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Research Paper

Part Load 2nd Law Analyses of, 3-Pressure Stage Turbines with 6 heaters, 350 MW Power Plants

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ABSTRACT
In this paper, the energy and exergy analyses of cogeneration thermal power plants are carried out at different operating loads. The considered power plant has a total power capacity of 350 MW, with a conventional steam Rankine cycle with high, intermediate and low pressure turbines, four low pressure heaters and two high pressure heaters. Detailed mathematical models are presented. Thermodynamic working fluid properties are obtained from THERMAX and MATLAB software packages. The studied boiler temperature, condenser pressure, and load percentage ranges are 400-800ºC, 4-10 kPa, and 60-100 %, respectively. The exergetic efficiency, exergy destruction, improvement potential, and exergy are determined. The total irreversibility decreases with the rise in the boiler temperature while it increases as condenser pressure drops. As the load increases by 1 %, the total irreversibility rise by 4.5 MW, with a maximum value of 440 MW.The rise in the condenser pressure makes the pump work to increase to 8.0 MW, while the cycle thermal efficiency slightly decreases to 46 %. The maximum improvement potential takes place in the steam generator, reheater, and condenser, with 163.0, 26.0, and 8.0 MW, respectively.The lowest exergetic efficiency is 9.2 % for the condenser, while the highest is for the deaerator with 97 %.This kind of study confirms which component has the priority for any service to be done in order to upgrade the considered power plant cycles.
Keywords: *Energy, Exergy, Efficiency, Exergy destruction, and energetic efficiency.*

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I. INTRODUCTION

No doubt, energy becomes essential for the economic and socialdevelopment, and for the rise of the quality of life. Much of the energy resources are currently produced andconsumed in ways that may couldn't be sustained. Such global energy resources are depleting, while thedemand for energy sharply rising. This could be due to the technology developments and upgrading of the living standards of people. This situation isbecoming increasingly critical. One approach to overcome such problem is to develop and improvethe renewable energy sources, while trying to improve the use of the conventional energy-related systems, leading to efficiently utilize the energy obtained from any source [1,2].

Reduction in the use of the fossil fuels resources and global warming process are two major concerns of the future energy systems. Once the available renewable energy resources are still limited at different parts of the world, mucheffort for high efficient use of energy systems is growing, where energy-related researchers have prompted to seek ways to design systems with low energy consumption, high performance and low environmental impact [3].Due to the continuously growing demand for the natural resources by the current energy conversion technologies and the serious concern for the quality of the environment, have achieved a new methodology that helps to understand and determine new performance items, leading to know how to upgrade the design and operation of the energy systems and prevent the residues from damaging the environment.

II. LITERATURE REVIEW

Thermoeconomics is nowadays a powerful tool to study and optimize the energy systems. This concerns the evaluation of the utility energy, exergy, and/or costs. These could be 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].Rashad et al. [5] has performed energy and exergy analyses for a steam power plant in Egypt. The primary aim of their research was 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. [6] explained 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. They conclude that the sliding pressure operation of the unit at part loads provides several benefits, and stated that the sliding pressure operation is suitable for once through units and thus it's a better way for operating at part load conditions.

Ehyaei et al. [7] 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 optimizationuses 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. [8] have 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.

Bresolin et al. [9] aimed to simulate the partial load characteristic with different control system, slidingpressure, throttling valve and nozzle valve control systems, of a steam turbine. The inlet pressurewhich was calculated with respect to Scheglíáiev and Stodola models, where the pressure is a function of the flow rate.Moreover, the best control system type dependson the turbine load, while the sliding pressure control is better adapted to higher loads.Bhattacharya [10]investigated the causes of the partial load conditions and the effects of steamextractingfrom the interstageof turbines, where the actual operating conditions have occurred in all typesof the turbines.

Malik et al. [11] carried out exergy and exergoeconomic analyses of simple typical thermal power plants. Their methodology was based on the Specific Exergy Costing approach and sensitivity cost analysis. 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. The exergoeconomic factors for the boiler, turbine, condenser and pump are 0.23, 0.35, 0.42, and 0.39, respectively. For the proposed conditions, the total cost of the plant is 14,000 $/hr, including 10,000 $/hr for the cost of the steam production at 650°C with a unit steam cost of 0.029 $/kWh. In this paper, a new case study for a larger cogeneration power plant cycle is introduced and analyzed in order to determine the main advanced parameters related to the energy utilization.

III. CASE STUDY

The case study represents a power plant with a desired total power capacity of 350MW. The power cycle under consideration is fundamentally a conventional steam Rankine cycle with high pressure steam generator, high,intermediate and low pressure turbines (HPT, IPT and LPT),having differentextraction points, boiler feed water pumps (BFP),a condensate extraction pump (CEP), four low pressure heaters (LPH) and two high pressureheaters (HPH), a deaerator (DEA), and a condenser (COND). Figure 1 shows the schematicdrawing of the studied power plant cycle. The state points were labeled to be referred to in the mathematical models.The nominal values of thedesign parameters are given in Table1.

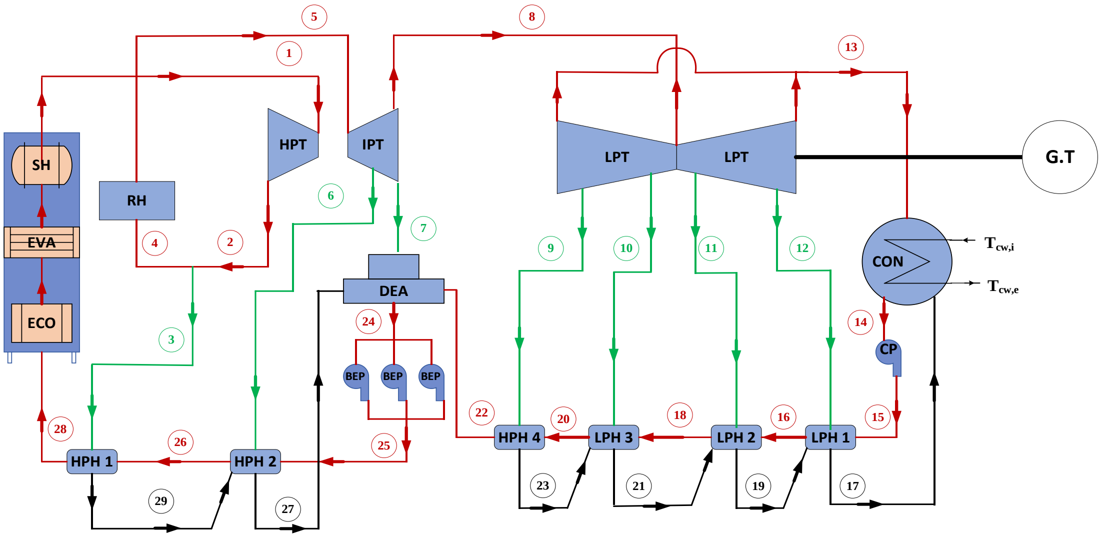


Figure 1 A Schematic of the considered power Plant.

Table 1Design parameters of the considered 350MW steam power plant.

Description of state	Value	Description of state	Value
HPT1 inlet temperature(°C)	538	Bleeding Pressure 10(bar)	3.28
HPT1 inlet Pressure(bar)	174.9	Bleeding Pressure 11(bar)	1.776
Reheat temperature(°C)	538	Bleeding Pressure 12(bar)	0.763
Reheat Pressure(bar)	44.8	Pump Efficiency %	75
Bleeding Pressure 2(bar)	44.8	Turbine Efficiency %	85
Bleeding Pressure 6(bar)	21.3	TTD(°C) for HPT	0
Bleeding Pressure 7(bar)	10.1	TTD(°C) for LPT	2.8
Bleeding Pressure 9(bar)	5.9	DAC(°C)	5.4

IV. MATHEMATICAL MODELING

Here, the mathematical model is based on the balances of the main three dimensions; mass, energy, and exergy of each component in the cycle. For steady state steady flow process with negligible kinetic and potential energy changes,mass, energy and exergy balances for any control volume can be expressed, respectively, by [11]:

$$\sum \dot{m}_i = \sum \dot{m}_o \ (1)$$

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

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

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

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

The specific flow of exergy is given by:

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

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 [11];

$$\dot{\Psi} = \dot{m}\psi (6)$$

Using the definitions of Fuel-Product-Loss (F-P-L) [12,13], fuel and product could be expressed by the exergy flow. Exergy balance for a single component (k) is given as:

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

Where $\dot{\Psi}_F$, $\dot{\Psi}_P$are the exergy required (fuel) to produce it, and the exergy destructed during the process, respectively,$and \dot{\Psi}_D$ (or $\dot{I}$) is the exergy rate of the desired product.Thus, the exergetic efficiency can be defined, according to Lozano and Valero [14] and Tsatsaronis and Winhold [15], for each single component (k) as follows;

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

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:

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

For the evaluation of the fuel exergy, the ratio of simplified exergy is defined as the follows [16,17]:

$$\frac{\Psi_{fuel}}{LHV} \approx 1.06 \quad (10)$$

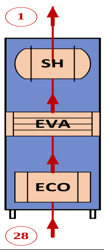
The concept of an exergetic ''improvement potential'' is useful when analyzing different economic processes or sectors. The improvement potential (IP) of a system or process is given by the following expression [18]:

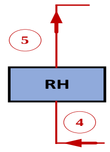
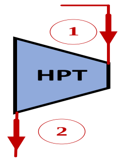
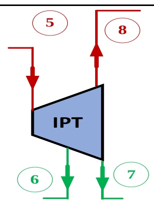
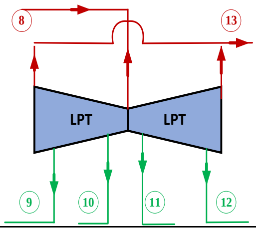
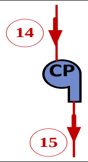
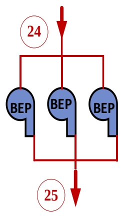
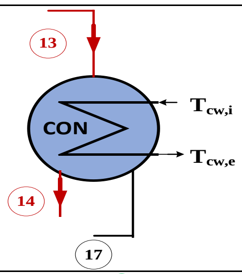
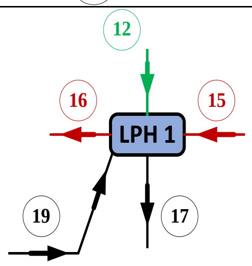
$$IP = (1 - \varepsilon_e)\dot{I} \quad (11)$$

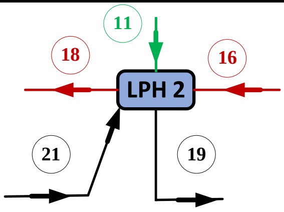
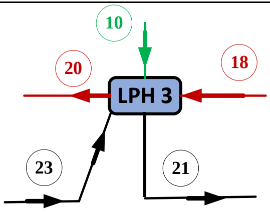
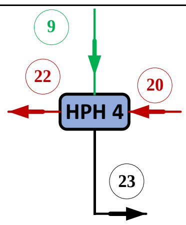
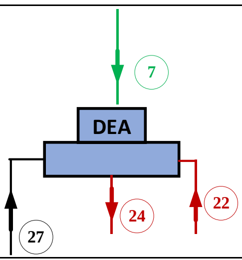
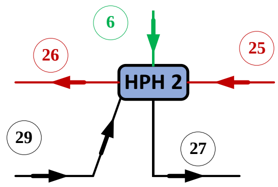
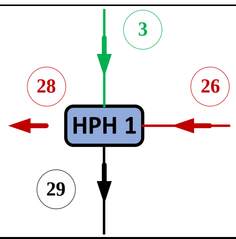
Table 2The calculations of the energy balance for each component.

Component	Energy balance,1st law of thermodynamics
SG	$\dot{m}_t(h_1 - h_{28})$
RH	$\dot{m}_t[(1-y_1)(h_5 - h_4)]$
HPT	$\dot{m}_t(h_1 - h_2)$
IPT	$\dot{m}_t[(1-y_1)h_5 - y_2h_6 - y_3h_7 - (1-y_1-y_2-y_3)h_8]$
LPT	$\dot{m}_t[(1-y_1-y_2-y_3)h_8 - y_4h_9 - y_5h_{10} - y_6h_{11} - y_7h_{12} - (1-y_1-y_2-y_3-y_4-y_5-y_6-y_7)h_{13}]$
CEP	$\dot{m}_t[(1-y_1-y_2-y_3)(h_{15} - h_{14})]$
BFP	$\dot{m}_t(h_{25} - h_{24})$
COND	$\dot{m}_t[(1-y_1-y_2-y_3-y_4-y_5-y_6-y_7)h_{13} + (y_4+y_5+y_6+y_7)h_{17} - (1-y_1-y_2-y_3)h_{14}]$
LPFWH(1)	$y_7 = \frac{(y_4+y_5+y_6)h_{17} + (1-y_1-y_2-y_3)h_{16} - (1-y_1-y_2-y_3)h_{15} - (y_4+y_5+y_6)h_{19}}{(h_{12} - h_{17})}$
LPFWH(2)	$y_6 = \frac{(y_4+y_5)h_{19} + (1-y_1-y_2-y_3)h_{18} - (1-y_1-y_2-y_3)h_{16} - (y_4+y_5)h_{21}}{(h_{11} - h_{19})}$
LPFWH(3)	$y_5 = \frac{(1-y_1-y_2-y_3)h_{20} + y_4h_{21} - (1-y_1-y_2-y_3)h_{18} - y_4h_{23}}{(h_{10} - h_{21})}$
LPFWH(4)	$y_4 = \frac{(1-y_1-y_2-y_3)h_{22} - (1-y_1-y_2-y_3)h_{20}}{(h_9 - h_{23})}$
DEA	$y_3 = \frac{h_{24} - (y_1+y_2)h_{27} + (y_1+y_2)h_{22} - h_{22}}{(h_7 - h_{22})}$
HPFWH(2)	$y_2 = \frac{y_1h_{27} + h_{26} - y_1h_{29} - h\_25}{(h_6 - h_{27})}$
HPFWH(1)	$y_1 = \frac{(h_{28} - h_{26})}{(h_3 - h_{29})}$

Table 3 F-P Exergy definition for each cycle component.

Components	Schematic	$\psi_{\mathbf{fuel}}$	$\psi_{product}$
SG		$\psi_{fuel,SG}$	$\psi_1 - \psi_{28}$

RH		$\psi_{fuel,RH}$	$\psi_5 - \psi_4$
HPT		$\psi_1 - \psi_2$	$\dot{W}_{HPT}$
IPT		$\psi_5 - \psi_6 - \psi_7 - \psi_8$	W_{IPT}
LPT		$\psi_8 - \psi_9 - \psi_{10} - \psi_{11} - \psi_{12} - \psi_{13}$	W_{LPT}
CEP		$\dot{W}_{CEP}$	$\psi_{15} - \psi_{14}$
BFP		$\dot{W}_{BEP}$	$\psi_{25} - \psi_{24}$
COND		$\psi_{13} - \psi_{14} + \psi_{17}$	$\psi_{cwe} - \psi_{cwi}$
LPFWH(1)		$\psi_{12} - \psi_{17} + \psi_{19}$	$\psi_{16} - \psi_{15}$

LPFWH(2)		$\psi_{11} - \psi_{19} + \psi_{21}$	$\psi_{18} - \psi_{16}$
LPFWH(3)		$\psi_{10} - \psi_{21} + \psi_{23}$	$\psi_{20} - \psi_{18}$
LPFWH(4)		$\psi_{9} - \psi_{23}$	$\psi_{22} - \psi_{20}$
DEA		$\psi_{7} + \psi_{22} + \psi_{27}$	ψ_{24}
HPFWH(2)		$\psi_{6} - \psi_{27} + \psi_{29}$	$\psi_{26} - \psi_{25}$
HPFWH(1)		$\psi_{3} - \psi_{29}$	$\psi_{28} - \psi_{26}$

V. RESULTS AND DISCUSSIONS

The energy and exergy analyses of the considered thermal power plant were carried out at dead state temperature and pressure of 24°C and 1bar, respectively. The thermodynamic properties are obtained from the use of the Excel package tools developed in the thermodynamics field as introduced elsewhere [11]. The platform of these tools is the Microsoft Excel [19-21].The first and second law of thermodynamics are applied to the studied steam power plant, more details are presented elsewhere [11, 22]. Referring to the results of the first law analysis, effects of the variation of the boiler steam temperature and condenser pressure on the total irreversibility and produced plant power are given in Figures2 and 3. This is done with a variable boiler temperature, and condenser pressure in the ranges of 400-800°C, and 4-10kPa, respectively. With the rise in the boiler temperature the total irreversibility and produced plant power are decreasing from 697.0 to 292.0 MW,and from 363.0 to 355.0MW respectively. In the other hand, with the rise in the condenser pressure, the total irreversibility and produced plant power are increasing from 438.0 to 452.0 MW, and from 358.0 to 358.0 MW, respectively.

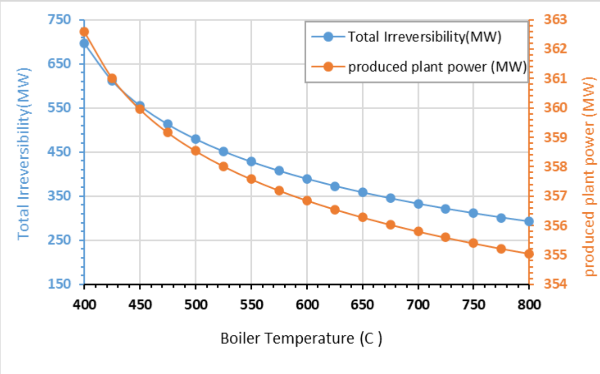


Figure 2Effects of the boiler steam temperature on the total irreversibility and produced plant power.

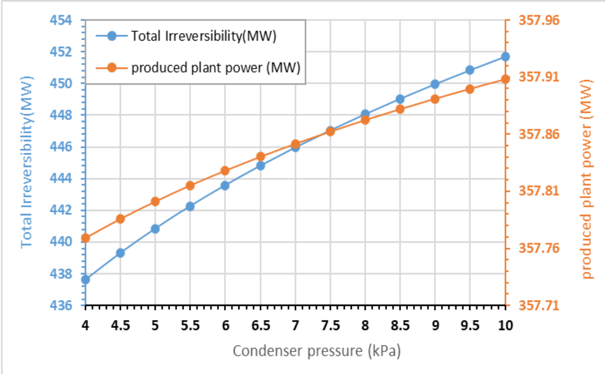


Figure 3Effects of the condenser pressure on the total irreversibility and produced plant power.

Effects of the boiler steam temperature and condenser pressure on thepump work and cycle thermal efficiencyare given in Figures4 and 5.With the rise in the boiler temperaturethepump work decreases from 12.6to5.0 MW,while the cycle thermal efficiency increases from 35to 57%.The rise in the condenser pressuremakes thepump work to increase from 7.8to8.0MW,while the cycle thermal efficiencyslightly decreases from 47 to46 %. Referring to Malik et al. [11],theirthermal efficiency of the simple cycle is lower, where it varies from40.2to 36.1%for the condenser pressure of 10 kPa.

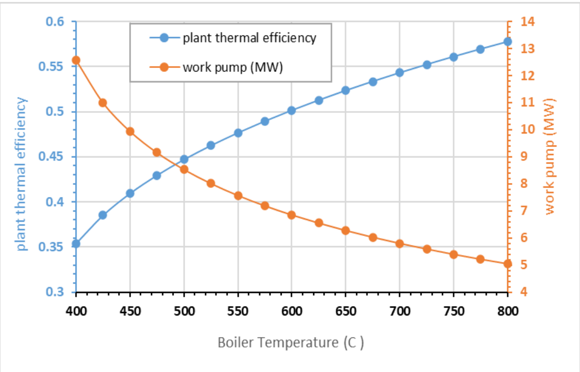


Figure 4Effects of the boiler steam temperature on the pump work and cycle thermal efficiency.

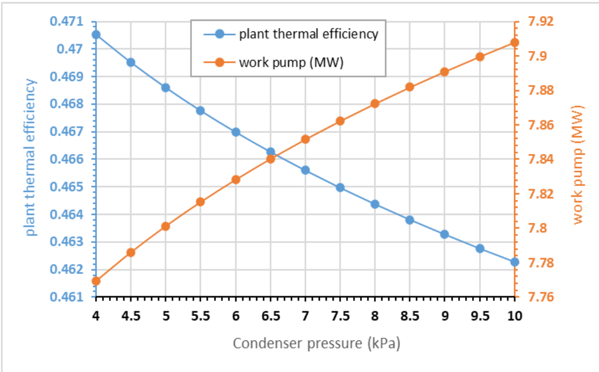


Figure 5Effects of the condenser pressure on the pumpwork and cycle thermal efficiency.

Referring to Figure 6, the outcome of the energy and exergy analyses is represented by the irreversibility amount of each component in the power plant.The maximum amounts of the irreversibility take place in the steam generator,reheater, and low pressure turbine, with values of 329.0, 57.60, and 18.70MW,respectively. The intermediate and high pressure turbines, and low pressure heater 1, have almost same irreversibility values of 6.4 MW. Figure 7represents the maximum amount of the improvement potentialwhich takes place in the steam generator, reheater, and then the condenser, with 163.0, 26.0, and 8.0 MW,respectively. Hence, these components have the priority for any service to be done in order to improve, update or over whole the considered plant power cycle. Malik et al. [11],found out higher relative values, with the maximum amounts of the irreversibility take place in the boiler, turbine, and condenser, with values of 363.0, 55.50, and 11.20 MW,respectively, while the present maximum amounts of the irreversibility take place in the boiler, condenser, and turbine with values of 214.6,11.70, and 5.80 MW,respectively.

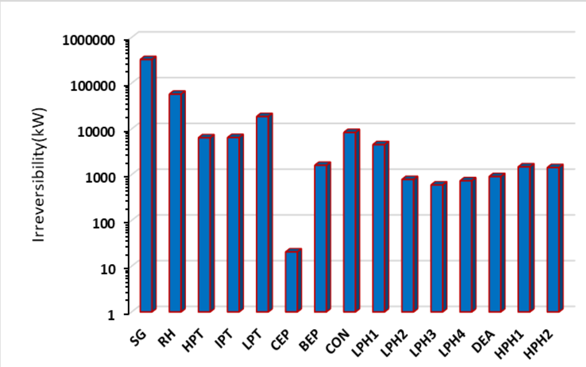


Figure 6The irreversibility of each component in the power plant cycle.

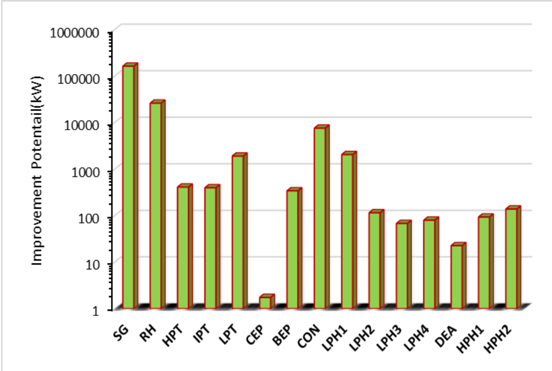


Figure 7The improvement potential of each component in thepower plant cycle.

The exergetic efficiencies of different components of the power plant cycleare introduced in Figure8.The lowest exergeticefficiency is9.2% for the condenser, while the highest is for the deaerator with 97 %. The steam generator has an efficiency of 50.3%. In simple words, this means a 49.7% of the exergy supplied to the steam generator is lost within it.Accordingly, Figure 8 could be considered as an indication of the lost exergy from each component.

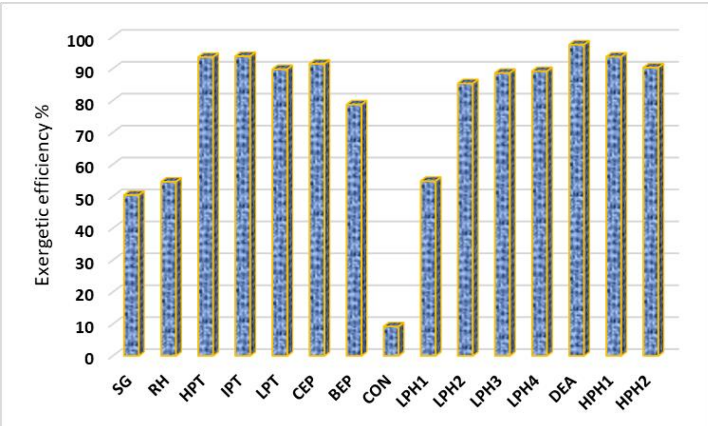


Figure 8 The exergetic efficiency of each component in thepower plant cycle.

As well known, the plant power generated from the plant depends mainly on the enthalpy differential drop and steam mass flow rate through the turbine. The total irreversibility and turbine plant powervary linearly with the partial load as shown in Figure 9. The analysis covers a range of 60 to 100% of the desired peak load. Here, the specific work increases, while the total generated power decreasesdue to the variation of the steam mass flow rate at fixed high pressure turbine. Here, as the load increases by 1 %, the total irreversibility rises by 4.5 MW, with a maximum value of 440 at full load.

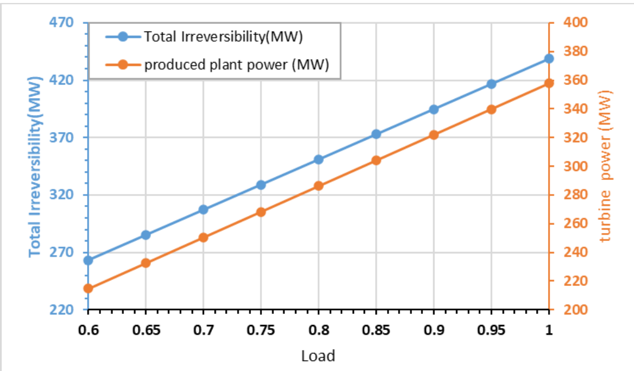


Figure 9 The total irreversibility and turbine output power at partial loads.

VI. CONCLUSIONS AND RECOMMENDATIONS

It is an indisputable fact that much saving could be achieved by making fluid and heat flow related improvements, leading to minimize much of the irreversibility processes. These practices provide useful benefits in order to have an efficiency energy achievement.The calculationof the exergetic efficiency, exergy destruction, improvement potential and exergy in thermal systemsis the performance study key for any thermal power cycle.

The maximum exergy loss and potential improvement were detected in the boiler, which confirms that the boiler has the priority for any service to be done in order to improve, update or over whole towards the considered plant power cycle. Such services could include heat transfer mechanism related to the pipes, avoiding any resistance addition, heat recovery channels, and secure an optimum burning process. According to the advanced presented results, a detailed service schedule could be prepared for the over whole for the desired power plant with the anticipated upgrading target.

Produced power is proportional with the steam flow rate and heat drop of steam turbine so this makepossible to arrange power by changing this parameter and sliding pressure boilers can also be used togovernthe load.Thefuture work must concern itself on how to improve the energy and exergy transferred to the steam in boiler.

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