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Advanced Exergoeconomic and Exergy Cost Sensitivity Analyses of Steam Power Plants

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Abstract

In this study, the exergy and exergoeconomic analyses of simple typical thermal power plants are carried out. The general methodology for defining and calculating exergetic efficiencies, exergy destruction, exergoeconomic factors, total cost, improvement potential and exergy related costs in thermal systems are presented. The procedure is based on the Specific Exergy Costing approach and sensitivity cost analysis. Thermodynamic working fluid properties are obtained by employing both THERMAX and MATLAB software packages. For the considered normal operating and economic conditions; the percentage ratio of the exergy destruction to the total exergy destruction and Potential Improvement was found to be maximum in the boiler, with 88.4% and 92.8%, respectively. The exergoeconomic factor is calculated for the boiler, turbine, condenser and pump, with values of 0.23, 0.35, 0.42, and 0.39, respectively. The total costs of exergy loss are 5153, 1737, 619, and 43 $/hr, for the boiler, turbine, condenser, and pump, respectively.

Sensitivity and parametric analyses confirm that the exergoeconomic factor, total annual plant cost, and unit cost of the work and steam, increase with the rise in the interest rate, while they decrease with increasing the annual number of working hours. With the increase of the working boiler temperature, the unit cost of work and steam drop, while the exergoeconomic factor and the total cost rise. The total cost, unit cost of work and steam, increase with the increase in the reference environmental temperature, however, the exergoeconomic factor decreases. For the proposed conditions, the total cost of the plant is 14,000 $/hr for a considered fuel cost of 0.0255 $/kWh, including 10,000 $/hr for the cost of the steam production at 650°C with a unit steam cost of 0.029 $/kWh. It's a valuable achievement to have determined values and clear parametric influences that could be of great assistance to the site engineers and operators to effectively establish their unique jobs, while playing with the conflicts of the use of energy, exergy, and cost.

Keywords: Energy, Exergy, Efficiency, Exergy destruction, total cost, and exergoeconomic factor.

Contents

1-Introduction

Many factors should be taken into consideration regarding the type of energy that could be used to increase the efficiency of energy systems. The selected energy type is one of the factors that should be economical. The next factor represents the cost conditions. The saving in energy or exergy is the prime objective of the conventional thermodynamic optimization process. This kind of optimization has benefits like an increase in energy or exergy efficiency or a decrease in the irreversibility of the system. However, this increase in the efficiency is achieved at the cost of the increase of the capital investment. Thus, it is difficult to reach the balance between thermodynamics and economics. It is well known fact, that same amount of energy in different thermal devices may have quite different amounts of exergy and thus different economic values. Hence, the conventional thermodynamic optimization is not able to differentiate between the complex relationship between the energy, exergy and cost values. In order to overcome this problem, the combination of the economic and thermodynamic optimization is made, which is called exergoeconomis. The exergoeconomic analysis, the combination of the concept of the cost which is an economic property, and the exergy which is an energetic property, is done in order to achieve the best balance between thermodynamics and economics [1].

The production process of complex energy systems can be evaluated on the basis of its economic profitability and energy efficiency with respect to the energy resource consumption. Therefore, the economic analysis can deal with the cost of fuel, operation and maintenance of the total plant or individual components, and other terms. However, it cannot provide any measure for how to allocate the cost between them and its product. On the other hand, thermodynamic analysis provides the efficiency of the individual component or the overall plant and locates and quantifies the irreversibilities, but cannot evaluate their significance in terms of the overall production process. Hence, the shortcoming of thermodynamics and economic analysis is overcome by the introduced exergoeconomic analysis [2]. In Figures 1 and 2, the steam thermal power cycle is represented, which works according to the ideal Rankine cycle. The processes and point status are indicted in the corresponding T-s diagram [3].

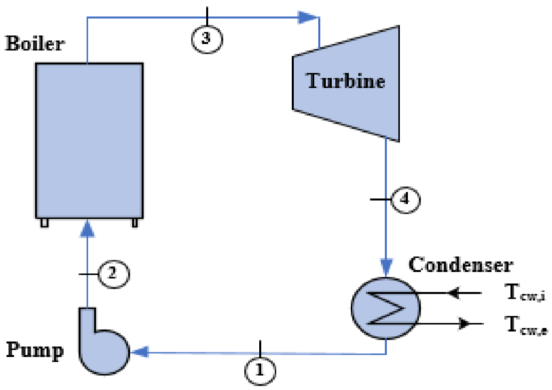


Figure 1. The schematic steam plant cycle.

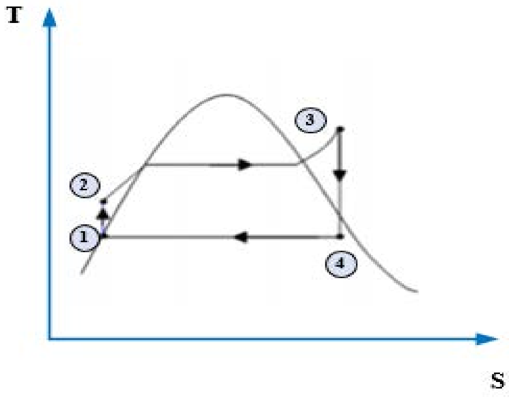


Figure 2. The steam power plant corresponding T-s diagram.

2-Literature Review

Thermoeconomics is nowadays a powerful tool to study and optimize the energy systems. This concerns the evaluation of the utility costs as products or supplies of production plants, and the energy costs between process operations or of the energy conversion systems. These types of costs are applied to the feasibility studies, investment decisions, comparing alternative techniques, operating conditions, cost-effective selection of equipment during installations, and exchange or expansion of the energy desired systems [4]. Bejan et al. [5] has explained the fundamentals of exergy analysis and entropy generation minimization, economic and exergoeconomic analyses. This work reviews many concepts, like the irreversibility, entropy generation or exergy destruction, where the exergy flows and accumulates in closed and open systems with heat transfer processes, and in power and refrigeration plants.

Ahmadi et al. [6] have performed thermodynamic modeling, exergy and exergoeconomic analyses, and optimization techniques. Their results confirm that the highest exergy loss related to the combined cycle plants is in the boiler. This is attributed to the high irreversibility during the combustion and due to the excessive temperature difference. Exergoeconomic analyses have shown that the greatest exergy loss cost is seen in the combustion chamber. They also emphasized that the rise in the input heat to the gas turbine creates a decreasing effect on the exergy loss cost of the plant. Manesh et al. [7] determined the optimum integration of a steam power plant, including a source and site utility system as a sink for the steam and power. This is done using the exergy, exergoeconomic, and exergoenvironmental analyses. The results indicate, that this type of integration represents an advantageous option from the exergetic, economic, exergoeconomic, and exergoenvironmental viewpoints.

Rashad et al. [8] has performed energy and exergy analyses for a steam power plant in Egypt. The primary aim of their research is to analyze each component of the system, separately, and identify the components that have the highest energy losses and exergy destruction. The maximum energy loss was found in the condenser where 56.4%, 55.2% and 54.4% of the input energy was lost to the surroundings at 50%, 75%, and full load, respectively. The calculated overall thermal efficiency based on the specific heat input to the steam was 41.9%, 41.7% and 43.9% at 50%, 75%, and 100%, respectively. Adibhatla et al. [9] explain the energy and exergy analyses of the thermal power plant at different loads under a constant and pure sliding working pressure. Their analysis is done at 100%, 80%, and 60% of the full load under constant and pure sliding pressure. The study shows that the boiler has the highest rate of exergy destruction of the plant. The study also reveals that there is a reduction in the rate of exergy destruction at part load conditions for the turbine in the case of the sliding pressure operation as compared to the constant pressure operation. Hence, the sliding pressure operation of the unit at part loads provides several benefits. Therefore, the sliding pressure operation is suitable for once through units and thus it's a better way of operating at part load conditions.

Bolatturk [10] has performed a thermodynamic and exergoeconomic analyses of the Cayirhan thermal power plant. He/She found out the thermodynamic properties at each and every point of the studied steam flow cycle using the engineering equation solver package program. Employing the obtained thermodynamic properties, the thermal and second law efficiencies were found to be 38% and 53%, respectively. The exergy destruction, improvement potential, and exergoeconomic factor were determined for each component in the plant. The maximum exergy destruction occurs in the boilers, and hence the improvement potential is the largest for the boiler. The exergoeconomic factor, is to be a maximum for the turbine group, followed by the boiler and finally the condenser. The low value of the exergoeconomic factor for the boiler leads to more exergy destruction to be occurring, and hence the improvement can be done by reducing the exergy destruction or increasing the investment on the boiler.

Ehyaei et al. [11] have examined the effects of an additional unit, to the inlet of a typical power plant in Iran, on the first and second law efficiencies. A new optimization is suggested in their study for the system optimization. This new optimization uses certain parameters, such as the first law efficiency, energy, and external costs, that are causing the air pollution. Their study detected that the addition of a unit to the inlet of the plant, the outlet power, first and second law efficiencies have respectively risen by 7%, 5.5% and 6%, with a 4% slump could be detected in the energy and pollution costs.

Selbas et al. [12] has performed a thermoeconomic optimization for a steam power plant with the help of the levelized cost method. The optimization is done with Matlab package. The stated design parameters are 20˚C ambient temperature and 0.1 MPa atmospheric pressure, and 12.5 MPa pump working pressure. The optimum operating values for a 500 MW steam power plant were determined under the specified design parameters of 900˚C boiler working temperature and 250 kg/s steam flow rate. They came up with a unit cost of steam as 0.538 $/MW and unit cost of electricity as1.18 $/MW. Their results show that due to the increase in the boiler temperature, the unit cost of steam and unit cost of electricity rise. The power output increases as well as the total irreversibility also increases. Hence, the optimization is to be done in order to achieve the maximum power output with minimum possible irreversibilities.

3- Modeling Of The Steam Power Plant

The proposed Steam Power Plant is represented in Figures 1 and 2. The plant consists of a boiler, turbines, condenser, feed pumps, and fittings. The nominal values of the design and economic parameters are given in table 1.

Table 1 Nominal operating conditions and the economical parameters of the studied steam power plant.

Parameters	Values	Parameters	Values
Environmental Temperature Ta	20 ℃	Pump efficiency ηp	0.75-0.8
Boiler Temperature Tb	400-800 ℃	Turbine efficiency ηT	0.8-0.85
Inlet Cooling Water Temperature Tcw,i	15-20 ℃	Lower heating value of the fuel LHV	42943.81 kJ/kg
Outlet Cooling Water Temperature Tcw,o	25-30 ℃	Cost of fuel Cf	0.011052$/kWh
References Pressure P0	101.325kPa	Real interest rate i-real	0.05
Condenser Pressure Pc	4-10kPa	inflation rate i-inf	0.07
Boiler Pressure Pb	12500kPa	total operating period of the system n	25 years
Steam mass flow rate $\dot{m}s$	200-300kg/sec	Annual operating hours of the unit N	8400 hours

3-1 Thermodynamic Modeling

Energy is the basic subject and concept of the thermodynamics. It’s one of the most significant aspects of the thermal engineering analysis. Mass, energy and exergy balances for any control volume of steady state steady flow process with negligible kinetic and potential energy changes can be expressed, respectively, by:

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

$$\sum_k \dot{Q}_k + \sum_i^n (\dot{m}_i h_i)_k = \sum_e^n (\dot{m}_e h_e)_k + \dot{W}_k \tag{2}$$

$$\sum_i^k \dot{\Psi}_{heat,k} + \sum_i^n \dot{\Psi}_{i,k} = \sum_e^n \dot{\Psi}_{e,k} + \dot{W}_k + \dot{I}_k \tag{3}$$

Where the subscriptions i, and e represent the inlet and exit states, and k stands for the desired cycle component. $\dot{Q}$ and $\dot{W}$ are the net heat and work inflow, $\dot{m}$ is the mass flow rate, h is the enthalpy, and $\dot{I}$ is the rate of irreversibility. The $\dot{\Psi}_{heat}$ is the net exergy transfer by the heat transfer at a temperature T, which is given by:

$$\dot{\Psi}_{heat,k} = \sum (1 - \frac{T_0}{T}) \dot{Q} \tag{4}$$

The specific flow of exergy is given by:

$$\psi = h - h_0 - T_0 (s - s_0) \tag{5}$$

Where s is the specific entropy, and the subscript 0 stands for the restricted dead state. Multiplying the specific exergy by the mass flow rate of the fluid gives the exergy rate as;

$$\dot{\Psi} = \dot{m}\psi \tag{6}$$

Using the definitions of Fuel-Product-Loss (F-P-L) [13,14], Fuel and Product could be expressed by the exergy flow. Exergy balance for a single component (k) is given as:

$$\dot{\Psi}_F = \dot{\Psi}_P + \dot{\Psi}_D \tag{7}$$

Where $\dot{\Psi}_F$, $\dot{\Psi}_P$ and $\dot{\Psi}_D$ (or $\dot{I}$) are the exergy rate of the desired product, the exergy required (fuel) to produce it, and the exergy destructed during the process, respectively. Thus, the exergetic efficiency can be defined, according to Lozano and Valero [15] and Tsatsaronis and Winhold [16], for each single component (k) as follows;

$$\varepsilon_{e,k} = \frac{product}{fuel} = \frac{\dot{\Psi}_P}{\dot{\Psi}_F} = 1 - \frac{\dot{\Psi}_D}{\dot{\Psi}_F} \tag{8}$$

The definitions of F-P for the current power plant are given in table 2. The exergetic efficiency of the power cycle is given as:

$$\varepsilon_e = \frac{\dot{W}_{net}}{\dot{m}_{fuel} \times \dot{\Psi}_{fuel}} \tag{9}$$

For the evaluation of the fuel exergy, the ratio of simplified exergy is defined as the following [5,17]:

$$\frac{\Psi_{fuel}}{LHV} \approx 1.06 \tag{10}$$

The concept of an exergetic ''improvement potential'' is useful when analyzing different economic processes or sectors. The improvement potential (IP) of a system or process is given by the following expression [18]:

$$IP = (1 - \varepsilon_e)\dot{I} \tag{11}$$

Table 2 F-P exergy definitions

Component	Fuel	Product	Component	Fuel	Product
Boiler	$\dot{\Psi}_{Fuel\ SG}$	$\dot{\Psi}_3 - \dot{\Psi}_2$	Condenser	$\dot{\Psi}4 - \dot{\Psi}1$	$\dot{\Psi}_{cw_e} - \dot{\Psi}_{cw_i}$
Turbine	$\dot{\Psi}_3 - \dot{\Psi}_4$	$\dot{W}\mathrm{T}$	Pump	$\dot{W}_{\mathrm{P}}$	$\dot{\Psi}_2 - \dot{\Psi}_1$

3-2 Thermo-Economic Modeling

In this study the specific exergy costing (SPECO) method [5] is adopted and applied in the present analysis. In this method, the cost rates of the exergy streams entering the kth component plus the cost rates associated with purchasing, maintaining and operating the same component are equal to the cost rates of the exergy streams leaving the component. In mathematical form, the cost balance equation for a given component can be written as:

$$\sum_i^n (c_i \dot{\Psi}_i)_k + \dot{Z}_k + c_{q,k} \dot{\Psi}_{q,k} = \sum_e^n (c_e \dot{\Psi}_e)_k + c_{W,k} \dot{W}_k \tag{12}$$

The annualized equipment cost ($/year) is given by:

$$\dot{C}_k = (PEC)_k \times CRF \tag{13}$$

Where $(PEC)_k$ is the equipment purchasing cost and CRF is the capital recovery factor given by:

$$CRF = \frac{i}{1-(1+i)^{-n}} \tag{14}$$

Here n is the life time of the equipment in years and i is the effective interest rate, given by;

$$i = \left(1 + i_{inf}\right) \times (1 + i_{real}) - 1 \tag{15}$$

Where i_{inf} is the inflation rate and i_{real} Is the real or desired interest rate. The capital cost rate ($/hr) can be written as;

$$\dot{Z}_k = \frac{\emptyset_k \times \dot{C}_k}{N} \tag{16}$$

The factor $\emptyset_k = 1.06$ takes into account the maintenance cost and N Annual operation hours of the plant.

Next, the Specific Exergy Costing (SPECO) technique is applied for each component, the specific exergy cost is defined as:

$$\dot{C}_{F.k} = \dot{\Psi}_{F,k} \times \dot{c}_{F.k} \tag{17}$$

$$\dot{C}_{P.k} = \dot{\Psi}_{P,k} \times \dot{c}_{P.k} \tag{18}$$

Table 3 presents the assumed economic model to estimate the purchase cost of different components [5,19–22]. Here, each component has a mathematical model for calculating the corresponding purchasing cost with definitions of a specified unity cost.

Table (3) Cost equations for the components of the plant.

Component	Purchasing cost ($)	Constants' definitions
SG	$Z_{SG}{=}740\dot{Q}^{0.8} exp(P(MPa){-}2)/14.29){\times}exp((T(℃){-}350)/446)$	$\dot{Q}(kW)$
ST	$Z_{ST}{=}a_1{\times}(\dot{W}ST)^{0.7}$	$a1{=}7000\$/(kW)^{0.7}$
Cond	$ZCond{=}a_2{\times}\dot{m}_{Cond}$	$a2{=}1773\$/kg{-}1.s$
BFP	$ZPump{=}a_3(\dot{W}_{Pump})^{0.7}$	$a3{=}3540\$/(kW)^{0.7}$

The cost rate of the destructed exergy within the component k, can be found as [23];

$$\dot{CD}_k = \dot{\Psi}_{D,k} \times \dot{c}_{f.k} \tag{19}$$

Exergoeconomic factor stands for the ratio of cost contribution with no relation to exergy to the total cost. When f has relatively high values, the monetary costs of the analyzed unit are heavily related to the investment and organizational costs. A lower f values indicate the vice versa. Accordingly, the single exergoeconomic factor is defined by the equation below for the k unit of the system [5,23] as;

$$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + \dot{CD}_k} = \frac{1}{1+(\frac{\dot{CD}_k}{\dot{Z}_k})} ; \qquad 0 \ll f_k \ll 1 \tag{20}$$

For the whole plant, the exergoeconomic factor is:

$$f = \frac{\dot{Z}_{plant}}{\dot{Z}_{plant} + \dot{CD}_{plant}} = \frac{1}{1+(\frac{\dot{CD}_{plant}}{\dot{Z}_{plant}})} ; \qquad 0 \ll f_k \ll 1 \tag{21}$$

High exergoeconomic factor implies low cost of the irreversibilities, while, higher exergoeconomic factor could be obtained by lowering the ratio of $\dot{CD}_{plant}/\dot{Z}_{plant}$. In order to estimate the cost of the exergy destruction for each component of the plant, one should solve the cost balance equations for each component for the application of the cost balance equation 12. Here, the number of unknown cost parameters is higher than the number of the cost balance equations for that component. Auxiliary exergoeconomic equations should be developed to solve this problem as follows;

$$[\dot{\Psi}_{xk}] \times [c_k] = [\dot{Z}_k] \tag{22}$$

Where $[\dot{\Psi}_{xk}], [c_k]\ and\ [\dot{Z}_k]$ are the matrices of the exergy rate, exergetic cost vector, and vector of $\dot{Z}_k$ economic factors, respectively. The system of the linear system equations are as follows;

$$\begin{bmatrix} 0 & \Psi_2 & -\Psi_3 & 0 & 0 & 0 \\ 0 & 0 & \Psi_3 & -\Psi_4 & W_{turbine} & 0 \\ -\Psi_1 & 0 & 0 & \Psi_4 & 0 & -\Psi_{cw,e} \\ \Psi_1 & -\Psi_2 & 0 & 0 & -W_{pump} & 0 \\ 0 & 0 & 1 & -1 & 0 & 0 \\ -1 & 0 & 0 & 1 & 0 & 0 \end{bmatrix} \times \begin{bmatrix} c_1 \\ c_2 \\ c_3 \\ c_4 \\ c_W \\ c_{cw,e} \end{bmatrix} = \begin{bmatrix} -Z_{boiler} - c_{fuel} \times \Psi_{fuel} \\ -Z_{turbine} \\ -Z_{condenser} \\ -Z_{pump} \\ 0 \\ 0 \end{bmatrix} \tag{23}$$

In order to carry out detailed analysis, different exergoeconomic parameters should be calculated for the evaluation of the thermal systems. For the kth component, these variables include; the exergetic efficiency, rate of exergy destruction, cost rates associated with the capital investment, operating and maintenance expenses, the exergy destruction cost rate, the relative cost difference, and the exergoeconomic factor.

4- Results and Discussions

The present results are obtained by employing various techniques. They are divided into three sections; firstly, results concern energy and exergy analysis; secondly, results related to exergoeconomic analysis; and thirdly, parametric effect and sensitivity analysis results. The thermodynamic properties are obtained from the use of the Excel package tools developed in the thermodynamics field. The tools developed by the University of Alabama research team. The platform of these tools is the Microsoft Excel [24-26]. The functions MMULT MINVERSE and WHAT-IF ANALYSIS are used to multiply the matrices and to find the inverse matrix and sensitivity analysis.

4-1 Energy and Exergy Analysis

The first and second law of thermodynamics are applied to the considered steam power plant, more details are presented elsewhere [27]. Referring to the results of the first law analysis, the variation of the total irreversibility and turbine power are given in Figure 3 and 4. This is done with a variable boiler temperature, in a rage of 350-800°C, for three different working fluid mass flow rates, 200, 250, and 300 kg/s. The total irreversibility rate of the plant system clearly depends linearly on the mass flow rate of the working fluid. Here, the maximum total irreversibilities of the system are 510 and 780 MW for the 200 and 300 kg/s, respectively. The total irreversibility increases nearly linearly with the boiler temperature variations for temperatures exceeding 500°C. The rates of the increase of the total irreversibilities with the boiler temperature are almost the same for the three mass flow rates, with a value of 0.333 MW/°C. With the rise in the boiler temperature, the plant output power should be increased as well, as indicated in Figure 4. The linearity of the power change with temperature is more clearly, with a rate of 0.286 MW/°C for the flow rate of 200 kg/s. The effect of the mass flow rate on the produced power is linear, with a gradient of 1.40 MW/kg/s for the boiler temperature of 600°C.

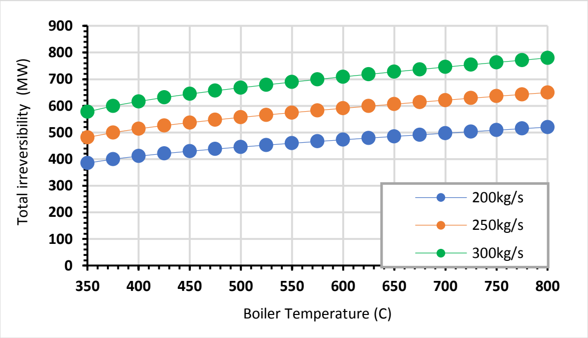


Figure 3 Variation of the total irreversibility with the boiler steam temperature for different steam mass flow rates.

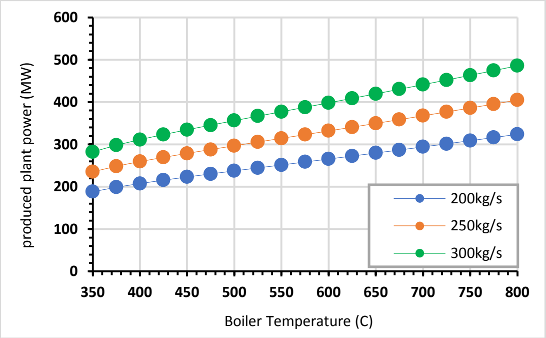


Figure 4 The produced plant power versus the boiler steam temperature for different steam mass flow rates.

The cycle thermal efficiency and quality of the steam at the low exit turbine pressure are increasing as the boiler temperature increases, as indicated in Figure 5 and 6. The efficiency varies mostly linearly with the boiler temperature above 500°C, with an efficiency grade of 0.012%/°C, with a maximum efficiency of 40.5% for a boiler temperature of 800°C. The steam quality seems to be more sensitive to the boiler temperature than the efficiency, with a quality of 0.84 and 0.93 for 500 and 700°C, respectively. Figure 6 shows the effects of the condenser pressure for a mass flow rate and boiler temperature 200 kg/s and 600°C, respectively. Here, the efficiency increases as the condenser pressure increases, however, the quality of the steam decreases with the pressure increase. Both functions are not linear. Referring to the T-s diagram, Figure 2, it is obvious to find as the condenser pressure rises, the saturation temperature rises leading to lower steam quality. The efficiency is 36.1%, while the quality is 0.757, for a condenser pressure of 10 kPa.

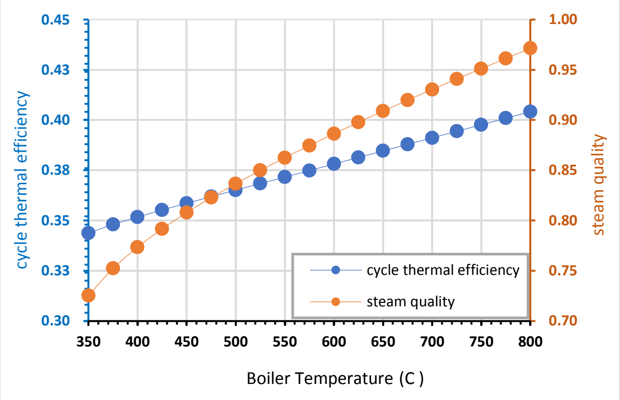


Figure 5 Effects of the boiler steam temperature on the steam quality and cycle thermal efficiency. , for a mass flow rate and condenser pressure of 200kg/s and 4kPa, respectively

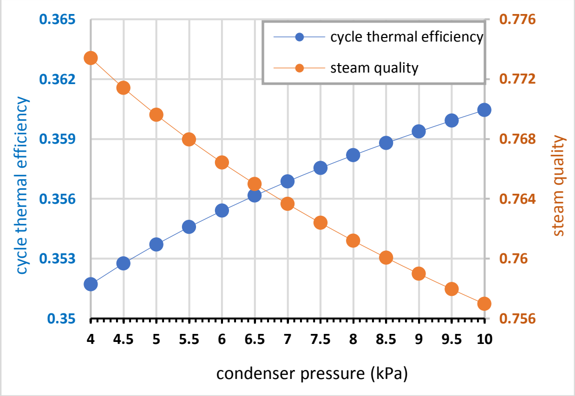


Figure 6 Effects of the condenser pressure on the steam quality and cycle thermal efficiency, for a mass flow rate and boiler temperature 200kg/s and 350°C, respectively

The results of the exergy destruction analysis shown in Figures 7 and 8, where the major source of exergy destruction is due to the boiler no matter what the boiler temperature and reference environment temperature are. However, the value of the exergy destruction does change moderately with the boiler and environment temperatures. Figure 9 and 10 show that the exergetic efficiencies of the turbine and pump do not change significantly with the boiler and environment temperatures, while the exergetic efficiency of the boiler increases significantly as the boiler temperature rises and decreases with the environmental temperature increase.

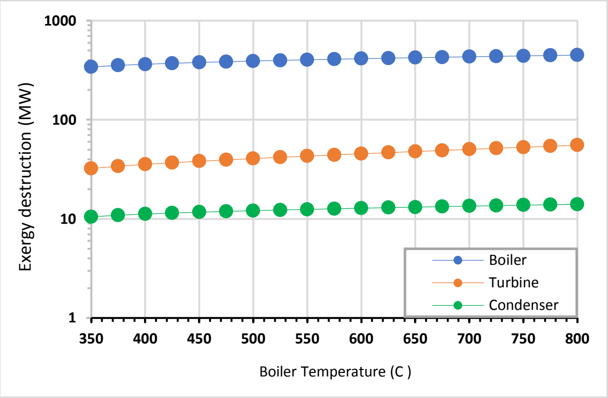


Figure 7 Effect of **the** boiler steam temperature on the exergy destruction.

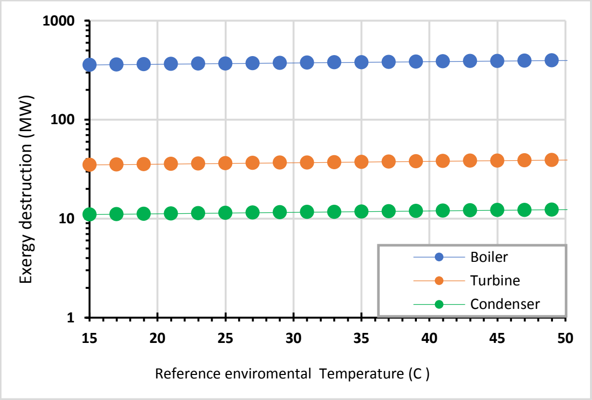


Figure 8 Effect of the reference environmental temperature on the exergy destruction.

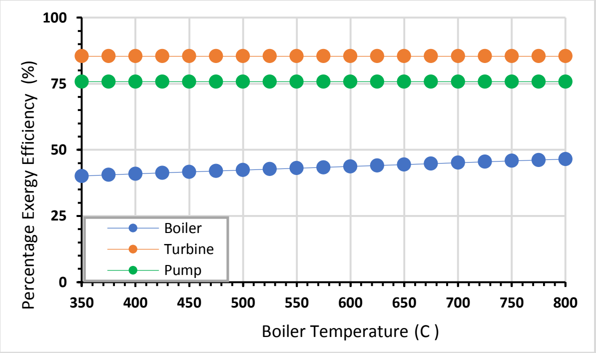


Figure 9 Effect of the boiler steam temperature on the exergetic efficiencies.

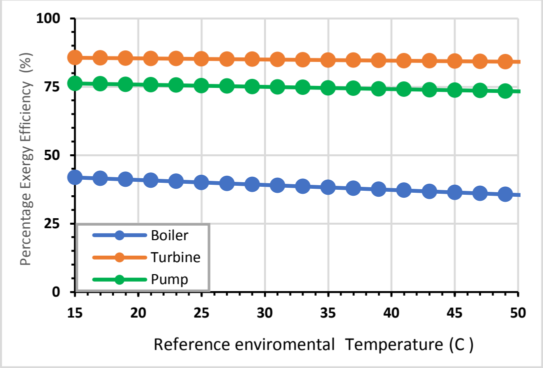
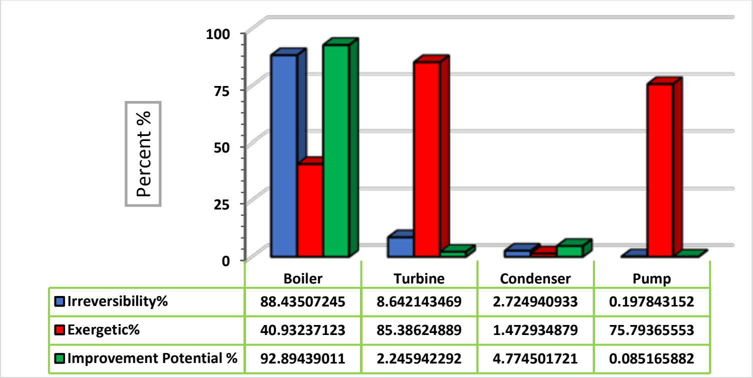


Figure 10 Effect of the reference environmental temperature on the Exergetic efficiencies.

The percentage values implemented in the bar chart of Figure 11, are for the irreversibility, exergetic, and improvement potential for the boiler, turbine, condenser, and pump. The maximum irreversibility and improvement potential are recorded for the boiler, while the maximum exergetic efficiency is for the turbine.



	Boiler	Turbine	Condenser	Pump
🟦 Irreversibility%	88.43507245	8.642143469	2.724940933	0.197843152
🟥 Exergetic%	40.93237123	85.38624889	1.472934879	75.79365553
🟩 Improvement Potential %	92.89439011	2.245942292	4.774501721	0.085165882

Figure 11 The exergetic efficiency, irreversibility, and improvement potential of the component of the plant(T_b=400C,T_a=20,P_c=4kPa,$\dot{m}$=200kg/s)

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4-2 Exergoeconomic Analysis Results

In order to conduct the required exergoeconomic analysis for the plant, the plant is considered to be operated 8400 hours annually, while the real interest rate is 0.05, with an inflation rate of 0.07, and the total expected life of the system is 25 years. Figures 12 and 13 present the effect of the boiler steam temperature and the reference environmental temperature on the exergoeconomic factor of the plant components. Here, as the boiler temperature increases, the exergoeconomic factor also increases with different factor gradient rate for the main components, while the exergoeconomic factor decreases as the reference environmental temperature increases. The influences of the interest rate and lifetime on exergoeconomic factor are shown in Figures 14 and 15. While the Interest rate increases, the exergoeconomic factor does not change significantly for mostly all components, however, as the lifetime increases the exergoeconomic factor also increases for each component.

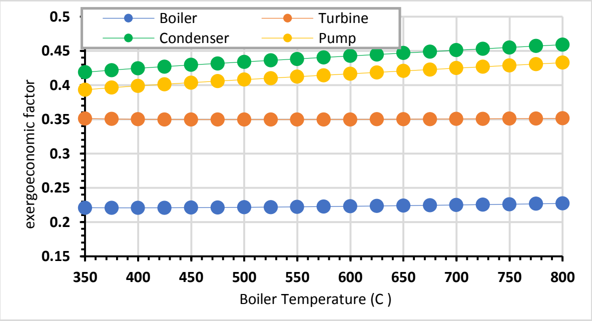

Figure 12 Effect of the boiler steam temperature on the exergoeconomic factor of the plant components.

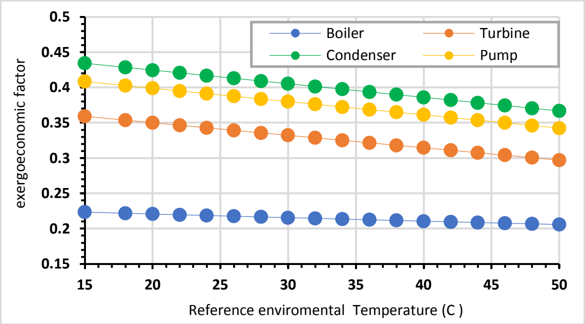

Figure 13 Effect of the reference environmental temperature on the exergoeconomic factor of plant components.

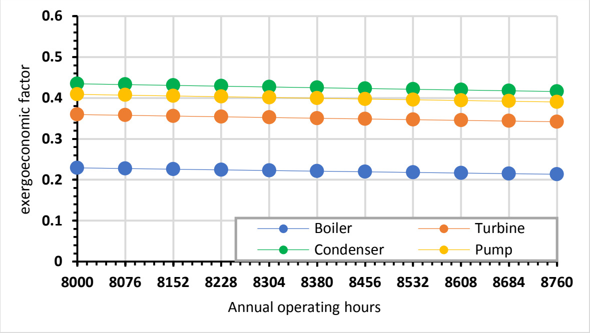

Figure 14 : Effect of the annual operating hours on the exergoeconomic factor of plant components.
(T_b=400C,T_a=20,P_c=4kPa,$\dot{m}$=200kg/s,i=0.12)

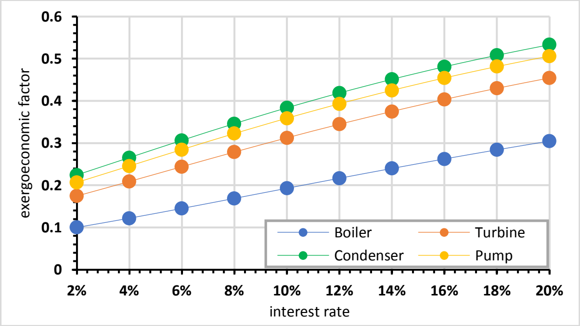

Figure 15 Effect of the interest rate on the exergoeconomic factor of plant components.
(T_b=400C,T_a=20,P_c=4kPa,$\dot{m}$=200kg/s,N=8400hr)

Figure 16 represents the effect of the unit cost of the fuel on the value of the exergoeconomic factor of the plant components, where four unit costs of fuel are considered. Here, as the unit cost of the fuel rises, the exergoeconomic factor drops for all components. The lowest value of the exergoeconomic factor is found in the boiler due to the high rate of the exergy destruction compared to the other components. Figure 17 introduces the effect of the unit cost of the fuel on the total cost of the plant components, where the lowest and highest values of the total cost are found in the pump and boiler with 12,666 and 94 $/hr, respectively. The total cost rises with the escalation in the unit cost of the fuel.

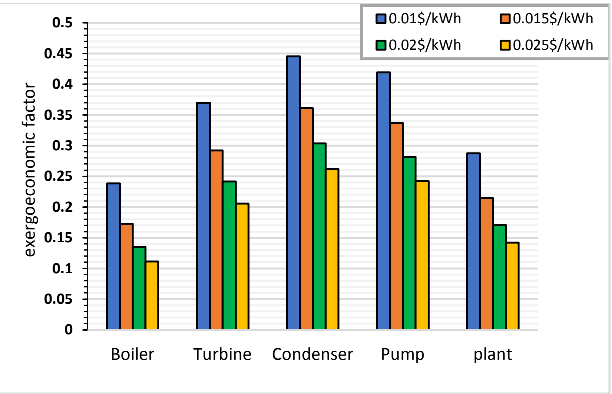

Figure 16 Effect of the unit cost of fuel on the exergoeconomic factor (T_b=400C,T_a=20,P_c=4kPa,$\dot{m}$=200kg/s,i=0.12,N=8400hr)

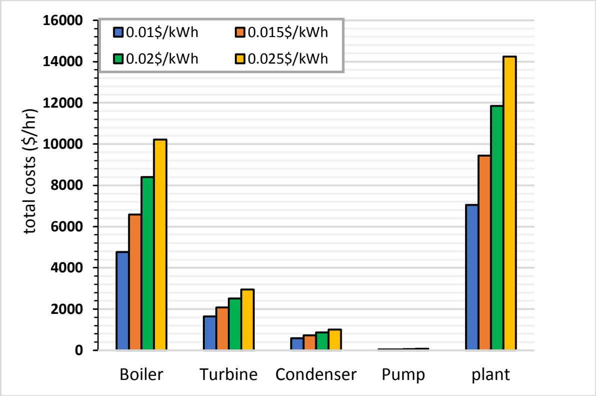

Figure 17 Effect of the unit cost of fuel on the total cost(T_b=400C,T_a=20,P_c=4kPa,$\dot{m}$=200kg/s,i=0.12,N=8400hr)

Figure 18 and 19 represent the effect of the boiler temperature and the reference environmental temperature, on the total annual cost of the components. Here, the costs of the main components, mostly do not affected by both temperatures, with the maximum cost comes from the boiler, followed by the turbine. Figures 20 and 21 indicate the effect of the annual operating number of hours of the power plant and the interest rate, on the total costs of the components. Here, the costs of the main components, mostly do not affected by the annual operating number of hours, while the costs of the components increase, slightly with the interest rate with almost the same gradient for all components.

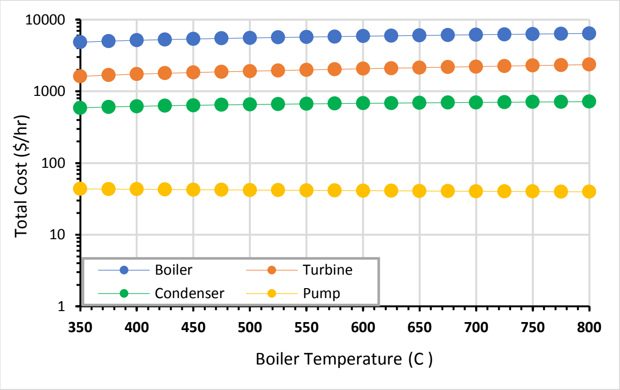

Figure 18 Effect of the boiler steam temperature on total cost of plant components.

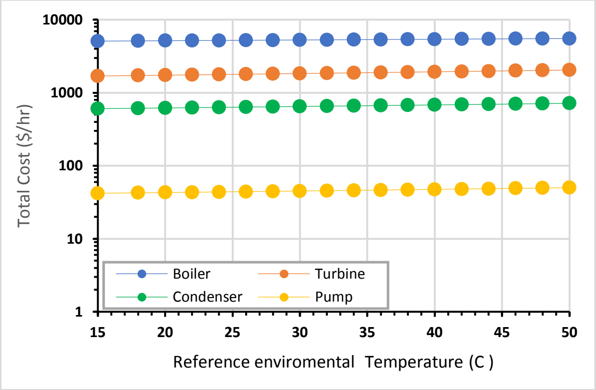

Figure 19 Effect of the reference environmental temperature on the total cost of plant components.

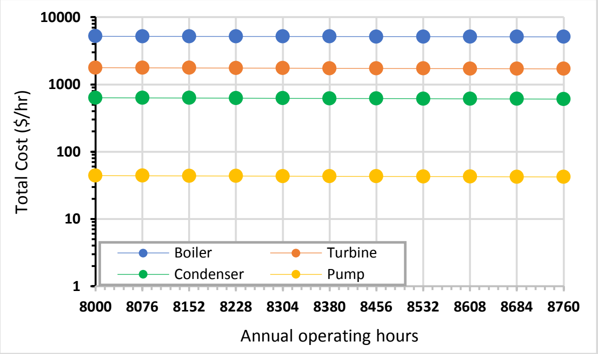

Figure 20 Effect of the annual operating hours on the total cost of plant components(T_b=400C,T_a=20,P_c=4kPa,$\dot{m}$=200kg/s,i=0.12)
.

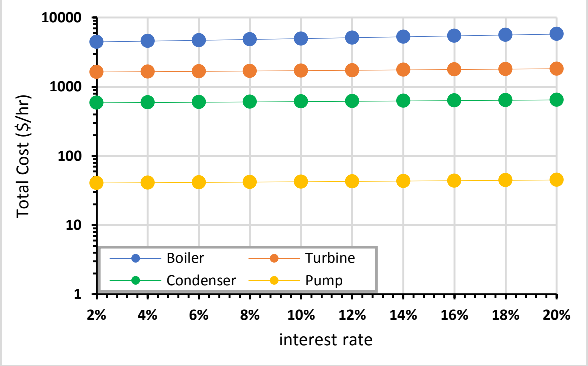

Figure 21 Effect of the interest rate on the total cost of the plant components(T_b=400C,T_a=20,P_c=4kPa,$\dot{m}$=200kg/s,N=8400hr)
.

4-3 Parametric Effect And Sensitivity Analysis Results

In order to evaluate the significance of a couple of operational and economic parameters, a parametric study is done to find out the expected variations in the performance of the plant and the associated cost of the outcome from the considered power plant. The influences of the boiler temperature and reference environmental temperature on the unit cost of work and steam are shown in Figures 22 and 23. With the increase of the boiler temperature, the unit cost of work and steam drop from 0.044 to 0.035 $/kWh, and from 0.023 to 0.030 $/kWh, respectively. However, the unit cost of work and steam rise with the increase of the reference environmental temperature from 0.040 to 0.046, and from 0.031 to 0.037 $/kWh, respectively.

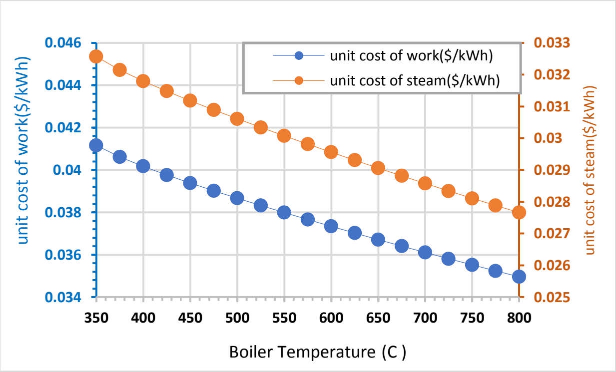

Figure 22 Effect of the boiler steam temperature on the unit cost of work and steam.

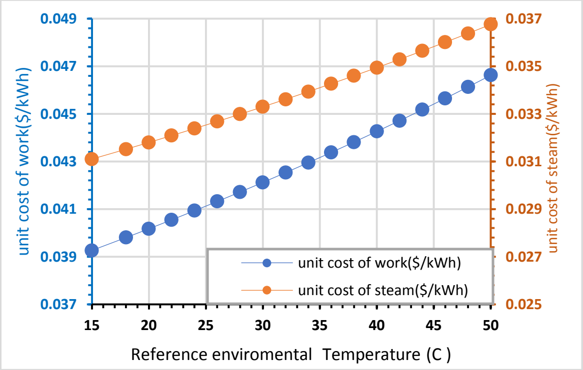

Figure 23 Effect of the reference environmental temperature on the unit cost of work and steam.

Figures 24 and 25 represent the effect of the number of the annual working hours of the plant and the interest rate on the unit cost of the work and steam. The unit cost of the work and cost of the steam drop from 0.041 to 0.040 $/kWh, and from 0.032 to 0.032 $/kWh, respectively, with the increase in the annual number of working hours from 8000 to 8760 hours. However, with the increase in the interest rate, from 2 to 20 %, the unit cost of the work and steam rise from 0.037 to 0.043, and from 0.029 to 0.034 $/kWh, respectively.

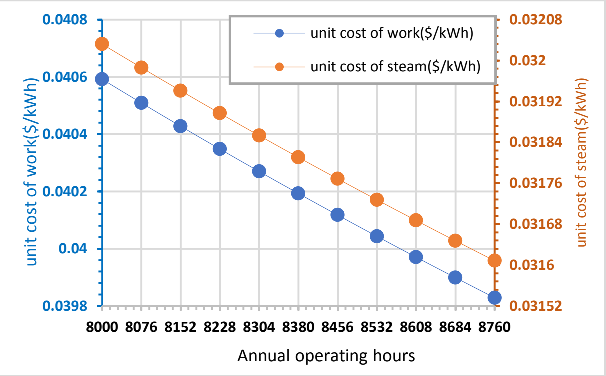

Figure 24Effect of the annual operating hours on the unit cost of work and steam.(T_b=400C,T_a=20,P_c=4kPa,$\dot{m}$=200kg/s,i=0.12)

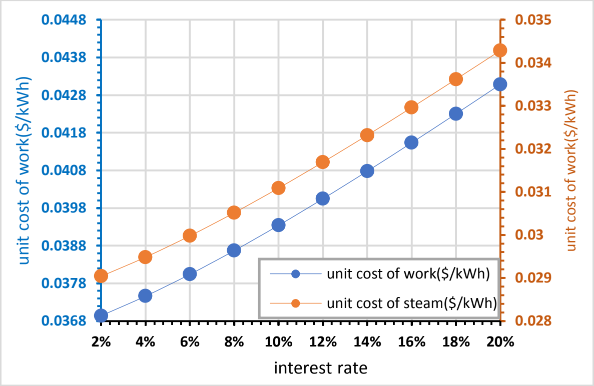

Figure 25 Effect of the interest rate on the unit cost of work and steam.(T_b=400C,T_a=20,P_c=4kPa,$\dot{m}$=200kg/s,N=8400hr)

The effect of the boiler temperature and reference environmental temperature on the exergoeconomic factor and total plant cost are presented Figures 26 and 27. The exergoeconomic factor and the total cost increase from 0.268 to 0.276, and 7000 to 9500 $/hr, with the increase in the boiler temperature, from 350 to 800°C, respectively. While, with the increase in the reference environmental temperature, from 15 to 50°C, the exergoeconomic factor decreases from 0.273 to 0.242 and the total cost increases from 7330 to 8350 $/hr.

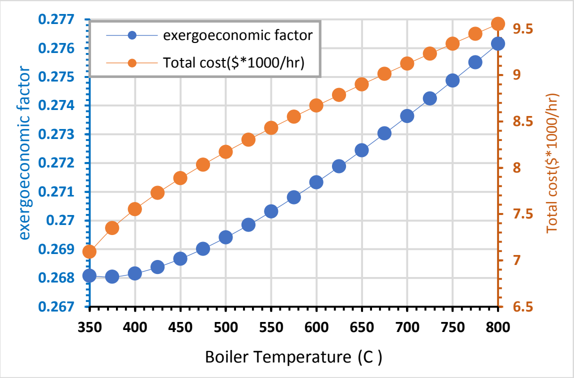

Figure 26 Effect of the boiler steam temperature on the exergoeconomic factor and total cost.

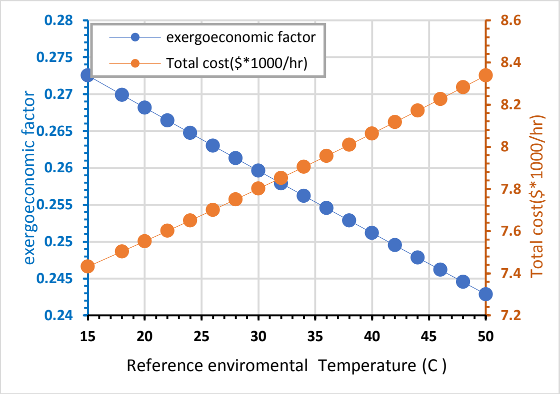

Figure 27 Effect of the reference environmental temperature on the unit cost of work and steam

Referring to Figures 28 and 29, the effect of the annual working number of hours of the plant and interest rate, on the exergoeconomic factor and total plant cost are determined. The Exergoeconomic factor decreases from 0.278 to 0.26 and the total cost rises from 7460 to 7680 $/hr, with the increase in the annual number of working hours from 8000 to 8760 hours. While with the increase in the interest rate, from 2 to 20%, the exergoeconomic factor and total cost increase from 0.2 to 0.32 and from 6700 to 8250 $/hr, respectively.

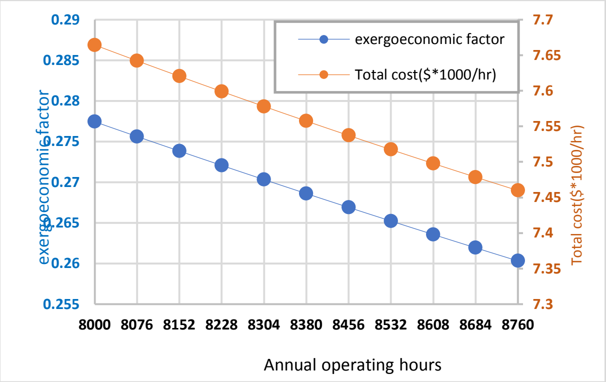

Figure 28 Effect of the annual operation hour of the unit on the exergoeconomic factor and total cost. (T_b=400C,T_a=20,P_c=4kPa,$\dot{m}$=200kg/s,i=0.12)

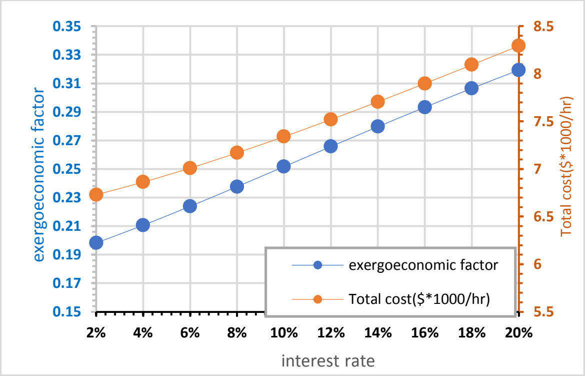

Figure 29 Effect of the interest rate on the unit cost of work and steam.(T_b=400C,T_a=20,P_c=4kPa,$\dot{m}$=200kg/s,N=8400hr)

5. Conclusions and Recommendations

It's with no doubt, it becomes necessary to improve the design and operation of the energy systems through the application of any new available methods. In this study, the exergy and exergoeconomic analyses have been applied to a case study steam power plant. The researchers succeeded in obtaining the thermodynamic properties by employing the THERMAX and MATLAB software packages. Mathematical models were developed and presented regarding mass, energy, exergy, and economy of the working power plant. The thermal and exergoeconomic analyses are used, leading to have valuable economic status benchmarks.

This paper succeeded to implement the Specific Exergy Costing approach to achieve the exergoeconomic factor, total cost of exergy loss, and average cost per unit exergy for the final products of the plant. The sensitivity analysis was considered, where the parametric investigation effects were carried out, including the annual working number of hours, interest rate, boiler temperature, and environmental temperature. For the considered case study status, the boiler in the plant reveled to have the highest amount of exergy destruction of 88.4%, leading to more attention should be paid towards boilers in terms of design, selection, operation, and maintenance, while in percentage terms, the improvement potential for the boiler is high with 92.8%.

The exergoeconomic factor, the total cost, the unit cost of work and steam increase with the escalation in the interest rate, while they drop with the increase in the annual working number of hours. The unit cost of work varies from 0.037 to 0.043 $/kWh with the rise in the interest rate from 2 to 20%, while it drops slightly from 0.041 to 0.040 $/kWh, with the increase in the annual number of working hours, from 8000 to 8760 hours.

With the increase in the boiler temperature, from 350 to 800°C, the exergoeconomic factor and total cost increase from 0.268 to 0.276, and 7000 to 9500 $/hr, respectively. The unit cost of work and steam increase from 0.0392 to 0.046, and from 0.031 to 0.0368 $/kWh, with the increase in the reference environmental temperature, from 15 to 35°C, respectively, while the exergoeconomic factor decreases from 0.273 to 0.242. The achieved present values and parametric influences could be of great help to the site engineers and operators to effectively establish their unique jobs while keeping an eye on the energy, exergy, and cost.

References

[1] İleri, A., Termoekonomi II: Optimizasyon ve Fiyatlandırma. Termodinamiğin İkinci Kanunu Çalışma Toplantısı, Erciyes Üniversitesi, TIBTD, Bölüm IX-28, Kayseri, 1990 (In Turkish).

[2] Sahoo P. Exergoeconomic analysis and optimization of a cogeneration system using evolutionary programming. Appl Therm Eng 2008;28(13):1580–8.

[3] Cengel A.Y., Boles A.M., Thermodynamics: An Engineering Approach. McGraw-Hill: New York, 1994.

[4] Silveira JL, Balestieri JAP, Almeida RA, Santos AHM. Thermoeconomic analysis: a criterion for the selection of cogeneration systems. 1996 International Mechanical Engineering Congress and Exposition—ASME Symposium on Thermodynamics and Design, Analysis and Improvement of Energy Systems, Atlanta, USA, vol. 36. 1996. p. 240–53.

[5] Bejan A, Tsatsaronis G, Moran M, Theraml Design and Optimization, A Wiley-Interscience publication, Singapore, 1996.

[6] Ahmadi P, Dincer I, Rosen MA. Exergy, exergoeconomic and environmental analyses and evolutionary algorithm based multi-objective optimization of combined cycle power plants. Energy 2011;36:5886–98.

[7] Khoshgoftar Manesh MH, Navid P, Baghestani M, Khamis Abadi S, Rosen MA, Blanco AM, et al. Exergoeconomic and exergoenvironmental evaluation of the coupling of a gas fired steam power plant with a total site utility system. Energy Convers Manage 2014;77:469–83.

[8] Rashad A, and Maihy A, Energy and Exergy Analysis of a Steam Power Plant in Egypt, 13th International Conference on Aerospace Sciences & Aviation Technology,2009.

[9] Adibhatla S, Kaushik S C, Energy And Exergy Analysis Of A Super Critical Thermal Power Plant At Various Load Conditions Under Constant And Pure Sliding Pressure Operation, Applied Thermal Engineering, Vol 73, pp51- 65,2014.

[10] Bolatturk A, Coskun A, Geredelioglu C, Thermodynamic And Exergoeconomic Analysis Of Çayırhan Thermal Power Plant, Energy Conversion and Management, vol 101, pp 371– 378,2015.

[11] Ehyaei MA, Mozafari A, Alibiglou MH. Exergy, Economic & Environmental (3E) analysis of inlet fogging for gas turbine power plant. Energy 2011;36:6851–61.

[12] Selbas R, Yazıcı H, Şencan A, Thermoeconomic Optimization Of The Steam Power Plant, International Journal Of Energy And Environment, Vol 1, pp 479-486,2010.2.2.

[13] Tsatsaronis G, Lin L. On exergy costing in exergoeconomics. In: Tsatsaronis G, Bajura RA, Kenney WF, Reistad GM, editors. Computer-aided energy systems analysis, vol. 21. New York: ASME; 1990. p. 1–11.

[14] Lazzaretto A, Andreatta R. Algebraic formulation of a process-based exergy-costing method. In: Krane RJ, editor. Symposium on thermodynamics and the design, analysis, and improvement of energy systems, vol. 35. New York: ASME; 1995. p. 395–403.

[15] M.A. Lozano, A. Valero, Theory of the exergetic cost, Energy 18 (9) (1993) 939– 960.

[16] G. Tsatsaronis, M. Winhold, Exergoeconomic analysis and evaluation of energy conversion plants-I: a new general methodology, Energy 10 (1) (1985) 69–80.

[17] J. Szargut, D.R. Morris, F.R. Steward, Exergy Analysis of Thermal, Chemical and Metallurgical Process, Hemisphere Publishing Co., New York, USA, 1988. 330p

[18] Fudholi A, Sopian K, Othman MY, Ruslan MH, Bakhtyar B. Energy analysis and improvement potential of finned double-pass solar collector. Energy Convers Manage 2013;75:234–40.

[19] Uche J, Serra L, Valero A. Thermoeconomic optimization of a dual-purpose power and desalination plant. Desalination 2001;136(1):147–58.

[20] Silveira JL, Tuna C. Thermoeconomic analysis method for optimization of combined heat and power systems. Part I. Prog Energy Combust Sci 2003; 29(6):479–85.

[21] Baghernejad A, Yaghoubi M. Multi-objective exergoeconomic optimization of an integrated solar combined cycle system using evolutionary algorithms. Int J Energy Res 2011;35(7):601–15.

[22] Xiong J, Zhao H, Zhang C, Zheng C, Luh PB. Thermoeconomic operation optimization of a coal-fired power plant. Energy 2012;42(1):486–96.

[23] A. M. Elsafi, "Exergy and exergoeconomic analysis of sustainable direct steam generation solar power plants," *Energy Convers. Manag.*, vol. 103, pp. 338–347, 2015.

[24] The University of Alabama, Mechanical Engineering, Excel for Mechanical Engineering project, Internet: http://www.me.ua.edu/excelinme/index.htm (Last accessed July 11, 2019).

[25] J. Huguet, K. Woodbury, R. Taylor, Development of Excel add-in modules for use in thermodynamics curriculum: steam and ideal gas properties, American Society for Engineering Education, 2008, AC 2008-1751.

[26] K. Mahan, J. Huguet, K. Woodbury, R. Taylor, Excel in ME: Extending and refining ubiquitous software tools, American Society for Engineering Education, 2009, AC 2009-2295.

[27] Elham M. Radwan and Mawadda A. Bahoor, Exergetic and Exergy Cost Sensitivity Analysis Of Steam Power Plants, B. Sc. Project, Mechanical Engineering Department, Faculty of Engineering, University of Tripoli, September, 2020.