EXERGO-ENVIRONMENTAL ANALYSIS FOR A 350 MW STEAM POWER STATION

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الملخص

في هذا العمل، يتم تقديم بارامترات مبنية على مفهوم الإكسيرجي، لعناصر محطة قدرة بخارية كمقاربة، للتعرف على تأثير هذه العناصر على البيئة أثناء تشغيلها. إلى جانب الكفاءة الإكسيرجية، يتم تقديم بارامترات أخرى، مثل بارامتر تحطيم الإكسيرجي، بارامتر التحطيم البيئي، مؤشر التحطيم البيئي، والمؤشر الحميد للبيئة. النتائج التي تم الحصول عليها من هذه المقاربة مفيدة ومهمة عند مقارنة وتقييم تأثير تلك العناصر على البيئة، وهو الهدف الرئيسي لهذا العمل. لتسليط الضوء على هذه المقاربة، تم اختيار محطة قدرة بخارية بقدرة 350 ميجاوات للتحليل، متضمنة العناصر الرئيسية للمحطة وهي مولد البخار، معيد التسخين، التوربينات البخارية، سخانات مياه التغذية ذات الضغط العالي والضغط المنخفض، جهاز نزع الهواء، المكثف، والمضخات. أظهرت النتائج أن مولد البخار ومعيد التسخين والمكثف لهم التأثير الأكبر على البيئة.

ABSTRACT

In this work, exergetic parameters for steam power plant components are established to recognize the impact of those components on the environment during their operation. Beside the exergetic efficiency, other parameters are introduced for the analysis, such as the exergy destruction factor, environmental destruction coefficient, environmental destruction index and environmental benign index. The obtained figures (numbers) of those parameters are significant for the time being when a comparison evaluation is to be made to recognize the impact of those components on the environment, which is the main objective of this work. To highlight the foregoing approach, a steam power plant of 350 MW is selected for the analysis. The main components of the plant are: a steam generator, a re-heater, steam turbines, high and low pressure feed-water heaters, a deaerator, a condenser and pumps. The results show that the steam generator, re-heater and condenser have the largest environmental impacts.

INTRODUCTION

The future obligation for the strategy of energy conversion systems is to decrease the environmental effects with restricted drawbacks on expenses, therefore the electrical power must be generated with low environmental impact [1]. The environmental concern is drawing attention due to complications such as environmental acidity, ozone depletion potential and global warming potential [2].

To measure the level of the environmental impact for producing electrical power, exergoenvironmental approach is demonstrated. The approach is an exergy based method, which is utilized to assess the environmental impact of a thermal system or its components during the operation. The negative impact is due to irreversibilities, rejecting materials and heat to the environment [3]. Reducing the exergy destruction and emission will reduce the environmental impact and increase the sustainability of the process as it extends the

lives of the present natural resources. Consequently, exergy could be addressed for the best utilization of the natural resources by reducing the exergy destruction and emission, and hence reducing the environmental impact [4]. The utilization of fossil fuel in generating electricity in power plants has a negative impact on the environment, which can be reduced by improving the overall exergetic efficiency [5]. Electrical power generation such as organic Rankine cycle operates on the renewable energy proves to be a promising eco-friendly technology [6]. The benefit of exposing the exergy concept in assessing the performance of thermal systems is to indicate the effect of decreasing the exergy destruction and losses on saving energy, reducing the environmental impact and raising the sustainable development [4], see Figure (1).
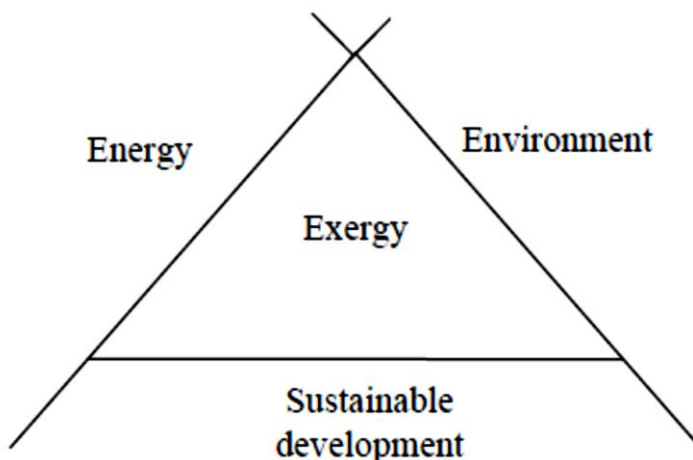
Figure 1: Confluence triangle exposed the task of the exergy analysis [4]

It is very important to realize that the increase in the exergetic efficiency will decrease the exergy destruction, reduce the degradation of the resources, reduce the environmental destruction and increase the sustainability of operation, see Figure (2).
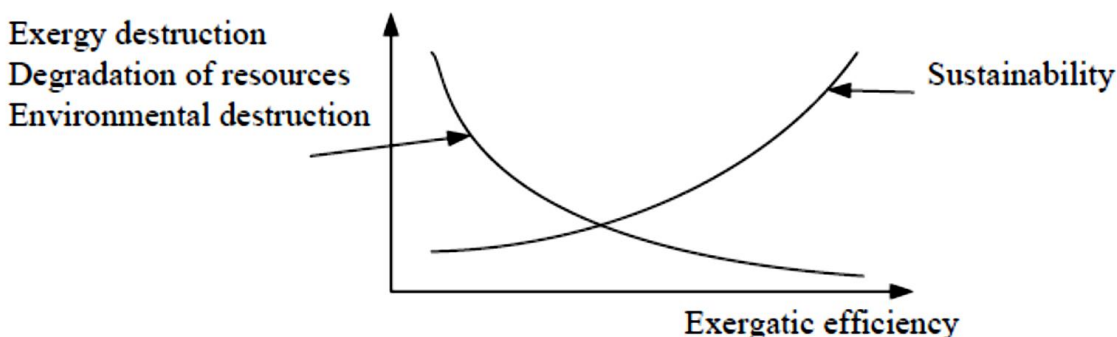
Figure 2: The environmental impact of the exergetic efficiency [4]

The environmental impact of the industrial processes which are based on exergy has been considered by many authors. An analysis motivated on studying the bottoming power cycles working with CO_2-based binary mixture, taking into account exergoenvironmental impact indices was introduced [7]. The goal was to weigh the benefits of using a CO_2-based mixture as a working fluid in closed Brayton bottoming power cycles in contrast with pure CO_2 working fluid. The environmental impact of heat pumps was studied [8]. The annual environmental impact related with the product was reduced by 9.5 % when the temperature differences in both heat exchangers were decreased. Geothermal water was used as an eco-friendly source of energy to power a

combined cycle of water and CO_2 power cycle [9]. The analysis was based on the concept of exergy where an exergoenvironmental factor was introduced to measure the environmental impact of the proposed power plant. To reduce the environmental damage, it was concluded that the heat exchangers should work at their pinch point.

Life Cycle and exergoenvironmental analyses were applied for organic Rankine cycle based on geothermal water as an energy source [10] . The applied approach permitted to recognize the components with the most environmental impact. Integrated arrangements for hydrogen and cooling productions combined with photo voltaic were studied to identify their environmental impacts. Environmental impact factors, such as, exergy destruction factor, environmental destruction coefficient, environmental destruction index and environmental benign index were introduced [5]. The environmental impact of cement production was investigated [3]. The analysis indicated that the exergy destruction caused by process and combustion releases in the kiln was the main cause of environmental impacts.

The exergoenvironmental study of 400 MW electrical power plant consists of a combined gas/steam turbine and a solar field was implemented [2]. The results showed that the condenser needed to rise its exergetic efficiency to decrease the environmental impact. An exergoenvironmental analysis for 220 MW steam power plant was performed [11]. It was found that the highest exergy destruction was in the boiler. Moreover, sustainability indicators such as environmental destruction factor, waste exergy ratio and sustainability index factors had been calculated. The environmental impact of hydrogen production by reforming of methane was investigated [12]. The study was based on combining the exergy and life cycle evaluation. It was concluded that the environmental impact could be reduced by improving the exergetic efficiency.

Reducing the environmental impact by capturing carbon dioxide emitted by a combined power plant was introduced [13]. The analysis which was based on chemical looping combustion approach showed a decrease on the environmental impact. The effect of temperature variations in the high climate regions from environmental view point was investigated [14]. It was found that the environmental impact was much less for the combined cycle than that for the conventional gas turbine cycle. A combined of exergy analysis with life cycle evaluation to examine the thermodynamic effectiveness and development of environmental impacts on plant components was introduced [15].

The method was used to allocate the environmental influences to the energy and material flows, besides the thermodynamic inefficiencies inside each component. The analysis exposed the dependence between thermodynamic performance and environmental impacts and among process components for a high-temperature solid oxide fuel cell with a combined biomass gasification process.

In this work, an exergoenvironmental analysis is performed for 350 MW steam power plant. The plant is proposed to be installed in west Tripoli-Libya. The analysis is based on the design data. Parameters such as exergy destruction factor, environmental destruction coefficient, environmental destruction and benign indices will be estimated.

MATERIALS AND METHODS

Figure (3) shows the selected steam power plant for the analysis. The software "Thermax" is used to generate the thermodynamic properties [16]. The Excel software is used to solve the linear equations to obtain the mass flow rates which are extracted to feed the feed-water heaters [17]. The design data for the selected power plant is shown in Table (1).
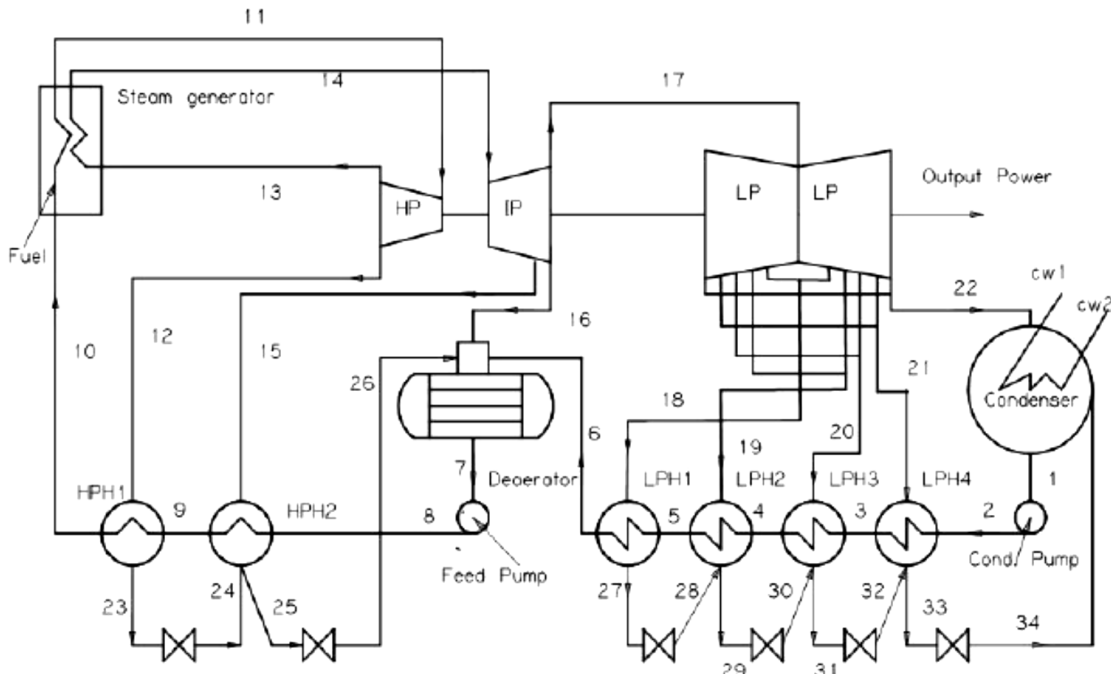
Figure 3: The selected steam power unit

The thermodynamic model

The details of the thermodynamic model can be found in [17]. Steady-state, steady-flow processes are assumed for the analysis. By neglecting the pressure drop, heat loss to the environment, and the change in the kinetic and potential energies, then:

The mass balance can be expressed as:

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

The first law of thermodynamic:

$$\sum_k \dot{Q}_k + \sum (\dot{m}_i h_i)_k = \sum (\dot{m}_e h_e)_k + \dot{W}_k \tag{2a}$$

The mass flow rate for the power cycle can be found as:

$$\dot{m}_{cycle} = \frac{\dot{W}(kW)}{w(\frac{kJ}{kg})} \tag{2b}$$

The first law efficiency is:

$$\eta = \frac{Rate\ of Energy\ (gained)}{Rate\ of\ energy(cost)} \tag{3}$$

The physical exergy can be expressed as:

$$\dot{\Psi} = \dot{m}[(h - h_0) - T_0(s - s_0)] \tag{4}$$

Where T_0 is the environmental temperature and taken as 25°C.

The exergy balance for the component "k" is expressed as"

$$\sum_i^N \left(1 - \frac{T_0}{T}\right)\dot{Q}_k + \sum_i^N \dot{\Psi}_{i,k} = \sum_e^N \dot{\Psi}_{e,k} + \dot{W}_k + \dot{I}_k \tag{5}$$

Table 1: Design data of the selected steam power unit [17]

High pressure turbine			Drain cooler approach	
Inlet temperature, T_{11} [^{o}C]		538	All heaters [^{o}C]	5.6
HPT inlet pressure, P_{11} [kPa]		17490	**Extracting pressures [kPa]**	
Reheater			Extracting (1), P12	4350
Inlet temperature, T_{14} [^{o}C]		538	Extracting (2), P_{15}	2030
Inlet pressure, P_{14} [kPa]		4350	Extracting (3), P_{16}	977
Efficiency			Extracting (4), P_{18}	549
Pumps [%]		75	Extracting (5), P_{19}	298
Turbines [%]		85	Extracting (6), P_{20}	161
Generator [%]		93.5	Extracting (7), P_{21}	69
Terminal temperatura difference				
High pressure heaters [^{o}C]		2.8		
Low pressure heaters [^{o}C]		0.0		

The Fuel-Product-Loss concept is applied (F-P-L). For a component (k) the exergy balance is written as:

$$\dot{\Psi}_F = \dot{\Psi}_P + \dot{\Psi}_D \tag{6}$$

The second-law efficiency (effectiveness) of every single component (k) is given by:

$$\varepsilon_k = \frac{\dot{\Psi}_P}{\dot{\Psi}_F} = 1 - \frac{\dot{\Psi}_D}{\dot{\Psi}_F} \tag{7}$$

The second-law efficiency (effectiveness) of the power cycle is given as:

$$\varepsilon = \frac{\dot{W}_{net}}{\dot{m}_{fuel} \times \psi_{fuel}} \tag{8}$$

The exergy of the hydrocarbon fuel is obtained by:

$$\frac{LHV}{\psi_{fuel}} \approx 1.00565 \tag{9}$$

The Fuel-Product definitions for the selected power plant are shown in Table (2).

Exergoenvironmental analysis
The exergy destruction for a component "k" is given by:

$$\dot{\Psi}_{D,k} = \dot{\Psi}_{F,k} - \dot{\Psi}_{P,k} - \dot{\Psi}_{L,k} \tag{10}$$

By rearranging we get:

$$\dot{\Psi}_{D,k} = \dot{\Psi}_{F,k}\left(1 - \frac{\dot{\Psi}_{P,k} + \dot{\Psi}_{L,k}}{\dot{\Psi}_{F,k}}\right) \tag{11}$$

Then:

$$\dot{\Psi}_{D,k} = \dot{\Psi}_{F,k}\left(1 - \varepsilon_k - r_{L,k}\right) \tag{12}$$

And:

$$\varepsilon_k = \frac{\dot{\Psi}_{P,k}}{\dot{\Psi}_{F,k}} \tag{13}$$

Exergy loss factor is defined as:

$$r_{L,k} = \frac{\dot{\Psi}_{L,k}}{\dot{\Psi}_{F,k}} \qquad 0 \leq r_{L,k} \leq 1 \tag{14}$$

Table 2: Fuel-Product exergy designations

Comp.	Fuel	Product	Comp.	Fuel	Product
SG	$\dot{\Psi}_{Fuel\_SG}$	$\dot{\Psi}_{11} - \dot{\Psi}_{10}$	HPH2	$\dot{\Psi}_{15} + \dot{\Psi}_{24} - \dot{\Psi}_{25}$	$\dot{\Psi}_9 - \dot{\Psi}_8$
RH	$\dot{\Psi}_{Fuel\_RH}$	$\dot{\Psi}_{14} - \dot{\Psi}_{13}$	DEA	$\dot{\Psi}_6 + \dot{\Psi}_{16} + \dot{\Psi}_{26}$	$\dot{\Psi}_7$
HPT	$\dot{\Psi}_{11} - \dot{\Psi}_{12} - \dot{\Psi}_{13}$	$\dot{W}_{HPT}$	LPH1	$\dot{\Psi}_{18} - \dot{\Psi}_{27}$	$\dot{\Psi}_6 - \dot{\Psi}_5$
IPT	$\dot{\Psi}_{14} - \dot{\Psi}_{15} - \dot{\Psi}_{16} - \dot{\Psi}_{17}$	$\dot{W}_{IPT}$	LPH2	$\dot{\Psi}_{19} + \dot{\Psi}_{28} - \dot{\Psi}_{29}$	$\dot{\Psi}_5 - \dot{\Psi}_4$
LPT	$\dot{\Psi}_{17} - \dot{\Psi}_{18} - \dot{\Psi}_{19} - \dot{\Psi}_{20} - \dot{\Psi}_{21} - \dot{\Psi}_{22}$	$\dot{W}_{LPT}$	LPH3	$\dot{\Psi}_{20} + \dot{\Psi}_{30} - \dot{\Psi}_{31}$	$\dot{\Psi}_4 - \dot{\Psi}_3$
Cond	$\dot{\Psi}_{22} - \dot{\Psi}_{34} - \dot{\Psi}_1$	$\dot{\Psi}_{cw2} - \dot{\Psi}_{cw1}$	LPH4	$\dot{\Psi}_{21} + \dot{\Psi}_{32} - \dot{\Psi}_{33}$	$\dot{\Psi}_3 - \dot{\Psi}_2$
HPH1	$\dot{\Psi}_{12} - \dot{\Psi}_{23}$	$\dot{\Psi}_{10} - \dot{\Psi}_9$	CEP	$\dot{W}_{CEP}$	$\dot{\Psi}_2 - \dot{\Psi}_1$
			FP	$\dot{W}_{FP}$	$\dot{\Psi}_8 - \dot{\Psi}_7$

Exergy destruction factor (σ)

Exergy destruction factor is considered as an exergy-based sustainability factor for a component in operation. It designates the reduction of the constructive impact of the component on the exergy-based sustainability. The constructive role of the component implies supplying more anticipated exergy output and lessening the irreversibilities and reducing the discarded exergy outputs throughout the component operation. The exergy destruction factor ""σ_k" is then defined as:

$$\sigma_k = \frac{\dot{\Psi}_{D,k}}{\dot{\Psi}_{F,k}} \qquad 0 \leq \sigma_k \leq 1 \tag{15}$$

Environmental destruction coefficient (β)

The environmental destruction coefficient of a component denotes its potential on the environmental destruction during its operation. To explore the constructive role of a component on exergy-bases sustainability, this coefficient should be defined on the exergy basis. A component with high exergetic efficiency has low potential in destroying the environment, and vice versa, a component with low exergetic efficiency has high potential in destroying the environment, because of that, it is proposed to define the environmental destruction coefficient as the inverse of the exergetic efficiency, such that, the environmental destruction coefficient of a component "β_k" is given as:

$$\beta_k = \frac{1}{\varepsilon_k} = \frac{\dot{\Psi}_{F,k}}{\dot{\Psi}_{P,k}} \qquad 1 \leq \beta_k \leq \infty \tag{16}$$

In real life applications, this coefficient should be near to ''1'' to specify that the component is environmentally friendly during the operation.

Environmental destruction index (δ)

Environmental destruction index "δ_k of a component is a significant parameter to denote whether or not the component harms the environment owing to its exergy destruction. The index might be given as:

$$\delta_k = (\sigma_k + r_{L,k}) \times \beta_k = \left(\frac{\Psi_{D,k}}{\Psi_{F,k}} + \frac{\Psi_{L,k}}{\Psi_{F,k}}\right) \times \frac{\Psi_{F,k}}{\Psi_{P,k}} = \frac{\Psi_{D,k} + \Psi_{L,k}}{\Psi_{P,k}} \qquad 0 \leq \delta_k \leq \infty \qquad (17)$$

Environmental benign index "μ_k"

Environmental benign index specifies the environmental suitability of a component. If so, in order to improve the environmental suitability of a component, its environmental destruction index should be lessened to be nearer to the finest reference value. The exergy destruction and exergy waste should be minimized, and the input exergy should be optimized for maximizing the useful product of the component. It is proposed to define the environmental benign index as the reverse of the environmental destruction index, that is:

$$\mu_k = \frac{1}{\delta_k} = \frac{\dot{\Psi}_{P,k}}{\dot{\Psi}_{D,k} + \dot{\Psi}_{L,k}} \qquad 0 \leq \mu_k \leq \infty \qquad (18)$$

Higher values indicate that the component operation is friendlier to the environment.

RESULTS AND DISCUSSION

Table (3) shows the exergy destruction in each component of the steam power plant. As expected the largest destructions are in the steam generator and the re-heater.

**Table 3: Fuel, Product and exergy destruction**

Item	$\dot{\Psi}_{D,k}$ (MW)	F (MW)	P (MW)	Item	$\dot{\Psi}_{D,k}$ (MW)	F (MW)	P (MW)
SG	412.532	757.934	345.402	LPH1	0.603	6.898	6.295
RH	70.976	141.590	70.614	LPH2	0.438	5.286	4.848
HPT	8.282	104.166	95.885	LPH3	0.582	5.362	4.780
IPT	8.021	108.666	100.645	LPH4	2.625	8.273	5.648
LPT	21.589	182.268	160.679	Cond.	13.732	18.789	5.057
CEP	0.086	0.302	0.216	Trap1	0.043	4.800	4.757
FP	1.161	6.907	5.746	Trap2	0.038	5.330	5.292
HPH1	1.633	23.674	22.041	Trap3	0.002	0.669	0.666
HPH2	1.353	13.778	12.425	Trap4	0.004	0.876	0.873
FWH	0.754	14.380	13.626	Trap5	0.006	0.779	0.773
				Trap6	0.009	0.110	0.101
Total Exergy destruction (MW)				544.4674082			

Figure (4) shows the exergetic efficiency of the plant's components. As can be seen, the lowest exergetic efficiency belongs to the steam generator, re-heater and condenser. The exergetic efficiency is a significant parameter for exergy-based sustainability of the plant's components. The exergetic efficiency is expressed as the ratio between the product and the fuel on exergy basis it must be maximized for a sustainable operation.
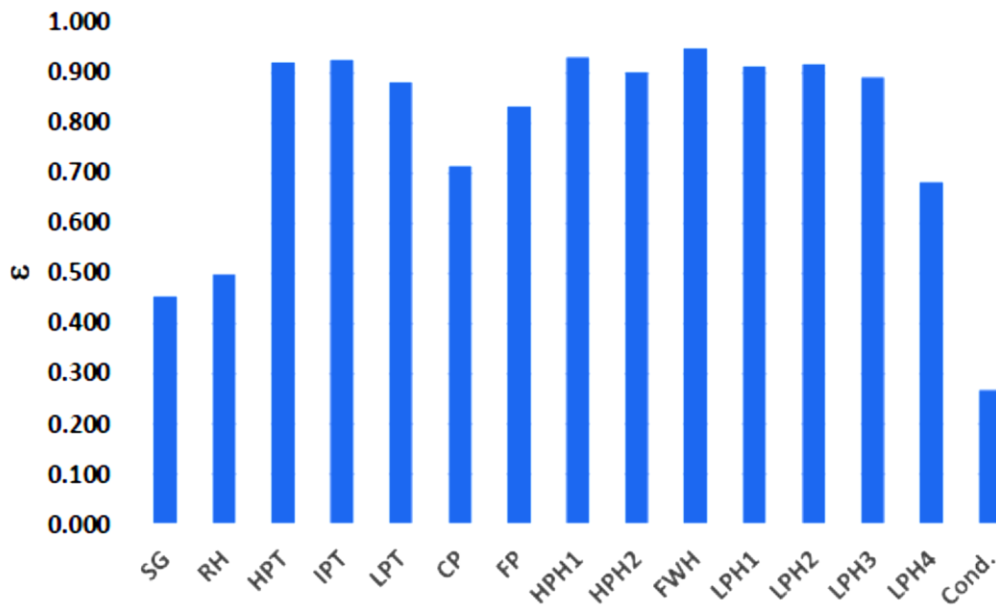
Figure 4: The exergetic efficiency of the plant components

The exergy destruction factor for the plant components is shown in Figure (5). The exergy destruction in a component reduces its sustainability of operation and can be represented by the exergy destruction factor. It is the ratio between the exergy destruction and the fuel exergy, for sustainable operation its value must be close to zero. Large exergy destruction factors such as for the steam generator, re-heater and condenser indicates low sustainability of operation.
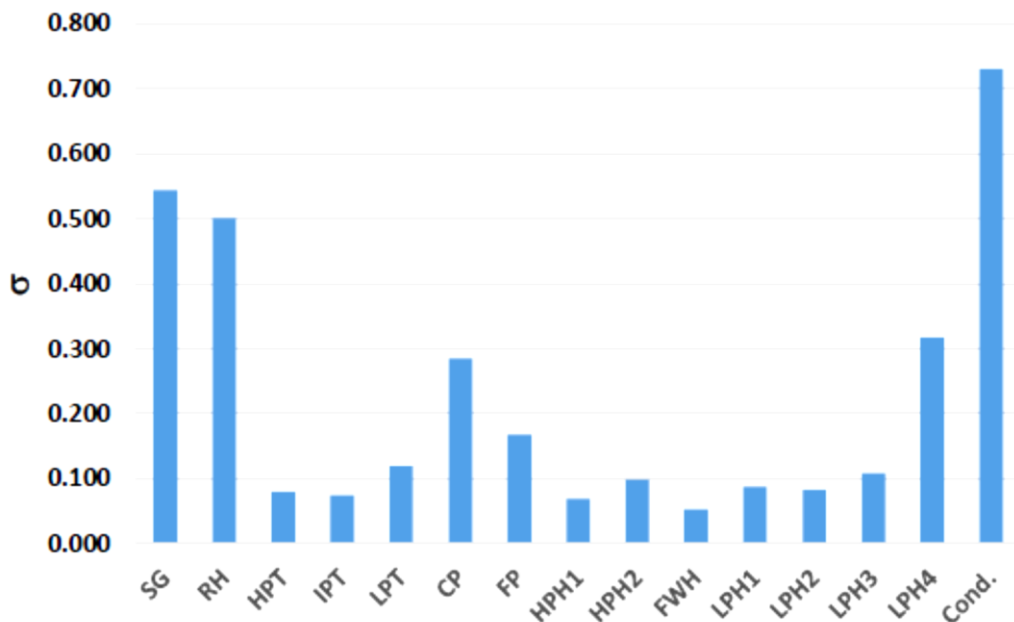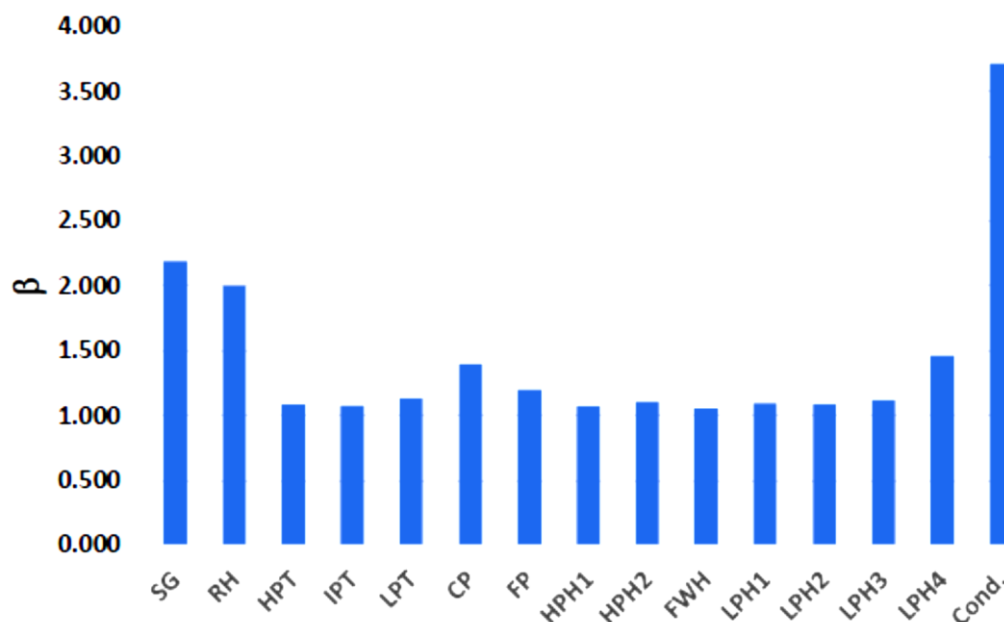

Figure 5: The exergy destruction factor

The large exergy destruction factor of the condenser is due to the large quantity of water (14951 kg/s) which is rejected to the environment with moderate temperature of 32°C. Furthermore, the large exergy destruction factors in the steam generator and the re-heater are due to the large exergy destruction and loss (483.5 MW) in these two components.
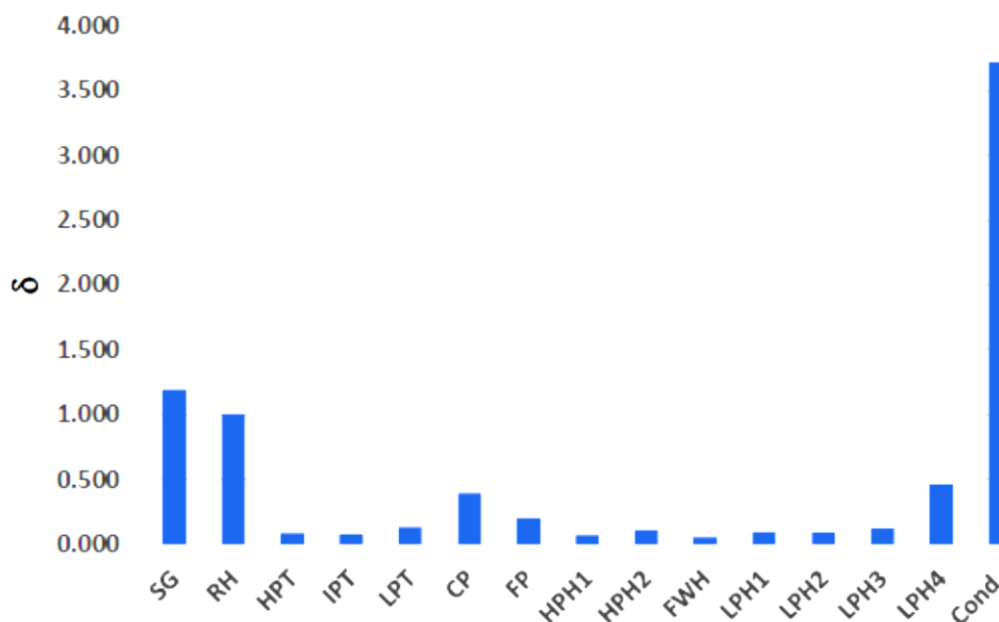
The environmental destruction coefficients for the plant components are shown in Figure (6). It is the reciprocal of the exergetic efficiency, and hence its value should be close to unity for sustainable operation. Large values such as for the condenser, steam generator and re-heater indicate unsustainable operation. The negative environmental impact of the condenser is also reported [2] Sustainable operations are found for turbines and heaters where the environmental destruction coefficients are close to unity.

Figure 6: The environmental destruction coefficient

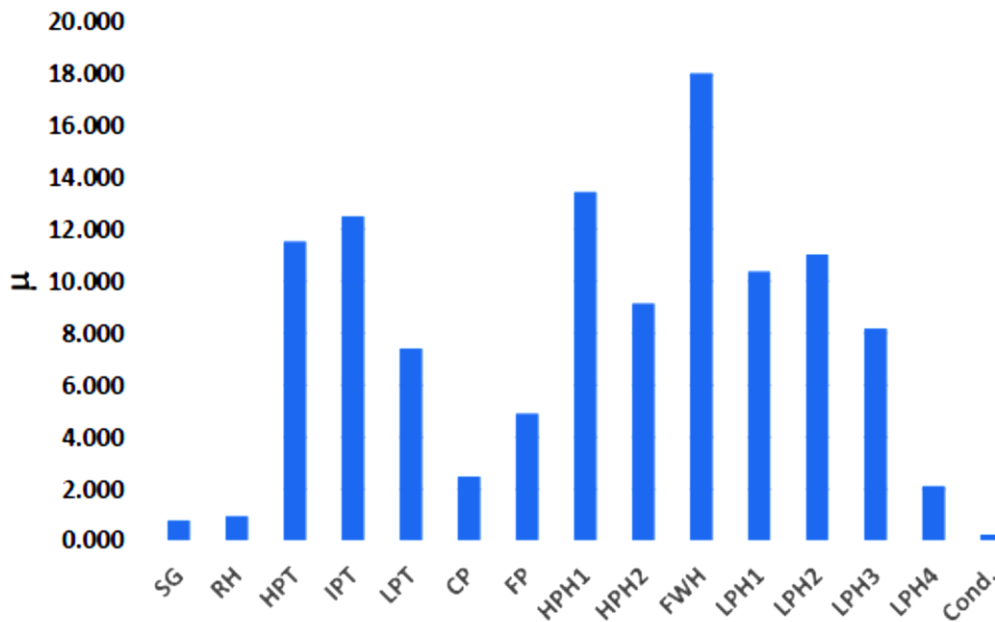The environmental destruction indices are shown in Figure (7).

Figure 7: The environmental destruction index

As stated before, it is the ratio of the exergy destruction and loss to the exergy of the product. Exergy destruction and loss to the environment create entropy and hence destroy the environment. The environmental destruction index should be close to zero for

environment friendly components such as turbines, heaters and pumps. As can be seen the index is relatively high for the steam generator, re-heater and condenser due irreversibilities and due to large release of cooling water in the condenser, and due to exhaust gases and heat rejection in the steam generator and re-heater. The largest environmental impact indices for the condenser and the boiler are also reported [18].

Figure (8) shows the benign index. It is the inverse of the environmental destruction factor. Eco-friendly components such as heaters and turbines have relatively large benign index, while extremely low values such as for the steam generator, re-heater and condenser indicate environmental unfriendly components.

Figure 8: The environmental benign index

The analysis is extended to explore the environmental impact of the whole plant. The exergetic efficiency of the steam power plant is found equal to38.91% and hence the environmental destruction coefficient is 2.57, this value should be close to unity for sustainable operation of the plant. Environmental destruction coefficient of 1.2853 were reported.[11]. The exergy destruction factor is found as 0.6052, by reducing the exergy destruction this value could be reduced to become close to zero for sustainable operation of the whole plant. The environmental destruction index is found equal to 1.57. The index should be close to zero for eco-friendly operation. The inverse of the environmental destruction index is the benign index with value of 0.6369, this value is too low for eco-friendly operation of the power plant.

CONCLUSIONS

To measure the level of the environmental impact of the components of a steam power plant, sustainability parameters based on the concept of exergy are highlighted. Eco-friendly components determine their sustainability of operation. Exergy based parameters such as exergetic efficiency, exergy destruction factor environmental destruction coefficient environmental destruction index and benign index are introduced. Low sustainable operations for the steam generator, re-heater and condenser as the exergy destruction factor, environmental destruction coefficient and environmental destruction index are relatively high. Besides, the analysis shows a high harmful impact of the steam

generator, re-heater, and condenser on the environment, where the environmental benign indices are relatively low compared to other plant components. The sustainability of the whole plant based on the exergy concept is checked. The overall exergetic efficiency should be improved for sustainable operation of the steam power plant. This goal can be achieved by operating the condenser near the pinch point and by improving the exergetic efficiency of the steam generator and the re-heater.

NOMENCLATURE

Symbol		Symbol		Greek letters	
$\dot{m}\ (\frac{kg}{s})$	mass flow rate	IPT	intermediate pressure turbine	σ	environmental destruction index
$\dot{Q}\ (kW)$	heat rate	SG	steam generator	**Subscripts**	
$\dot{W}\ (kW)$	power	RH	re-heater	i	inlet
$\dot{I}\ (kW)$	irreversibility	HPT	high pressure turbine	e	exit
h (kJ/kg)	enthalpy	CEP	condensate pump	o	ambient
s (kJ/kg.K)	entropy	FP	feed pump	F	fuel
T (K)	temperature	**Greek letters**		P	product
w (kJ/kg)	specific work	η	thermal efficiency	D	destruction
LHV (kJ/kg)	lower heating value	ε	exergetic efficiency		
LPT	low pressure turbine	β	exergy destruction factor		
HPH	high pressure heater	δ	environmental destruction coefficient		
LPH	low pressure heater	μ	environmental destruction benign		

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