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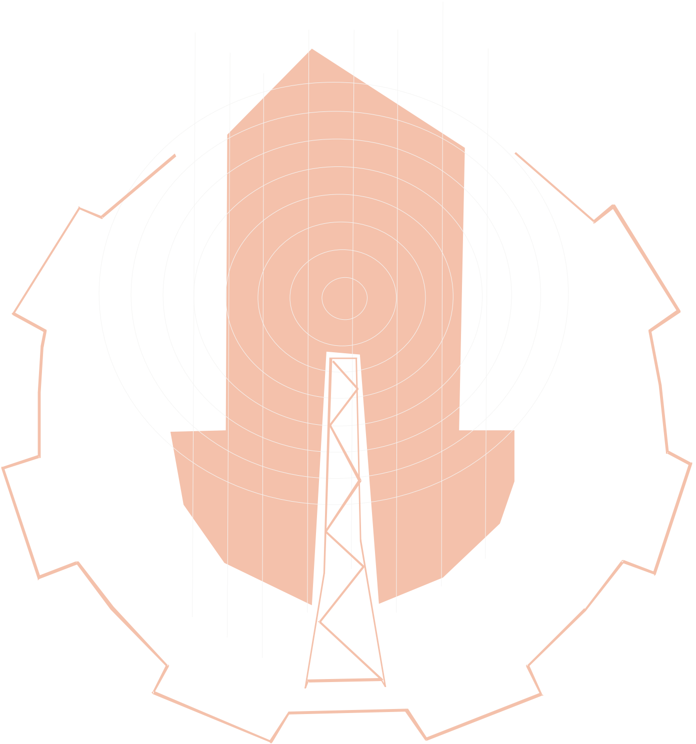

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Contents المحتويات

Research Papers in English

الأوراق البحثية باللغة العربية

THERMOECONOMIC ANALYSIS OF ALKHOMS STEAM POWER PLANT AT DIFFERENT OPERATING LOADS

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الملخص

تم إجراء تحليل إقتصادي–حراري لمحطة الخمس البخارية، ذات القدرة التصميمية 120 MW بإستخدام بيانات حقيقية لثلاثة أحمال مختلفة، حيث كان العامل الرئيسي في تغير الأحمال هو كمية البخار المُشغل للمحطة، والأحمال قيد الدراسة هي: (حمل كامل) 120 MW و (حمل جزئي) 60 MW و (الحمل التشغيل الحالي) 100 MW، علماً بأن المحطة حاليا تشتغل بدون مسخنات الضغط العالي. تم تطبيق قوانين الديناميكا الحرارية لتحليل المنظومات الحرارية التي تؤدي إلى حساب الفاعلية والإكسيرجي المرتبطة بالتكاليف للمنظومة، إضافة لحساب اللاإنعكاسية والتكاليف المرتبطة بها. بُنيت هذه الطريقة على تحليل التكاليف النوعية للاكسرجي.

أظهرت نتائج تحليل الاكسيرجي أن الفعالية إرتفعت من 37.74% عند الحمل الحالي إلى 40.96% عند الحمل الكلي، بذلك إنخفضت نسبة اللاإنعكاسية إلى اكسرجي الوقود من 65.92% عند الحمل الحالي إلى 59.6% عند الحمل الجزئي لتصل إلى 57.9% عند الحمل الكلي، بينما أظهرت نتائج التحليل الإقتصادي الحراري أن تكلفة الطاقة المولدة عند الحمل الحالي كانت 0.177 $/kWh و 0.113 $/kWh عند الحمل الجزئي و 0.102 $/kWh عند الحمل الكلي مع الأخذ في الإعتبار الإرتفاع في سعر الوقود على مدار عمر المحطة. أظهرت النتائج أيضا أن تكلفة الطاقة المهدورة (اللاإنعكاسية) في الغلاية تمثل أكبر قيمة بين إجمالي التكاليف وتتغير قيمتها من 8296 $/h عند الحمل الحالي إلى 6560 $/h عند الحمل الكلي، بينما تقل قيمتها بقيمة ملحوظة عند الحمل الجزئي وذلك لإنخفاض معدل إستهلاك الوقود، بينما مثلت تكاليف اللاإنعكاسية لباقي وحدات المحطة قيم اصغر.

ABSTRACT

Exergoeconomic (thermoeconomic) analysis is performed on Alkhoms steam power plant. The nominal power of the plant is 120 MW. The analysis is based on real-time data and performed for three different loads. The main factor of load variation is the variation of the steam mass flow rate. These loads are 120 MW (full load), 60 MW (part load), and 100 MW (real-time operation). It is worth to mention that high-pressure heaters are out of service these days. A systematic and general methodology for defining and calculating exergetic efficiencies, exergy destruction, and exergy related to costs in thermal systems is presented. The methodology is based on the Specific Exergy Costing (SPECO) method.

Results of the exergy analysis showed the exergetic efficiency (effectiveness) increases from 34.74% at the real-time operation to 40.96% at full operating load, and hence the ratio of the total exergy destruction to fuel input exergy decreases from 64.46% at a real-time operation to 59.6 at part load up to 57.88% at full operating load. The exergoeconomic analysis results the average specific cost is 0.177 $/kWh at real-time operation and 0.113 $/kWh at part load, and 0.102 $/kWh at full operating load taking into consideration the escalation of fuel price (levelized fuel cost). It is found that the cost of exergy destruction in the steam generator presents the main contribution to the total cost of exergy loss; its value varies in the steam generator from 8296 $/h at the real-time operation to 6560 $/h at full operating load, while exergy destruction cost at part load is at a notable value of 3495 $/h due to low fuel consumption. The contributions and the variation of exergy destruction cost with load are lower for the other components.

KEYWORDS: Exergy; Operating Load; Thermoeconomic Analysis; Specific Exergy Costing; Cost of Exergy Destruction

INTRODUCTION

Thermoeconomic analysis attains the objective by relating the theories of cost (an economic property) and exergy (an energetic property), both having the features of shortage and dissipation. Thermoeconomic analysis offers information that is not offered through traditional energy analysis and economic estimates but vital to the design and operation of a cost-effective system [1].

The conventional thermodynamic optimization process of an energy-generating system usually emphasizes energy-saving or exergy saving. This type of optimization has several disadvantages: An increase in efficiency or a decrease in the irreversibility of the system will result in a decrease in fuel consumption. However, this is generally accomplished with a corresponding increase in capital cost. Thus it is challenging to reach a balance between thermodynamics and economics. Such optimization is usually based on the first and second laws of thermodynamics (i.e., the conservation law of energy and the irreversibility of exergy). As known, the same amount of energy in different thermal devices may have quite different amounts of exergy and therefore quite different economic values. Thermodynamic optimization is thus unable to differentiate the complex relationship among energy, exergy, and cost. A combination of economic analysis and thermodynamic optimization is one of the ways to overcome these difficulties inherent in conventional methods [2].

The thermoeconomic approach, therefore, permits engineers to assess the cost of consumed resources, money, and system exergy destruction "irreversibilities" in terms of the overall production and enables them to exploit these resources effectively. By allocating costs to flow streams in each process, thermoeconomic helps in the assessment of the economic effect of exergy destruction. Thermoeconomic not only helps in locating inefficiencies and their economic effect during plant operation, but it can also be used in optimizing the design of the new plants and assessing rational prices of the plant’s products. Therefore, it is for these reasons that exergy and thermoeconomic analysis are being implemented to assess the performance of thermal plants and to investigate improvement potentials [3].

The objectives of thermoeconomic analysis [1]:are:

i. To calculate separately the cost of each product generated by a system having more than one product.
ii. To understand the cost formation process and the flow of costs in the system.
iii. To optimize specific variables in a single component.
iv. To optimize the overall system.

Alkhoms steam power plant has been chosen as a 'case study' to illustrate the thermoeconomic approach. It was commissioned in the early eighties; it has four units with a 120 MW each unit. All units powered with heavy fuel oil with lower heating value 43240.7kJ/kg [4], each unit consist of three turbines, high, intermediate, and low-pressure turbine, the steam inters the high-pressure turbine at 128 MPa, 535°C, six bleedings in the cycle, three to high pressure heaters, two low pressure heaters, and one to the deaerator as shown in Figure (1).

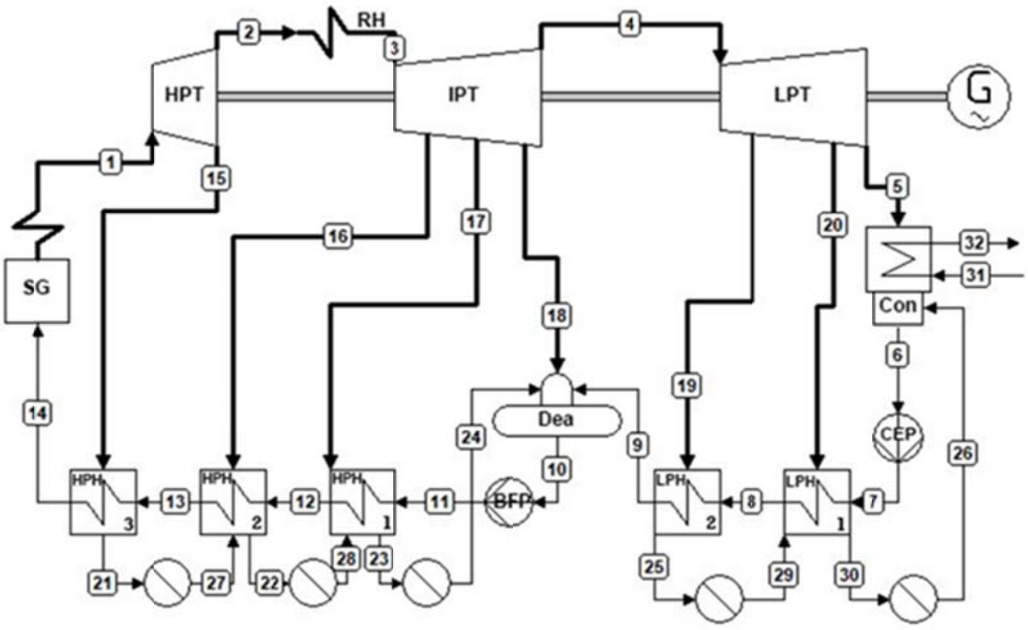


Figure 1: Alkhoms power plant schematic flow diagram

MATHEMATICAL MODEL

Exergy may be defined as the maximum reversible work which is obtainable when a system is brought reversibly from its given state to the environmental dead state during which the stream may exchange heat only with the environment state at T_0, P_0. Thus, the exergy of a system of the matter is a property of two states, the state of the system and the state of the environment [5]:

$$\psi = (h - h_0) - T_0(s - s_0) \tag{1}$$

By neglecting the change in the kinetic and potential energies, the first law of thermodynamics (energy balance) applied to an open system at steady-state is expressed as:

$$\dot{W}_{CV} + \sum \dot{m}_e h_e = \sum \dot{m}_i h_i + \sum \dot{Q}_{CV,j} \tag{2}$$

The amount of exergy entering a steady-state, steady-flow system in all forms (heat, work, mass transfer) must be equal to the amount of exergy leaving plus the exergy destroyed. Then the rate of exergy destroyed can be written as:

$$\dot{\Psi}_D = \sum_{j\neq 0} \left(1 - \frac{T_0}{T_j}\right) \dot{Q}_{CV,j} + \sum_i \dot{m}\psi - \dot{W}_{CV} - \sum_e \dot{m}\psi \tag{3}$$

The input and output exergies for a component may be expressed as the fuel and the product of that component, $\dot{\Psi}_F$ and $\dot{\Psi}_P$, respectively [6]. An exergy rate balance for an adiabatic system is then given by:

$$\dot{\Psi}_F = \dot{\Psi}_P + \dot{\Psi}_D \tag{4}$$

From the fuel product role concept (see Table (1)).

Table 1: Fuel product streams identification for each component

No	component	Fuel	Product
1	Steam generator	Ψ_{SG}	Ψ_1–Ψ_{14}
2	Reheat	Ψ_{RH}	Ψ_3–Ψ_2
3	Steam turbine	$\Psi_1- \Psi_2-\Psi_{15}+ \Psi_3- \Psi_{16}-\Psi_{17}-\Psi_{18}-\Psi_5-\Psi_{19}- \Psi_{20}$	W_{ST}
4	Condenser	$\Psi_5+\Psi_{26}-\Psi_6$	$\Psi_{32}-\Psi_{31}$
5	Condensate pump	W_{CEP}	$\Psi_7- \Psi_6$
6	Low pressure heater 1	$\Psi_{20}+\Psi_{29}-\Psi_{30}$	$\Psi_8-\Psi_7$
7	Low pressure heater 2	$\Psi_{19}-\Psi_{25}$	$\Psi_9-\Psi_8$
8	Deaerator	$\Psi_9+\Psi_{18}+\Psi_{24}$	Ψ_{10}
9	Boiler feed pump	W_{BFP}	$\Psi_{11}- \Psi_{10}$
10	High pressure heater 1	$\Psi_{17}+ \Psi_{28}-\Psi_{23}$	$\Psi_{12}- \Psi_{11}$
11	High pressure heater 2	$\Psi_{16}+\Psi_{27}-\Psi_{22}$	$\Psi_{13}-\Psi_{12}$
12	High pressure heater 3	$\Psi_{15}-\Psi_{21}$	$\Psi_{14}- \Psi_{13}$

The exergetic efficiency for any component k is defined as [7]:

$$\varepsilon_k = \frac{\dot{\Psi}_P}{\dot{\Psi}_F} \tag{5}$$

and the plant net exergetic efficiency is defined as:

$$\varepsilon_{net} = \frac{\dot{W}_{net}}{\dot{m}_{fuel} * \psi_{fuel}} \tag{6}$$

The exergy of heavy fuel oil can be estimated as [8]:

$$\frac{\Psi_f}{LHV} = 1.06 \tag{7}$$

where LHV is the lower heating value of the fuel.

THERMOECONOMIC ANALYSIS

The cost rate ($/h) of the input and exit streams are given as [9]:

$$\dot{C}_i = c_i\dot{\Psi}_i;\ \dot{C}_e = c_e\dot{\Psi}_e \tag{8}$$

Applying the SPECO method for every component as given by [3], the system is given as following where more than one exergy stream enters and/or exits, the sum of the cost rates of exiting exergy streams is equal to the sum of all cost rates of entering streams plus the circumstantial capital investment and operating and maintenance cost, accordingly, for a component k that receives heat transfer q and generates power W, one can write:

$$\sum_e \dot{C}_{e,k} + \dot{C}_{W,k} = \dot{C}_{q,k} + \sum_i \dot{C}_{i,k} + \dot{Z}_k \tag{9}$$

where $\sum_e \dot{C}_{e,k}$ is the sum of the cost rates of the streams exiting component k, $\dot{C}_{W,k}$ is the cost rate of the work generated by component k, $\dot{C}_{q,k}$ is the cost rate of the heat transfer received by component k and $\sum_i \dot{C}_{i,k}$ is the sum of the cost rates of the streams entering component k.

The cost of exergy destruction is given as [10].

$$\dot{C}_{D,k} = c_{F,k}\dot{\Psi}_D \tag{10}$$

The cost equations of different components [11-13] are shown in Table (2):

The capital investments to be converted to annual cost by using the capital recovery factor:

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \qquad (11)$$

where n is the lifetime of the equipment in years to be taken as 35yrs and i is the effective interest rate, which takes into consideration inflation rate as 10% and real interest rate 7%. The effective intrest rate is given as by [13]:

$$i = \left(1 + i_{inf}\right)(1 + i_{real}) - 1 \qquad (12)$$

Table 2: Equations formulas for calculating the steam power plant equipment costs.

Component	Capital investment cost	Remarks
SG& RH	$Z_{SG} = 740(\dot{Q})^{0.8} e^{\left(\frac{P(MPa)-2}{14.29}\right)} e^{\left(\frac{T(°C)-350}{446}\right)}$	$\dot{Q}(KW)$
Steam turbine	$Z_{ST} = a_1\left(\dot{W}_{ST}\right)^{0.7}$	$a_1 = 7000 \frac{\$}{(KW)^{0.7}}$
Pumps	$Z_{ST} = a_2\left(\dot{W}_{pump}\right)^{0.7}$	$a_2 = 3540 \frac{\$}{(KW)^{0.7}}$
Feedwater heater	$Z_{FWH} = 66\dot{Q}\left(\frac{1}{TTD + a_3}\right)$	$a_3 = \{\frac{4 for\ LPH}{6 for\ HPH}\}$
Deaerator	$Z_{DEA} = a_4(\dot{m}_{Dea})^{a_5}$	$a_4 = 145315 \frac{\$}{kg^{-1}s}$; $a_5 = 0.7$
Condenser	$Z_{con} = a_6 \dot{m}_{con}$	$a_6 = 1773 \frac{\$}{kg^{-1}s}$

The capital cost rate $\dot{Z}_k$ of a component k can be expressed as:

$$\dot{Z}_k = \frac{\varphi_k \times PEC_k \times CRF}{3600 \times N} \left(\frac{\$}{s}\right) \qquad (13)$$

Where φ_k is the maintance cost factor equals to 1.06, PEC is the purchasing cost of the component k and N is the operating hours per year equals to 7500 h.
The cost equations are derived for each component and tabulated in Table (3).
The levelized fuel costs according to [14]:

$$\text{fp}_{levelized} = \frac{\text{fp}\left\{ \left[1 - \left(\frac{1+\sigma}{1+i}\right)^n\right] \Big/ (i - \sigma) \right\}}{SPWF} \qquad (14)$$

where fp is the fuel price, σ is the escalation rate, and SPWF is the series present worth factor which is given by:

$$SPWF = \frac{(1+i)^n - 1}{i(1+i)^n} \qquad (15)$$

Table 3: Cost balance equations of each component and auxiliary equations

No	Component	Cost balance equation
1	SG	$c_1\Psi_1 - c_{14}\Psi_{14} = Z_{SG} + c_f\Psi_{SG}$
2	RH	$c_3\Psi_3 - c_2\Psi_2 = Z_{RH} + c_f\Psi_{RH}$
3	ST	$-c_1\Psi_1 + c_2\Psi_2 - c_3\Psi_3 + c_5\Psi_5 + c_w W_{ST} + c_{15}\Psi_{15} + c_{16}\Psi_{16} + c_{17}\Psi_{17} + c_{18}\Psi_{18} + c_{19}\Psi_{19} + c_{20}\Psi_{20} = Z_{ST}$
4	CON	$-c_5\Psi_5 + c_6\Psi_6 - c_{26}\Psi_{26} + c_{32}\Psi_{32} = Z_{con}$
5	CEP	$-c_6\Psi_6 + c_7\Psi_7 - c_w W_{CEP} = Z_{CEP}$
6	LPH1	$c_8\Psi_8 + c_{30}\Psi_{30} - c_{20}\Psi_{20} - c_7\Psi_7 - c_{29}\Psi_{29} = Z_{LPH1}$
7	LPH2	$c_9\Psi_9 + c_{25}\Psi_{25} - c_{19}\Psi_{19} - c_8\Psi_8 = Z_{LPH2}$
8	DEA	$c_{10}\Psi_{10} - c_{18}\Psi_{18} - c_9\Psi_9 - c_{24}\Psi_{24} = Z_{DEA}$
9	BFP	$c_{11}\Psi_{11} - c_{10}\Psi_{10} - c_w W_{BFP} = Z_{BFP}$
10	HPH1	$c_{12}\Psi_{12} + c_{23}\Psi_{23} - c_{17}\Psi_{17} - c_{28}\Psi_{28} - c_{11}\Psi_{11} = Z_{HPH1}$
11	HPH2	$c_{13}\Psi_{13} + c_{22}\Psi_{22} - c_{12}\Psi_{12} - c_{16}\Psi_{16} - c_{27}\Psi_{27} = Z_{HPH2}$
12	HPH3	$c_{14}\Psi_{14} + c_{21}\Psi_{21} - c_{15}\Psi_{15} - c_{13}\Psi_{13} = Z_{HPH3}$

Since there are 34 streams including the fuel and power streams, another set of 22 auxiliary equations are needed to find the unknowns.

It is assumed zero cost for the cooling water stream (stream 31), and the unit cost of the fuel stream is 0.035 $/kWh, then the required auxiliary equatios are reduced to 20 equations.

Applying the fuel cost rules (F-P rules) [3], the 20 auxilliary equations are formulated as:

$c_1-c_2=0$; $c_2-c_{15}=0$; $c_3-c_4=0$; $c_4-c_{16}=0$; $c_{16}-c_{17}=0$ $c_{17}-c_{18}=0$; $c_{18}-c_{19}=0$; $c_{19}-c_{20}=0$; $c_{20}-c_5=0$; $c_6-c_5=0$; $c_{15}-c_{21}=0$; $c_{16}-c_{22}=0$; $c_{17}-c_{23}=0$; $c_{19}-c_{25}=0$; $c_{20}-c_{30}=0$; $c_{21}-c_{27}=0$; $c_{22}-c_{28}=0$; $c_{23}-c_{24}=0$; $c_{25}-c_{29}=0$; $c_{30}-c_{26}=0$.

The exergoeconomic factor expresses as a ratio the contribution of the non-exergy related cost to the total cost increase [15].

$$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + \dot{C}_{D,k}}\ , 0.0 \le f_k \le 1.0 \qquad (16)$$

The case study description and the Mathematical model applied to the considered steam power plant, more details are presented elsewhere [16].

RESULTS AND DISCUSSION

The exergetic efficiencies at full load operation (120 MW) and real time operation (100 MW) are calculated as 40.96% and 34.74 %, respectively. It is found that, the exergy destruction of the plant increases from 168.4 MW at the full-load operation to 198.18 MW when the plant operates without high-pressure feed-water heaters (real time operation). As can be shown in Figure (2), the steam generator contributes to 73% of the total exergy destruction at full load and increases to 78% at real-time operation. Other details of exergy analysis are found in the appendicies 1-4.

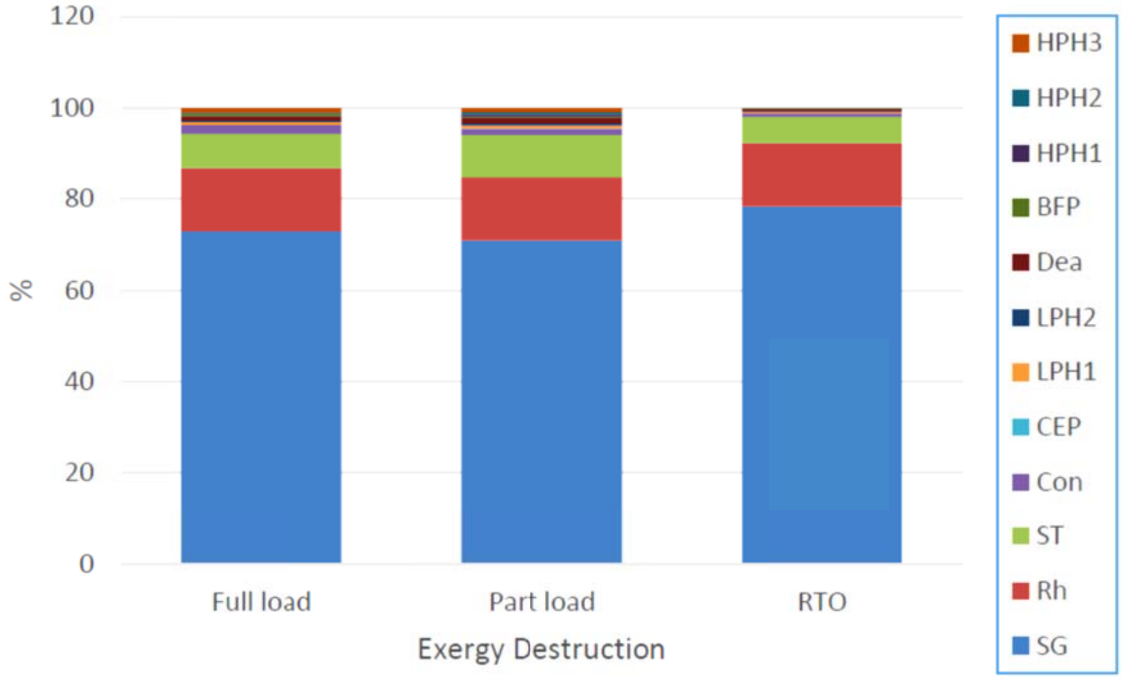
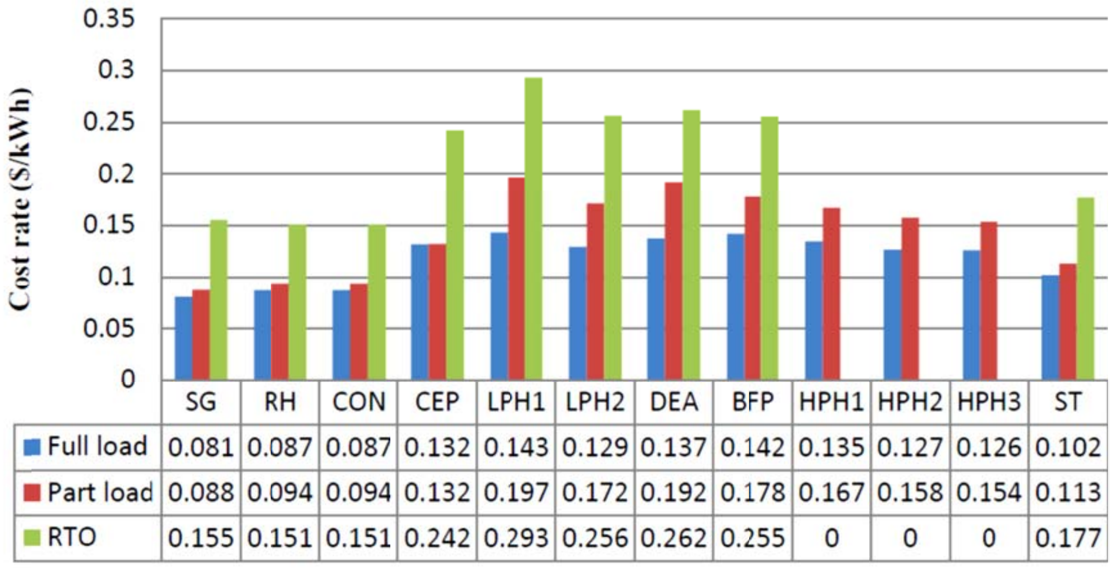


Figure 2: Exergy destruction percentage of the plant at different loads

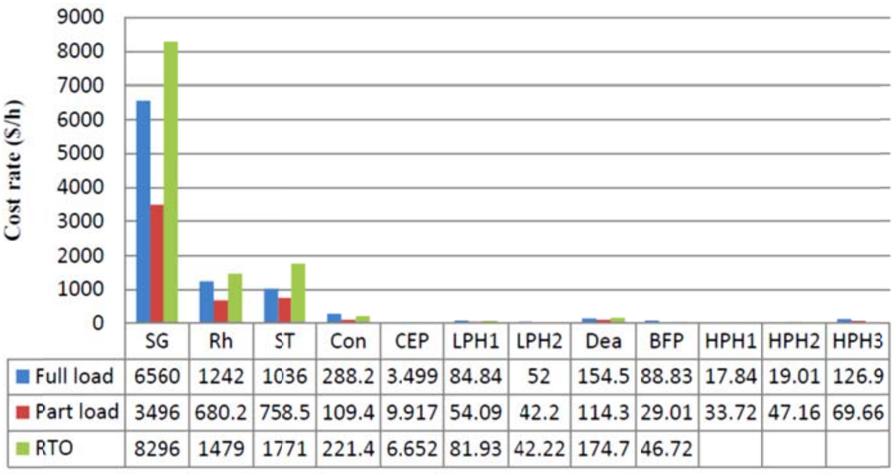
The unit cost associated with the exergy of different product streams for each component is shown in Figure (3). Due to deficiency of the real time operation (RTO), the unit cost of different streams are the largest, while the smallest unit costs are found at full load operation.



	SG	RH	CON	CEP	LPH1	LPH2	DEA	BFP	HPH1	HPH2	HPH3	ST
Full load	0.081	0.087	0.087	0.132	0.143	0.129	0.137	0.142	0.135	0.127	0.126	0.102
Part load	0.088	0.094	0.094	0.132	0.197	0.172	0.192	0.178	0.167	0.158	0.154	0.113
RTO	0.155	0.151	0.151	0.242	0.293	0.256	0.262	0.255	0	0	0	0.177

Figure 3: Products unit cost for plant components for different loads.

The cost rate ($/h) of exergy destruction for the plant's components is shown in Figure (4).



	SG	Rh	ST	Con	CEP	LPH1	LPH2	Dea	BFP	HPH1	HPH2	HPH3
🟦 Full load	6560	1242	1036	288.2	3.499	84.84	52	154.5	88.83	17.84	19.01	126.9
🟥 Part load	3496	680.2	758.5	109.4	9.917	54.09	42.2	114.3	29.01	33.72	47.16	69.66
🟩 RTO	8296	1479	1771	221.4	6.652	81.93	42.22	174.7	46.72			

Figure 4: Cost rate associated with exergy destruction for plant components for different loads

The cost of exergy destruction in the steam generator presents the main contribution to the total cost of exergy destruction. The irreversibility rate and the cost of fuel affect substantially the cost of the exergy destruction within the steam generator. At full load operation, the cost rate of the exergy destruction is 6560 $/h. When the plant operates without high-pressure heaters, that is when the irreversibility rate increases, the cost rate increases to 8296 $/h. However, at part load operation less fuel is required for the operation and that reduces the cost rate to 3495 $/h.

Figure (5) shows the value of the exergoeconomic factor for the plant's component. Its value is typically lower than 55% for heat exchangers, between 35 and 75% turbines, and above 70% for pumps. Both the capital cost rate and cost rate of the exergy destruction control the value of the exergoeconomic factor. The high values imply a high capital cost rate, and low values imply a high irreversibility cost rate. For instance, the exergoeconomic factors at full load operation for HPH1 and HPH2 (heat exchangers) are greater than 55% (around 70%) and that means the capital cost of those heaters is relatively high. However, the exergoeconomic factor for the steam generator is much lower than 55% (around 15%) and that means the cost rate of the irreversibility is so high and must be lowered.

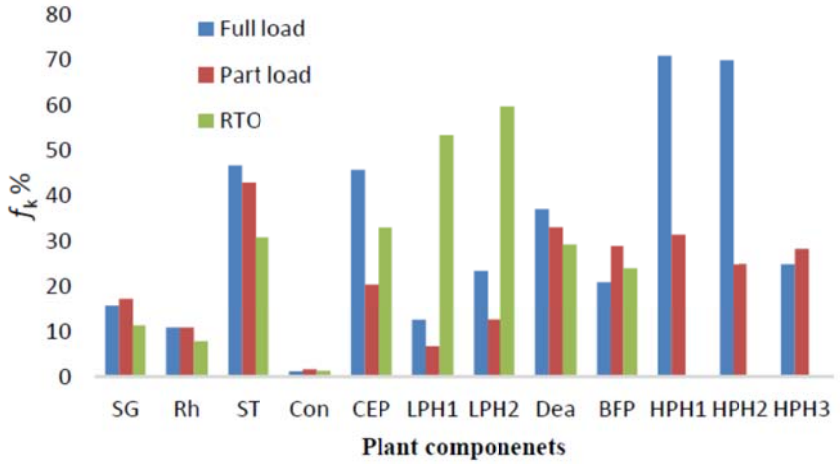


Figure 5: The exergoeconomic factor f_k for plant components, at different loads.

Other results are found in appendices 1-4.

CONCLUSIONS

Thermoeconomic (Exergoeconomic) approach is adopted in the current paper to evaluate the performance of a typical steam power plant. Alkhoms steam power plant is taken as a vehicle to explore the importance of such an approach. The following conclusions are drawn:

1- Exergoeconomic approach is a powerful tool that can be adopted as an evaluation method of preliminary designs before commissioning and to evaluate and rate individual systems.
2- Specific Exergy Costing (SPECO) is adopted in the analysis.
3- Cost estimations for the capital cost of the equipment are adopted due to the lack of actual prices.
4- Three operating conditions are considered in the analysis, the full load and part load conditions, the third operating condition is the real-time operating condition resulted from the outage of the high-pressure heaters.
5- Exergy analysis shows the most exergy destruction occurs in the steam generator, and for the plant, the total exergy destruction increases to 186 MW at the real-time operation condition.
6- Thermoeconomic analysis reveals that the unit cost of the plant exergy product increases from 0.102 $/kWh at full load operation to 0.177$/kWh at real-time operation.
7- The exergoeconomic factor is relatively high for the feed-water heaters and low for the steam generator.

NOMENCLATURE

BFP	boiler feed pump	**Sub.**		**Greek letters**	
c	specific cost [$/kWh]	BFP	boiler feed pump	ψ	exerg [kJ/kg]
$\dot{C}$	cost rate [$/h]	CEP	condensate pump	$\dot{\Psi}$	exergy rate [kW]
CEP	condensate pump	e	exit	ε	effectiveness
CON	condenser	k	component		
DEA	deaerator	Con	condenser		
h	enthalpy [kJ/kg]	o	ambient		
HPH	high pressure heater	i	inlet		
HPT	high pressure turbine	j	Heat source index		
IPT	internidiate pressure turbine	D	destruction		
LPH	low pressure heater	F	fuel		
LPT	low pressure turbine	P	product		
RH	reheater	SG	steam generator		
$\dot{Q}$	heat rate [kW]	RH	reheater		
s	specific entropy [kJ/kg.K]	CV	control volume		
SG	steam generator	ST	steam turbine		
T	temperature [^{o}C]	W	work		
$\dot{W}$	power [kW]	q	heat		
Z	cost [$]				
$\dot{Z}$	cost rate [$/s]				

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Appendix 1: Exergy steams, steams cost per unit of exergy, and exergy cost rates at different loads.

	Full load			Part load			Real time operation		
State	$\dot{\Psi}$(MW)	c($/kWh)	$\dot{C}\left(\$/_{h}\right)$	$\dot{\Psi}$(MW)	c($/kWh)	$\dot{C}\left(\$/_{h}\right)$	$\dot{\Psi}$(MW)	c($/kWh)	$\dot{C}\left(\$/_{h}\right)$
1	144.091	0.0805	11603.528	72.465	0.087	6359.898	111.934	0.145	16334.924
2	98.669	0.080	7945.750	44.183	0.087	3877.791	82.241	0.145	12001.790
3	121.913	0.0867	10580.363	56.658	0.093	5306.855	101.614	0.142	14501.040
4	65.848	0.086	5714.692	29.798	0.093	2791.024	60.295	0.142	8604.567
5	5.594	0.086	485.483	1.523	0.093	142.663	5.247	0.142	748.887
6	0.069	0.086	6.063	0.051	0.093	4.787	0.064	0.142	9.228
7	0.150	0.718	108.004	0.081	0.132	10.708	0.172	0.945	163.536
8	1.874	0.187	351.801	0.593	0.196	116.690	1.738	0.156	272.287
9	4.119	0.149	614.263	1.404	0.171	240.933	3.812	0.179	686.163
10	8.309	0.147	1222.302	2.847	0.191	546.600	6.455	0.198	1281.637
11	10.265	0.149	1532.058	3.653	0.177	649.480	7.704	0.200	1546.287
12	13.045	0.140	1834.642	4.852	0.167	810.975	NA	NA	NA
13	17.150	0.131	2247.346	6.495	0.157	1024.656	NA	NA	NA
14	21.195	0.129	2740.950	8.359	0.153	1285.273	NA	NA	NA
15	7.051	0.080	567.849	3.176	0.087	278.768	NA	NA	NA
16	4.549	0.086	399.556	2.114	0.093	198.051	NA	NA	NA
17	3.375	0.086	292.931	1.5395	0.093	144.216	NA	NA	NA
18	4.933	0.086	428.1234	2.206	0.093	206.665	3.640	0.142	519.525
19	3.101	0.086	269.127	1.347	0.093	126.188	2.408	0.142	343.773
20	2.464	0.086	213.891	1.017	0.093	95.293	1.952	0.142	278.636
21	1.440	0.080	115.978	0.518	0.087	45.526	NA	NA	NA
22	1.363	0.086	118.369	0.476	0.093	44.669	NA	NA	NA
23	1.346	0.086	116.823	0.457	0.093	42.850	NA	NA	NA
24	1.028	0.086	89.281	0.457	0.093	42.805	NA	NA	NA
25	0.259	0.086	22.531	0.085	0.093	8.041	0.201	0.142	28.781
26	0.019	0.086	1.706	0.003	0.093	0.295	0.006	0.142	0.871
27	1.083	0.080	87.231	0.509	0.087	44.727	NA	NA	NA

28	0.954	0.086	82.879	0.476	0.093	44.662	NA	NA	NA
29	0.225	0.086	19.569	0.076	0.093	7.206	0.076	0.142	10.906
30	0.023	0.086	2.071	0.004	0.093	0.397	0.018	0.142	2.645
W	123.431	0.101	12487.601	63.372	0.113	7165.892	106.807	0.166	17760.663
cw_{out}	2.238	0.216	484.606	0.307	0.455	139.929	2.238	0.166	743.752

Appendix 2: Exergetic, and exergoeconomic results at full load.

Component	Exergetic efficiency %	Exergy destruction (MW)	Exergy destruction percentage %	Exergy Destruction cost rate ($/h)	Exergoeconomic Factor %
SG	50.0	122.824	72.605	6560.067	15.6
Rh	49.9	23.261	13.750	1242.384	10.8
ST	90.6	12.779	7.554	1029.145	46.8
Con	40.3	3.305	1.953	286.834	1.1
CEP	8.8	0.822	0.486	83.248	11.2
LPH1	64.6	0.941	0.556	81.740	13.1
LPH2	79.0	0.596	0.352	51.760	23.4
Dea	82.4	1.771	1.047	153.738	37.0
BFP	69.1	0.873	0.516	88.408	20.9
HPH1	93.1	0.204	0.120	17.754	71.0
HPH2	94.9	0.217	0.128	18.918	70.0
HPH3	72.0	1.566	0.925	126.125	24.8

Appendix 3: Exergetic, and exergoeconomic results at part load.

Component	Exergetic efficiency %	Exergy destruction (MW)	Exergy destruction percentage %	Exergy Destruction cost rate ($/h)	Exergoeconomic factor (%)
SG	49.4	65.448	70.910	3495.602	17.1
Rh	49.4	12.736	13.806	680.229	10.8
ST	87.9	8.642	9.369	758.505	42.8
Con	20.8	1.1678	1.266	109.385	1.5
CEP	25.4	0.087	0.095	9.916	20.3
LPH1	47.0	0.577	0.626	54.093	6.6
LPH2	64.2	0.450	0.488	42.199	12.6
Dea	70.0	1.220	1.322	114.285	32.9
BFP	75.8	0.256	0.278	29.012	28.9
HPH1	76.9	0.360	0.390	33.723	31.4
HPH2	76.5	0.503	0.545	47.160	24.8
HPH3	70.1	0.793	0.860	69.659	28.2

Appendix 4: Exergetic, and exergoeconomic results at real time operation.

Component	Exergetic efficiency %	Exergy destruction (MW)	Exergy destruction percentage %	Exergy destruction cost rate ($/h)	Exergoeconomic Factor %
SG	20.1	152.030	78.448	8119.927	11.9
Rh	43.6	24.979	12.889	1334.161	8.9
ST	90.4	11.249	5.805	1641.746	33.2
Con	43.1	2.950	1.522	421.049	0.75
CEP	12.5	0.757	0.391	126.041	7.5
LPH1	77.8	0.444	0.229	63.488	61.2
LPH2	93.9	0.132	0.068	18.947	78.7
Dea	86.6	0.998	0.515	142.442	34.7
BFP	83.2	0.251	0.129	41.857	26.4