for the study which is first thermodynamically modelled in Engineering Equation Solver (EES) software and simulated under various operating and economic conditions. The impacts of operating parameters like condenser pressure, main steam pressure and temperature on performance characteristics namely net power output, energy and exergy efficiencies are analyzed.

2. Process description

The schematic diagram of the unit under study is shown in Fig.1. The plant has three identical and same capacity units each comprises of 50 MW units with total capacity of 150 MW however, first and third units are dysfunctional and dormant due to various technical reasons so in this study Unit#2 has been analyzed which is active, operative and functional. The water at 200 ton/hr is superheated in the FBC boiler to the temperature of 540°C and pressure of 9 MPa. The superheated steam is directed to the turbine through main pipe and main stop valve achieves its regulation. The expansion of the steam is performed in the impulse turbine in 21 stages. The last stage stands for condenser pressure equivalent to 8.04 kPa. A total of six main steam extractions is taken off from the turbine at different stages for feed water heating. Furthermore, around ten different steam flow streams shown as 1-9 and 42 in the diagram are the steam leakages throughout the plant to improve the cycle thermodynamically as some of them are used as motive steam for gland ejector and while others are discharged into the main big extractions lines to help in feed water heating properly and perfectly. The steam with the flow rate of 140 tons/hr at condenser pressure is discharged into

the condenser. Circulating in the tubes of the condenser is the cold water at the mass flow rate of 9850 tons/hr which enters at atmospheric pressure and temperature (nearly at 32°C and 0.1013 MPa). The condensate accumulates in the hot well. The two steam jet air ejectors (also referred as gland ejector and main ejector) are arranged alongside the condenser. The source of motive steam for these ejectors is the discharge steam from the deaerator. The steam flow in the respective ejectors is expanded, mixes with the non-condensables and then condenses by transferring their heat to the condensate exiting the condensate pump. The condensate from the ejectors is drained back to the hot well, where it mixes with the condensate of the main condenser and is discharged as single stream passing through the two ejectors. The three closed type LP heaters are arranged next to the two air ejectors. The drain from the LP heater 2 and 3 is cascaded back to LP heater 1; thus, all the drains then accumulated in LP heater 1 equals the total steam flow extracted for the LP heaters. The condensate is then pumped and mixes with the feedwater stream exiting the LP heater 1. The resultant stream then passes through the next two LP heaters (heater 2 and 3) and then enters the open type feedwater heater. The steam from the deaerator at 13 and 14 are used as motive steam for the two ejectors, while the streams 11 and 12 are evaporated in the atmosphere. The drain from the HP heaters 1 and 2 is also throttled back to the deaerator. The resultant stream exiting the deaerator is the saturated water corresponding to the deaerator pressure. This saturated water is pumped through the boiler feed pump, and it then circulates through two HP heaters. The final stream at the exit of HP heaters enters the FBC and hence completes the cycle.

The main assumptions made for analysis are given below:

- Steady state flow conditions prevail for all fluid streams with negligible changes in kinetic and potential energies.
- The dead-state condition is at 101.32 kPa and 25 °C.
- Isentropic efficiencies of turbine, Generator efficiency and pump are 85%,96% and 90%, respectively.
- The coal is lignite and its heating value and flow are 12.02 MJ/kg and 14.5 kg/s respectively.

3. Thermodynamics model equations

The main equations based on three fundamental principles are utilized for the model development, as given below. The conservation of mass, first law and second law of thermodynamics for a steady flow process reduce to the form given in Eqns. (1) to (3), respectively.

$$\sum \dot{m}_i = \sum \dot{m}_e \tag{1}$$

$$\dot{Q} - \dot{W} + \sum \dot{m}_i h_i - \sum \dot{m}_e h_e = 0 \tag{2}$$

$$\dot{E}x_Q - \dot{E}x_W + \sum \dot{m}_i ex_i - \sum \dot{m}_e ex_e - \dot{E}x_D = 0 \tag{3}$$

In Eqn. (3) left hand side consists of exergy transfer due to heat and work, inlet and exit fluid physical exergy flow, and exergy destruction rate. The specific physical exergy flow of the fluid is given by Eq. (4).

$$ex = (h - h_0) - T_0(s - s_0) \tag{4}$$

In Eqn. (4) the subscript 0 refers the dead-state condition as defined in the assumptions.

The performance parameters are calculated using Eqns. (5) to (8).

$$\dot{W}_{total} = \dot{W}_{turbine} - (\dot{W}_{cp} + \dot{W}_{fwp} + \dot{W}_{LPHp}) \tag{5}$$

$$\dot{W}_{NET\ PLANT} = \dot{W}_{total} \times Generator_{efficiency} \tag{6}$$

$$EnE = \frac{\dot{W}_{net\ plant}}{\dot{Q}_f} \tag{7}$$

$$ExE = \frac{\dot{W}_{net\ plant}}{\dot{Ex}_f} \tag{8}$$

In Eqn. (5) various terms are defined in Eqns. (8) to (11).

$$\begin{aligned}\dot{W}_{turbine} = {} & \dot{m}_{72}(h_{72} - h_{15}) + \dot{m}_{73}(h_{15} - h_{16}) + \dot{m}_{74}(h_{16} - h_{18}) \\ & + \dot{m}_{75}(h_{18} - h_{23}) + \dot{m}_{76}(h_{23} - h_{26}) + \dot{m}_{77}(h_{26} - h_{27}) \\ & + \dot{m}_{78}(h_{27} - h_{41})\end{aligned} \tag{9}$$

$$\dot{W}_{cp} = \dot{m}_{52} v_{52} \int_{52}^{54} dP \tag{10}$$

$$\dot{W}_{fwp} = \dot{m}_{63} v_{63} \int_{63}^{64} dP \tag{11}$$

$$\dot{W}_{LPHp} = \dot{m}_{35} v_{35} \int_{35}^{37} dP \tag{12}$$

The energy and exergy inputs (fuel) as defined in Eqns. (7) and (8) are defined by Eqns. (13) and (14), respectively.

$$\dot{Q}_f = \dot{m}_f \times LHV \tag{13}$$

$$\begin{aligned}\dot{Ex}_f = \dot{m}_f \times \Bigg[& \left(1.0437 + 0.1882 \times \frac{H}{C} + 0.061 \times \frac{O}{C} + 0.0404 \times \frac{N}{C}\right) \\ & \times \{LHV_f + (h_{fg,water} \times m_{moisture})\} + \{m_S(ex_S - LHV_S)\}\Bigg]\end{aligned} \tag{14}$$

All enthalpies and exergies are calculated under dead state conditions

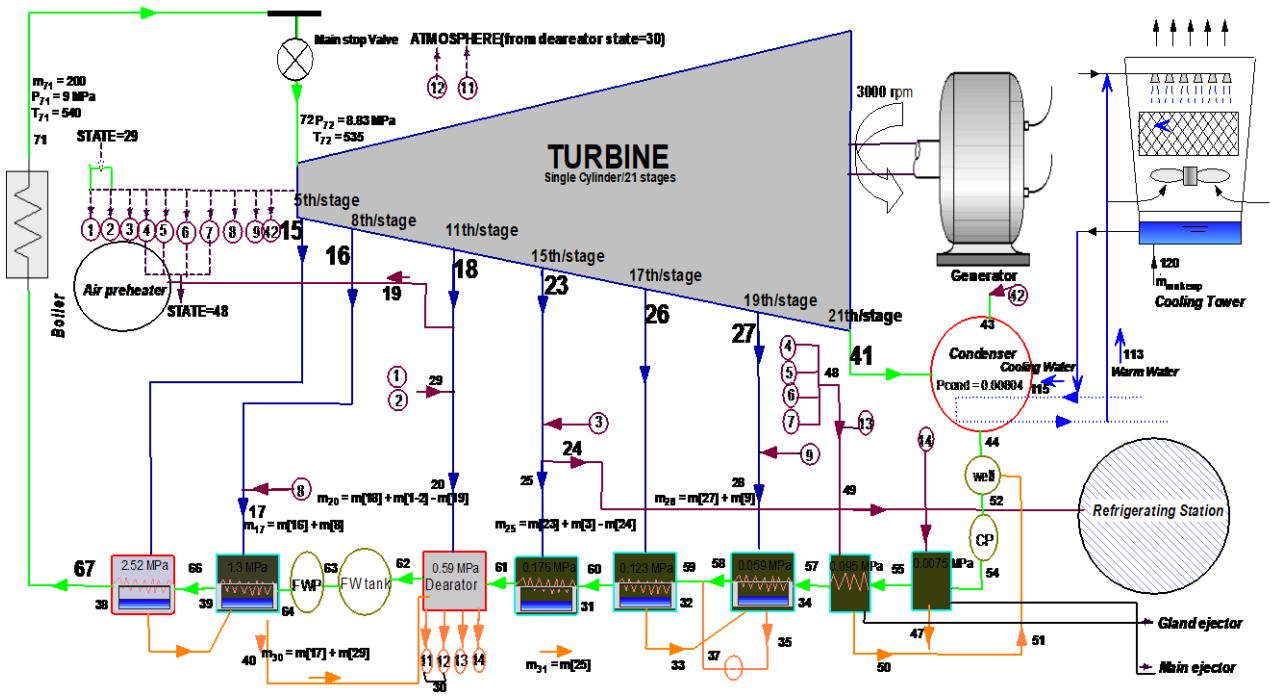

Figure 1 Schematic diagram of 50 mw (FBC) Lakhra power plant [15]

4. Economic model

The main parameter used for economic assessment is Levelized cost of electricity (C_L), which is defined by Eqn. (15).

$$C_L = \frac{\dot{C}_T}{\dot{W}_{net}} \qquad (15)$$

In Eqn. (15) numerator refers to total cost rate consisting of total capital cost rate and running fuel cost, as given in Eqn. (16).

$$\dot{C}_T = \left(\sum_i \dot{Z}_i + c_F \dot{m}_F LHV_F\right) \qquad (16)$$

In Eqn. (16) $\dot{Z}_i$ is total capital cost rate defined by Eqn. (17) while c_F represents specific fuel cost.

$$\dot{Z}_i = \frac{PEC_i \times CRF}{N} \times (1 + \varphi) \qquad (17)$$

In Eqn. (17) N and φ represent number of hours of plant operation per annum and maintenance cost factor, respectively. The total capital cost rate of components is estimated in \$/h by multiplying a capital recovery factor (CRF) given by Eqn. (18) after adding the purchased equipment cost (PEC) and maintenance cost. PEC of each component is calculated by cost functions given in Table 1.

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \qquad (18)$$

Table 1: Cost functions in terms of thermodynamics parameters for the system components [17].

COMPONENT	COST FUNCTIONS
Boiler	$PEC_{Boiler} = 208582 \times (\dot{m}_{Boiler})^{0.8} \times \exp\left(\frac{P_{steam}-28}{150}\right) \times \left(1 + 5 \times \exp\left(\frac{T_{steam}-593}{10.42}\right)\right) \times \left(1 + \left(\frac{1-0.9}{1-\eta_{Boiler}}\right)^7\right)$, P and T are in bar and °C, respectively.
Deaerator	$PEC_{DE} = 145315 \times (\dot{m}_{steam})^{0.7}$
Steam turbine	$PEC_{ST} = 3880.5 \times \dot{W}_{ST}^{0.7} \times \left[1 + \left(\frac{0.05}{1-\eta_{s,ST}}\right)^3\right] \times \left[1 + 5 \times exp\left(\frac{T_{in}-866}{10.42}\right)\right]$
Condenser	$PEC_{Cond} = 280.74 \times \frac{\dot{Q}_{Cond}}{(k \times LMTD)_{Cond}} + 746 \times \dot{m}_{cw} + 70.5 \times \dot{Q}_{Cond} \times (-0.6936 \times \ln(\bar{T}_{cw} - T_{wb}) + 2.1898)$ where, $k = 2200\ W/m^2\ K$, $\bar{T}_{cw}$ and T_{wb} are average cooling water temperature and wet-bulb temperature, respectively.
Condenser and feedwater pumps	$PEC_{cp} = 705.48 \times \left(1 + \frac{0.2}{1-\eta_{s,cp}}\right) \times \dot{W}_{cp}^{0.71}$ $PEC_{fwp} = 705.48 \times \left(1 + \frac{0.2}{1-\eta_{s,fwp}}\right) \times \dot{W}_{fwp}^{0.71}$

5. Results and discussion

In this section, results of thermoeconomic analysis of the power plant are discussed along with the discussion on parametric study exhibiting the impacts of operating parameters on levelized cost. In this regard, net power output, energy, exergy efficiencies and levelized cost are nominated as performance parameters, whereas condenser pressure, main steam pressure, temperature and interest rate are considered as operating parameters. Then regression and polynomial analysis is depicted and lastly, the results of optimization are discussed.

5.1 Parametric study of economic assessment

A sequence of simulations in which one or several independent variables (operating parameters) of the system are varied to examine their influence on the dependent variables (performance and levelized cost) is called parametric study. Such an investigation is performed to define, analyze and examine the different relationships among the variables.

Keeping in view the constraints in practice and prevailing economic situation, the variation in the independent variables of the power plant under study, i.e., condenser pressure, main steam pressure , temperature and interest rate are made in the ranges of 7.1-95 kPa, 6000-9000 kPa 400-540 C and 3-7.6%, respectively.

The rise in the plant performance due to variation in the operating parameters as discussed above always accompanied with a proportional increase in costs that stems due to development in the turbine and boiler, for example. The incremental revenues generated by the improved power outputs with higher efficiencies may only be acceptable if the economic parameters also indicate the same. Therefore, following section discusses the economic appreciation of the power plant. In base-case scenario (designed operating conditions), the economic analysis reveals a levelized cost of US$0.0654/kWh. The parametric-based economic analysis is illustrated in Fig. 2. The impact of interest rate on levelized cost is exhibited in Fig. 2 (a), which shows an upward trend in the levelized cost with an increase in the interest rate due to rise in the capital investment rate of the components. Fig. 2 (b) and (c) illustrate the impact of main steam pressure and temperature on the levelized cost, which shows rising trend in levelized cost with these parameters. The main reason of such trend is corresponding increase in the capital cost rate of components for them to withstand rising thermal stresses due to increase in these parameters.

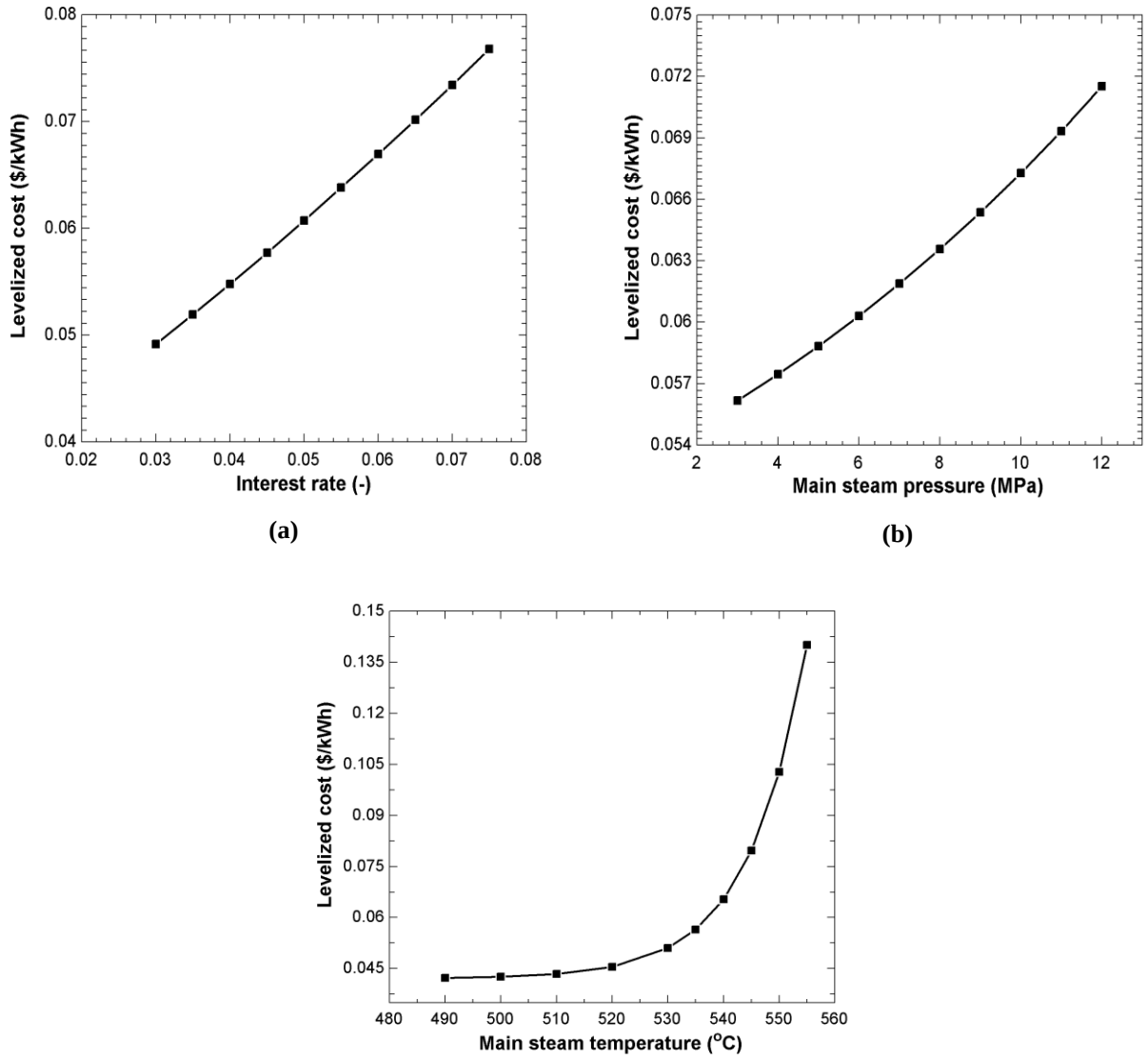

Figure 2: Effect of (a) interest rate (b) main steam pressure and (c) main steam temperature on levelized cost

5.2 Optimization

Optimization is a phenomenon of maximization and/or minimization of objective functions by changing the single or multiple predictor variables(s). In this study, performance is optimized (maximized) with respect to main steam pressure and temperature, and condenser pressure while levelized cost is optimized (minimized) on interest rate. The optimization technique used here is Genetic algorithm that is a built-in method available with EES software. The optimization results are tabulated in Table 2 indicating that for maximum performance main steam pressure and temperature should be kept as high as possible and condenser pressure should be at lowest possible value. The levelized cost is minimum when interest rate is lowest. The optimal values of main steam pressure and temperature in minimizing the levelized cost are arrived at their high and low values, respectively. This is because the capital cost rate increases when main steam temperature increases more significantly than if main pressure increases. This may become more clear if cost functions of boiler and turbine are referred (Table 1). The capital costs of these components are more sensitive with main steam temperature than pressure.

Table 2: Optimization results

Objective function	**Optimum value**	**Main Steam Pressure (MPa)**	**Main Steam Temperature(C)**	**Condenser Pressure (MPa)**	**Interest rate**
Energy efficiency (Maximum)	31.25 %	9	539	0.007	-
Exergy efficiency (Maximum)	26.43 %	8.97	540	0.007	-
Net power output (Maximum)	53.786 MW	8.91	539	0.007	-
Levelized Cost ($/kWh)	0.0486	8.95	490	-	0.030

5.2.1 Multiple polynomial regressions modelling of thermodynamic parameters

5.2.1.1 Condenser regression modelling

The correlation between condenser pressure and performance parameters produces the below equations through applying regression technique.

$$Exergy_{Efficiency} = 2.77439007E + 01 - 2.04752624E + 02 * Pcond + 2.20410861E + 03 * Pcond^2 - 9.73955645E + 03 * Pcond^3$$

$$Energy_{Efficiency} = 3.27921046E + 01 - 2.42008848E + 02 * Pcond + 2.60516215E + 03 * Pcond^2 - 1.15117394E + 04 * Pcond^3$$

$$Wtotal = 5.64965333E + 04 - 4.16949784E + 05 * Pcond + 4.48835572E + 06 * Pcond^2 - 1.98332304E + 07 * Pcond^3$$

5.2.1.2 Main steam temperature regression modelling

The correlation between Main steam Temperature and performance parameters produces the below equations through applying regression technique.

$$Exergy_{Efficiency} = 6.07901389E + 00 + 5.09244801E - 02 * T[71] - 4.07776135E - 05 * T[71]^2 + 2.89272842E - 08 * T[71]^3$$

$$Wtotal = 1.23790528E + 04 + 1.03700508E + 02 * T[71] - 8.30378476E - 02 * T[71]^2 + 5.89063266E - 05 * T[71]^3$$

$$Energy_{Efficiency} = 7.18513454E + 00 + 6.01905585E - 02 * T[71] - 4.81973960E - 05 * T[71]^2 + 3.41908133E - 08 * T[71]^3$$

5.2.1.3 Main steam pressure regression modelling

The correlation between Main steam Pressure and performance parameters produces the below equations through applying regression technique.

$$Wtotal = 3.92842293E + 04 + 3.16513245E + 03 * P[71] - 2.40333041E + 02 * P[71]^2 + 7.04723499E + 00 * P[71]^3$$

$$Exergy_{Efficiency} = 1.92914095E + 01 + 1.55430989E + 00 * P[71] - 1.18020977E - 01 * P[71]^2 + 3.46070417E - 03 * P[71]^3$$

$$Energy_{Efficiency} = 2.28016213E + 01 + 1.83712784E + 00 * P[71] - 1.39495749E - 01 * P[71]^2 + 4.09040438E - 03 * P[71]^3$$

5.2.1.4 Multiple polynomial regression modelling of combined perspective of thermodynamic parameters

Multiple regression models are made to investigate the behavior of predictor variables on response variables and the effects and the impact on each other. For the better understanding and comprehension, the equations have been brought by correlating the performance parameters with the operating parameters.

$$Exergy_{Efficiency} = -5.77634216E + 04 + 3.29753709E + 04 \times P_{main\ steam} - 3.74098208E + 03 \times P_{main\ steam}{}^2 + 1.41452561E + 02 \times P_{main\ steam}{}^3 - 2.18861857E + 02 \times T_{main\ steam} + 4.09258573E - 01 \times T_{main\ steam}{}^2 - 2.55529988E - 04 \times T_{main\ steam}{}^3 - 8.56031141E + 02 \times Pcond + 2.00392921E + 04 \times$$

$Pcond^2 - 1.45239198E + 05 \times Pcond^3$

$$Energy_{Efficiency} = 5.52311915E + 04 - 2.93852731E + 04 \times P_{main\ steam} + 3.32656412E + 03 \times P_{main\ steam}{}^2 - 1.25509224E + 02 \times P_{main\ steam}{}^3 + 1.73209435E + 02 \times T_{main\ steam} - 3.20083060E - 01 \times T_{main\ steam}{}^2 + 1.97630163E - 04 \times T_{main\ steam}{}^3 + 3.00942756E + 02 \times Pcond - 1.21694455E + 04 \times Pcond^2 + 1.08604892E + 05 \times Pcond^3$$

$$Wtotal = 1.81259573E + 08 - 9.66563322E + 07 \times P_{main\ steam} + 1.09420829E + 07 \times P_{main\ steam}{}^2 - 4.12827312E + 05 \times P_{main\ steam}{}^3 + 5.72299024E + 05 \times T_{main\ steam} - 1.05913927E + 03 \times T_{main\ steam}{}^2 + 6.55000695E - 01 \times T_{main\ steam}{}^3 + 1.28979821E + 06 \times Pcond - 4.31873105E + 07 \times Pcond^2 + 3.69694226E + 08 \times Pcond^3$$

Conclusion

This study presented a comprehensive thermodynamics and economic analyses of a selected unit of Lakhra power plant, Pakistan. First the model of the plant was developed using EES software and simulated for base-case and varying operating and economic parameters. In base-case with designed operating conditions, the net power output, energy and exergy efficiencies and levelized cost were calculated as 53.5 MW, 31.02%, 26.24 % and 0.065356 $/kWh, respectively. From the results of parametric study, it can be concluded that condenser pressure, main steam pressure and temperature flatly affects the performance and levelized cost. The performance characters tend to increase with increase in main steam pressure and temperature and decrease in condenser pressure. Furthermore, economic analysis revealed that rise in interest rate, main steam pressure and temperature increase the levelized cost, more significantly with interest rate and main steam temperature. The optimization results showed maximum performance parameters and minimum levelized cost with given optimal operating and economic parameters. It can be suggested the decision on performance improvement should only be made after comprehensive financial assessment for which this study may play an important role.

Nomenclature

ex	*Specific exergy flow (kW)*
Ex_D	*Exergy destruction rate (kW)*
h	*Specific enthalpy (kJ/kg)*
I	*Interest rate (%)*
$\dot{m}$	*Mass flow rate (kg/s)*
N	*Number of operating hours per year (h)*
N	*Useful life of plant (years)*
P	*Pressure (kPa or MPa)*
$\dot{Q}$	*Heat flow rate (MW)*
S	*Specific entropy (kJ/kg.K)*
T	*Temperature (^oC)*
$\dot{W}$	*Power (MW)*

$\dot{Z}$	*Capital cost rate ($/h)*

Abbreviations

CRF	*Capital Recovery Factor*
Cp	*Condenser pump*
FBC	*Fluidized-Bed Combustion*
Fwp	*Feedwater pump*
LMTD	*Log-mean Temperature Difference*
PEC	*Purchased-Equipment Cost*

Greek letter

Φ	*Maintenance factor*

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