Simulation and Optimization of Tehran Oil Refinery Steam Network in view of Exergetic, Exergoeconomic and Environmental Analysis

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ABSTRACT

Due to the importance of energy consumption in a steam network of oil refinery as a significant unit, present study is concerned with the optimization of an oil refinery steam network. Here, the attempt was made to use concepts such as first and second thermodynamic laws, thermo-economic, environmental and economic discussions to investigate three different scenarios about Tehran refinery steam network. The first scenario was a base case in which boiler efficiency was 67%. The second scenario was the same as the first scenario, except that boilers efficiency was 86%. The third scenario was also similar to the base one. However, the difference was that one of the boilers was eliminated from the site. Instead, two gas turbines with heat recovery steam generator were introduced and the boiler efficiency was 86%. The obtained results showed that the annual cost of second and third scenarios fell to the rate of 22% and 42% respectively compared to the first scenario. To carry out thermodynamic modeling of some equipment such as steam turbines, gas turbines, and thermal recovers, Star software was utilized.

1. Introduction

More than half of the fuel required to provide energy needs in the industry is used for steam production. Utility systems in chemical sectors constitute an essential part of the plant. These systems supply the required electricity and the power necessary to drive process units, heat needs for thermal recycling network recovery and steam at different levels of pressure.

Concerning the increasing cost of energy resources, energy consumption optimization has been one of the most important fields of study in recent years. Because oil, gas and petroleum trades constitute Iranian industries to a large extent, research on energy systems in these sectors have become even much more critical.

CO_2 reduction through optimization of a steam network in Petroleum Refineries was evaluated by Jafari Nasr and Khodaei [2]. Also, in another work, Khodaei and Jafari Nasr evaluated a steam network of Tehran oil refinery in two scenarios of fixed fuel fraction and light fuel fraction. Furthermore, different situations were introduced using HRSG instead of two boilers. Besides, both economic and environmental issues were simultaneously evaluated with each other and the best scenario was chosen considering carbon dioxide taxes [3]. Jafari Nasr et al. also applied an optimization method to oil refinery steam management with the consideration of CO_2 emission. The steam network of Tehran Oil Refinery was considered as an industrial case study. Then, various scenarios were proposed to modify the interface [3].

Modeling and optimization of the steam turbine network for an ethylene plant were applied by Li et al. They proposed a hybrid model for the steam turbines in site utility which combined an improved neural network model with the thermodynamic model. Then, a nonlinear programming (NLP) model of the steam turbine network was used to minimize the total steam cost. The results showed that the hybrid model could estimate and evaluate the performance of steam turbines. Also, significant cost savings could be made by optimizing the steam turbine network operation at no capital cost [4].

Steam system network synthesis with hot liquid reuse was also proposed by Sheldon and Majozi. The Shaft work and optimum steam levels were incorporated [5]. Cumpston and Pye applied exergoeconomic optimisation for steam networks through connecting solar-thermal dish arrays [6].

In the same vein, Wang et al. introduced a novel model for steam transportation by considering the drainage loss in the pipeline networks. Drainage loss terms comprised of a proposed steam transportation model. The proposed model achieved an accurate estimation of drainage/heat loss along the pipes [7].

As the review of existing literature shows, exergertic, exergoeconomic and environmental analysis of steam network have not been considered simultaneously. In this paper, these studies were performed for steam network simultaneously. In this regard, different scenarios were found and exergetic, exergoeconomic and environmental views were evaluated in different situations.

The first Scenario (base) was refinery steam network in its current situation in which Boiler efficiency is 67%. The second scenario was similar to the first scenario, except that boilers efficiency was the same as that of their performance at the early two years (boiler efficiency is 86%).The third situation was the same as the base scenario with the difference that one of the [1] boilers was removed from the site. Instead, two gas turbines with heat recovery were set. The total amount of steam produced by these two recovery boilers was the same as steam generated by the removed boiler.

In the first step, these three scenarios are examined using the first law of thermodynamics. In the second stage, equations associated with exergy and its wastes for individual network devices in each scenario will be examined.

In the third stage, a thermoeconomic analysis will be carried out. In the fourth stage, an economic analysis will be investigated in order to compare the annual total cost in the three studied scenarios. Finally, the result of thermodynamic exergy, thermoeconomic, an environmental and economic analysis will be compared and contrasted for the three scenarios.

2. Steam Network Description

Steam is the most fundamental element in a steam network. Components of a steam network are generally divided into two major groups: producers and consumers of steam and each of these groups provide special requirement of the system.

2.1. Description of Steam Network Studied

There are four boilers in Tehran Refinery North branch whose main responsibility is to provide the steam pressure of 650 psi.

The headers of steam network involve three different types: high-pressure headers with 650 psi, average-pressure headers with 300 psi and low-pressure header with 60 psi. In fact, the 650 psi header is an energy resource for moving three condensing steam turbines with a capacity of 7.5 MW. These three turbines are connected to a generator that is used only for the electric power generation.

In addition to those three turbines, 650 psi steam makes 22 other turbines move. These headers are located between MP & HP as well as those between LP & MP. The turbines are only driver turbines. They have the capability of providing power for pumps and compressors. There are also two hot and cold condensate headers with the temperature of 257F and 212F within the network.

There are 21 steam consuming processes in North branch of the refinery as well as nine steam producing processes. They consume/produce steam at different levels while they are connected to different headers.

It is worth mentioning here that only 8 active turbines existing in the steam network were simulated in this paper. They include three condensing turbines and five back parishes in which larger turbines namely T1, T2 are connected to couple generator (Figure1). Also, different scenarios are shown in Figure 1-a,1-b and 1-c.

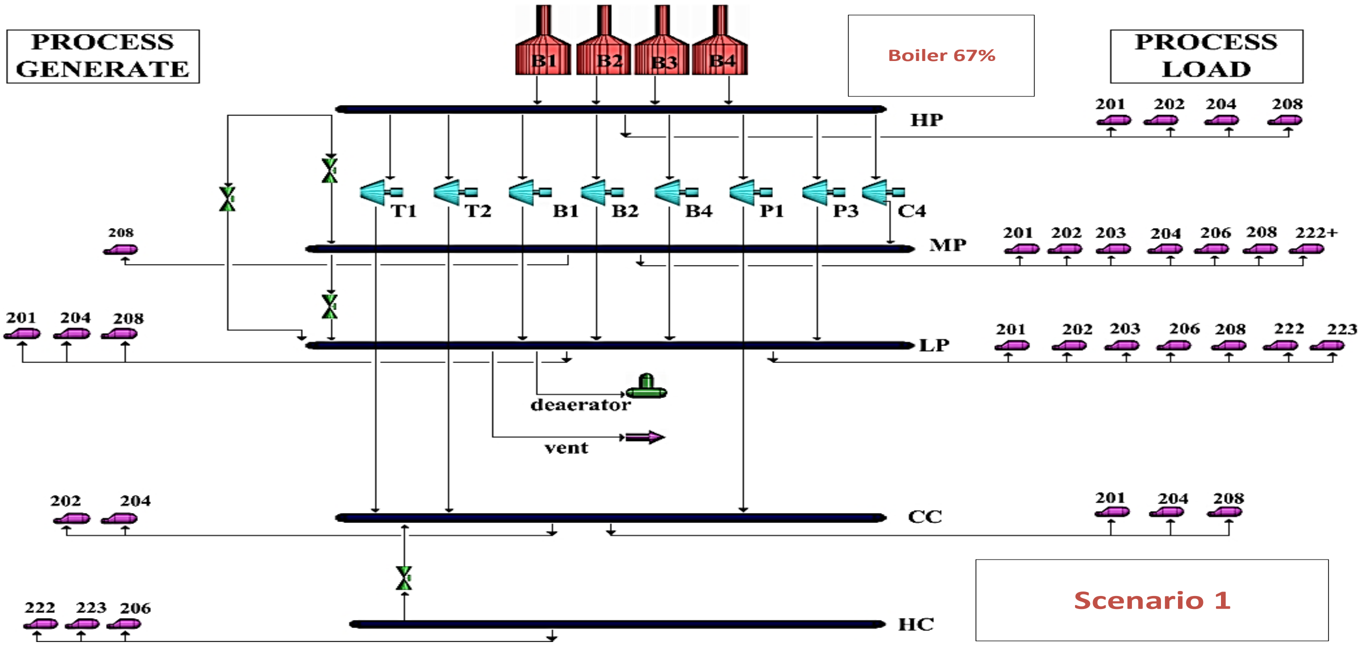

Figure 1. a. Tehran Refinery Steam network (Scenario 1)

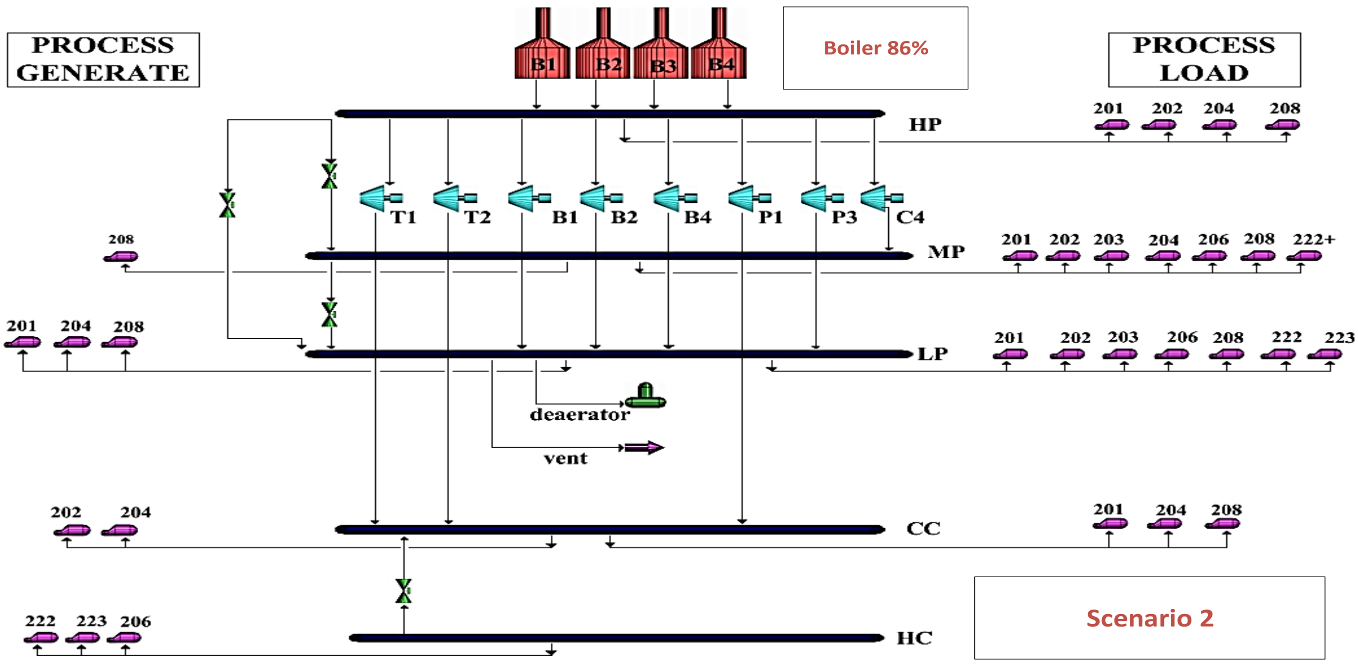

Figure 2. b. Tehran Refinery Steam network (Scenario 2)

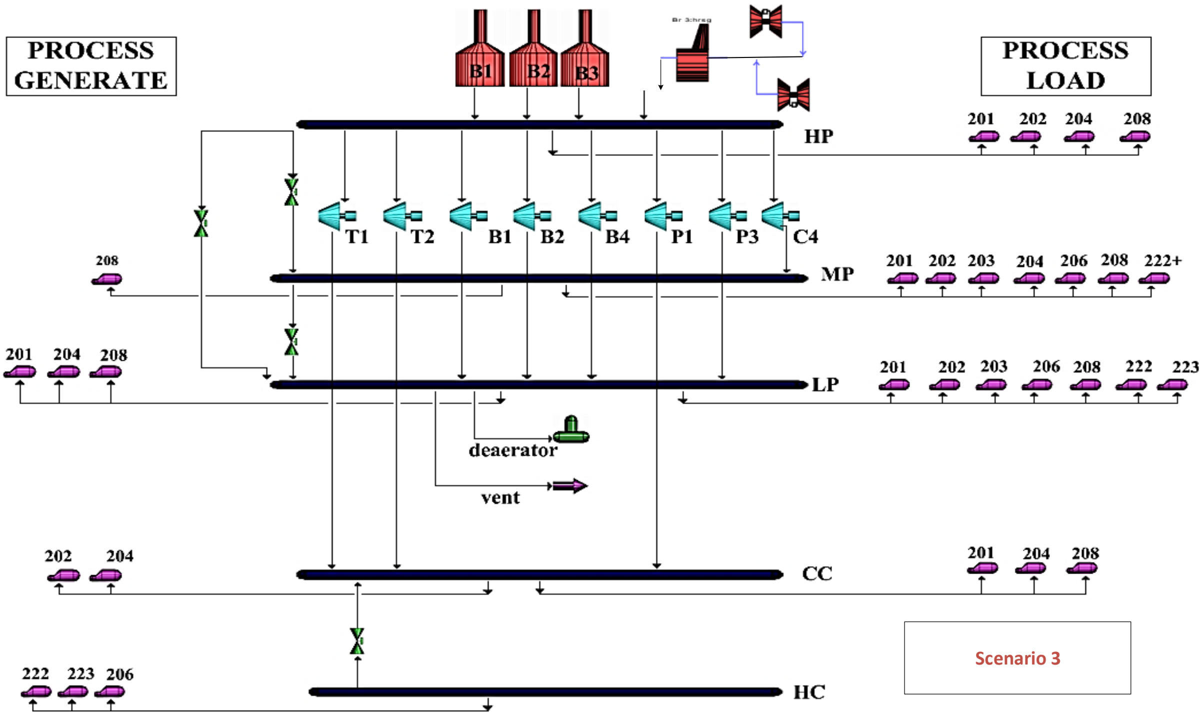

Figure 3. c.Tehran Refinery Steam network (Scenario 3)

3. Thermodynamic Relations

In thermodynamic analysis, mass and energy balance equations are used in each system component. Having determined the temperature and the flow rate, we can deal with enthalpy, entropy, and other thermodynamic parameters to analyze the systems and elicit the required information.

3.1. Boiler

While balancing the flow rate equations, it is important to keep in mind that 5% of the steam volume is used for Blowdown. In fact, the amount of produced steam in each boiler is less than the amount of feed water into the boiler. The required water for boilers can be obtained through equation (1).

$$\dot{m}_{bfw} = 4 \times \frac{\dot{m}_{boi\ steam}}{0.95} \quad (1)$$

The equations used for steam generation of boilers have been taken from Aguilar, et al. (2007). To this end, we use equation (2).

$$\dot{Q}^{boi}_{stm} = \frac{\dot{Q}^{boi}_{fuel}}{B^{boi}} - D^{boi} \quad (2)$$

Constants B & D are the regression coefficients used to show the difference between natural gas and fuel oil the amount of which are clear from Table 1 below.

Table 1. Regression Coefficient B & D for the calculation of steam generation in boilers at part load operation

constants	natural gas	fuel oil	unit
B^{boi}	1/113	1/072	-
C^{boi}	1/522	1/522	MW
D^{boi}	1/383	1/422	-

By obtaining fuel heat, we can calculate the numerical value of fuel flow rate and boiler efficiency through equations 3 & 4 below:

$$\dot{m}_{fuel} = \frac{Q_{fuel}}{NHV} \quad (3)$$

$$\eta^{boi} = \frac{\dot{Q}^{boi}_{steam}}{\dot{Q}_{fuel}} \quad (4)$$

Net Heating Value for fuel oil as a boiler fuel is considered as 41000 kj.kg $^{-1}$.

3.2. Deaerator

The amount of steam regressed in deaerator equals 70 % of the steam consumed in the process units. Also, 5% of the steams incoming into deaerator are wasted away. Consequently, writing mass-balance equation for deaerator, the amount of water required for feeding can be obtained through equation (5).

$$\dot{m}_{tw} = \dot{m}_{bfw} + \dot{m}_{vent} - \dot{m}_{cr} - \dot{m}_{d\,Steam} \quad (5)$$

To obtain the temperature of water input to the boiler, it is required to use energy balance equations of deaerator. Due to the insufficient information about the refinery in some sections, the temperature of some streams such as the regressive steam as well as that of feeding water was assumed as a fixed number by the researcher.

However, attempts were made to make the logical and natural assumptions. To do so, the numerical values and numbers were taken from other Iranian refineries such as Shiraz refinery For example, the regressive condensed steam, as well as feeding water temperature, were considered 80 and 20 degrees centigrade respectively.

Equation (6) represents energy balance for deaerator.

$$\dot{m}_{tw}h_{tw} + \dot{m}_{d\,steam}h_{dsteam} + \dot{m}_{CR}h_{CR} = \dot{m}_{bfw}h_{bfw} + \dot{m}_{vent}h_{vent} \quad (6)$$

3.3. Gas Turbine Equations

To obtain turbines productivity power, Star software was utilized [9. Some equations of resource [10] have been used in this software.

$$W = n.m - W_{int} \quad (7)$$

$$n = \frac{L+1}{b}\,\Delta H_{iso} \quad (8)$$

$$W_{int} = \frac{L}{b}(\Delta H_{iso}.m_{max} - a) \quad (9)$$

Power change graph is a non-linear one which can be approximated by a straight line, namely Willan's line. 'n' is the slope of Willan's line and 'W' is the intercepting line. Here in equations is the length of intercepting line which is usually between 0.05 and 2. a and b are constant coefficients at the base of saturated temperature whose values for back pressure & condensing turbines are listed in Table (2).

Table 2. The constant a & b for the calculation of power at part load operation for condensing turbines and back pressure turbines

	Back- pressure turbines		Condensing turbines	
	w < 2000 kw	w > 2000 kw	w< 2000 kw	w > 2000 kw
a (kw)	1/08ΔT_{SAT}	4/23ΔT_{SAT}	0/662ΔT_{SAT}	-463+3/53ΔT_{SAT}
b (-)	1/097+/00172ΔT_{SAT}	1/155+/000538ΔT_{SAT}	1/191+/000759ΔT_{SAT}	1/22+/000148ΔT_{SAT}

4. Exergy

Exergy is the maximum useful activity which is achieved through the amount of energy a person uses from the available energy or materials. In exergy analysis, the ultimate goal is to determine the location and amount of irreversible productions during different thermodynamic cycles and investigating factors affecting irreversible production [11].

4.1. Balancing Exergy Rate for Volume Control in Steady State

Considering the point that while investigating the problem, equipment was found as a volume control in the steady state.

The amount of exergy destruction for the equipment situated in steady state can be determined using equation (10).

$$\sum_j \dot{E}_{q,j} - \dot{W}_{cv} + \sum_i \dot{E}_i - \sum_e \dot{E}_e - \dot{E}_D = 0 \quad (10)$$

Where $\dot{E}_{q,j}$ is interpreted as exergy transfer caused by energy transfer which is released as heat per unit of time.

$\dot{W}_{cv}$ indicates to the ratio of energy time to the work done. $\dot{E}_e$, $\dot{E}_i$ respectively stand for exergy transfer by the flow through volume control output and input.

$\dot{E}_D$ represents the exergy destruction time ratio because of irreversible processes inside the control volume.

$$\dot{E}_{q,j} = \left(1 - \frac{T_o}{T_j}\right)\dot{Q}_j \quad (11)$$

$$\dot{E}_i = \dot{n}_i \bar{e}_i \quad (12)$$

$$\dot{E}_e = \dot{n}_e \bar{e}_e \quad (13)$$

Where Tj, $\bar{e}_i$ and $\bar{e}_e$ respectively refer to boundary temperature, molar exergy in the input and molar exergy in output [10].

5. Economic Analysis

5.1. Thermo-economic Analysis

To calculate the costs in an exergo-economic analysis, costs balance is required Costs balance for the entire system in the stable mood which is defined as equation (14).

$$\dot{C}_{p,tot} = \dot{C}_{F,tot} + \dot{Z}^{cl}_{tot} + \dot{Z}^{OM}_{tot} \quad (14)$$

According to this equation, the rate of costs associated with system products ($\dot{C}_p$) equals the total costs associated with fuel($\dot{C}_F$), capital cost (Z_{cl}), maintenance and operations(Z_{OM}).

5.2. Exergy Flow Costing

Within the process of costing exergy flow, a cost is assigned to each flow.The cost rate of j-th material flow is considered as $\dot{C}_J$.It is defined as exergy flow rate $\dot{E}_J$ times mean cost for each exergy unit, c_j. Equation (15)

$$\dot{C}_J = c_j \times \dot{E}_J \tag{15}$$

Also, a cost is attributed to exergy transfer related to work and heat transfer based on what follows:

$$\dot{C}_w = c_w \times \dot{W} \tag{16}$$

$$\dot{C}_q = c_q \times \dot{E}_q \tag{17}$$

In these equations, c_j ، c_w، c_q represent the average cost per each exergy unit, and dollar divided by KJ measures it.

The cost rate for each material or energy flow in each system will be calculated using the cost balance equation and ancillary costs equations [11].

5.3. Equipment Cost Estimation

The best procedure for equipment cost estimation is to use manufacturer's catalogs. However, in this paper, we used cost functions for equipment cost estimation. These features have been elicited from Thermo flow software. [11]

The price of the equipment at present can be obtained by multiplying riceamount in the past to the current index ratio to the index value in the history. In equation (18) I_{new} and I_{ref} refer to current year index cost and reference year respectively.

$$C_{new} = C_{ref}\left[\frac{I_{new}}{I_{ref}}\right] \tag{18}$$

5.4. Calculating Equipment Annual Price

Since the equipment price functions are based on Dollar, the cost of purchasing equipment using the conversion factor of investment costs will be transformed to annual costs. Equation (19).

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{19}$$

Where i and n stand for interest rate and equipment life span, respectively. In this paper, the lifespan equaled 60 years, and the annual interest rate assumed to be 20%.

6. Results

6.1. The Results of Thermodynamic Analysis

6.1.1. Boilers

The kind of fuel used for the four boilers in the refinery is 4th-grade fuel oil whose net heat value is 41 $Mj.kg^{-1}$.

In this steam network, the amount of steam generated for each steam turbine was fixed, and its value was 74 $kg.\ s^{-1}$ [12] See Table (3).

Table 3. Thermodynamic Results for Boilers

scenario	the number of boiler	efficiency each boiler %	The steam generated by each boiler (kg.s^{-1})	fuel consumption each boiler (kg.s^{-1})
1	4	67	18.5	1.8
2	4	86	18.5	1.4
3	3	67	18.5	1.8

6.1.2. Steam Turbines

Since after the removal of anti-pressure valves (let down), steam flow rate passing through the valves are only devoted to B_1, B_2, C_4 turbines, it can be observed that numerical values related to these turbines vary. What's more, the amount of steam produced in the grid by the steam generator equipment was considered fixed in all scenarios. Numerical values related to all scenarios were fixed as well. (See Table 4a & 4b).

Table 4a. Power and Efficiency Turbines with Considering Letdown.

turbine	isentropic power turbine (KW)	isentropic efficiency	the actual production capacity (kw)
T1	6627.83	0.83	5478.08
T2	6995.24	0.83	5848.76
B1	708.16	0.71	503.73
B2	708.16	0.71	503.73
B4	1063.1	0.75	793.36
P1	2408.1	0.77	1855.06
P3	92.12	0.011	1.05
C4	2583.45	0.83	2147.15

Table 4b. Power and Efficiency Turbines without Considering Let down.

turbine	isentropic power turbine (KW)	isentropic efficiency	the actualproduction capacity (kW)
T1	6627.83	0.83	5478.08
T2	6995.24	0.83	5848.76
B1	1601.91	0.77	1234.85
B2	1601.91	0.77	1234.85
B4	1063.1	0.75	793.36
P1	2408.1	0.77	1855.06
P3	92.12	0.011	1.05
C4	2637.56	0.83	2198.86

If steam flow rate passing through the valves are only devoted to B_1, B_2, C_4 turbines, production capacity in the network almost 3% (which is equivalent to 5.1MW) will increase.

6.2. The Results Obtained from Thermoeconomic Analysis

As it can be observed from Table (5), power production cost rate in turbines at baseline scenario and situation 3 was more significant than scenario 2. On the other hand, scenario 2 efficiency was more than the other two. Without considering the valves, the power production cost rate in turbines B_1, B_2, C_4 was more than that of times with valves. The reason is that steam consumption increased, and as a result, the costs increased in these turbines (Tables 6a, 6b).

Table 5. The rate of steam production costs

$\dot{C}_{STEAM}(\$.s^{-1})$	Baseline scenario	scenario 2	scenario 3
boiler 1	0.307	0.239	0.307
boiler 2	0.307	0.239	0.307
boiler 3	0.307	0.239	0.307
boiler 4	0.307	0.239	0
HRSG 1	0	0	0.284
HRSG 2	0	0	0.284

Table 6a: The rate of power production costs with considering let down

$\dot{C}_{STEAM}(\$.s^{-1})$	scenario1	scenario 2	scenario 3
T1	0.1238	0.0965	0.1238
T2	0.13075	0.10186	0.13075
B1	0.01242	0.00967	0.01242
B2	0.01242	0.00967	0.01242
B4	0.01865	0.01453	0.01865
P1	0.045	0.03506	0.045
P3	0.001616	0.001259	0.00162
C4	0.03678	0.028656	0.03678
GT1	0	0	0.40165
GT2	0	0	0.40165

Table 6b. The rate of power production costs without considering let down.

$\dot{C}_{STEAM}(\$.s^{-1})$	Scenario1	scenario 2	scenario 3
T1	0.1238	0.09651	0.1238
T2	0.13075	0.10186	0.13075
B1	0.0281	0.02189	0.0281
B2	0.0281	0.02189	0.0281
B4	0.01865	0.014528	0.01865
P1	0.045	0.03506	0.045
P3	0.001616	0.001255	0.00162
C4	0.03755	0.029256	0.03755
GT1	0	0	0.40165
GT2	0	0	0.40165

6.3. The Result of Environmental Analysis

To estimate the number of environmental pollutants by devices consuming fuels, AP-42 Standard issued by environment organization was applied. Through this standard norm, one can obtain the kind of fuel and its features and the type of equipment used in which fuel is burnt. Every pollutant can be assigned a diffusion coefficient [7].

Applying this diffusion coefficient, the amount of all pollutants emission can be determined in terms of fuel flow rate. The amount of pollutants emission for three scenarios can be seen in Table (7).

Since boilers efficiency in scenario 2 was greater than baseline scenario, the amount of fuel burnt in scenario 2 was less than that of the baseline scenario. This matter decreased environmental pollutants emission compared to other times. In those three scenarios because of adding two gas turbines, the amount of pollution was considerably enhanced. Figure 2 shows CO_2 Emissions on environment.

Table7. The emissions of various pollutants in the 3 scenarios

Emissions rate ($kg.hr^{-1}$)	scenario1	scenario 2	scenario 3
CO	16.88	13.148	61.65
CO_2	79893	62242	115528
SO_2	1772	1380.6	1329
NOx	158.64	123.6	238

6.4. Results of Economic Analysis

In economic analysis, electric power price issued annually by the steam network was calculated regarding both cases with and without valves profile. Also, the cost of maintenance and repair was ignored. Performance costs only included fuel costs.

In the base scenario as well as scenario 2, no new equipment was added to the steam network. Furthermore, the annual investment costs became zero.

However, in scenario 3, because of adding a gas turbine and heat recovery steam generator to the site, the annual investment costs would not be zero. As indicated in Table (8) and Figures 3a and 3b, it can be concluded that total annual cost in scenario two toward base scenario reduced about 23%. Comparing situation three toward base scenario represents 42% decrease. But the environmental pollutants increased, consequently. As shown in Figure 3a scenario 3 was the best scenario based on the price of power generation. Also, as illustrated in Figure 3b, situation 3 was the best scenario because of TAC. Also, location 2 was in rank two because of the price of export power and TAC.

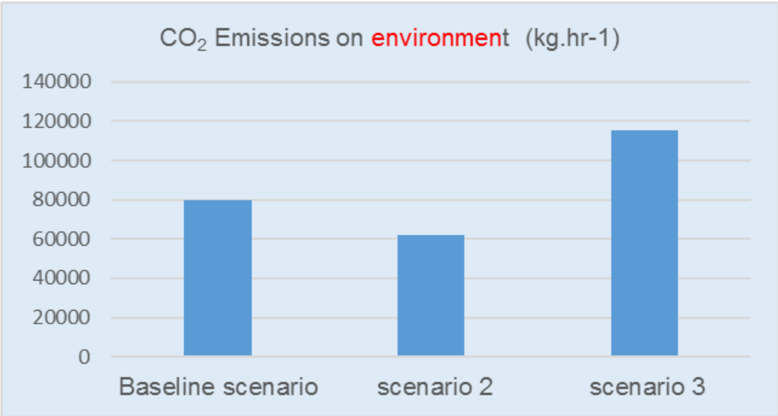

Figure 2. CO_2 Emissions on environment

Table 8. Comparison of the income from the export of electrical power produced in the scenarios

		Scenario 1	scenario 2	scenario 3
Total Electrical Power export price (MM$/Year)	Considering the Pressure relief valve	10.757	10.757	42.145
	without Considering the Pressure relief valve	11.707	11.705	43.095
Total Operating Cost (MM$/Year)		204.821	159.57	154.782
Total Capital Cost (MM$/Year)		0	0	0.323
Total Annualized Cost (MM$/Year)	Considering the Pressure relief valve	194.065	148.815	112.961
	without Considering the Pressure relief valve	193.114	147.865	112.01

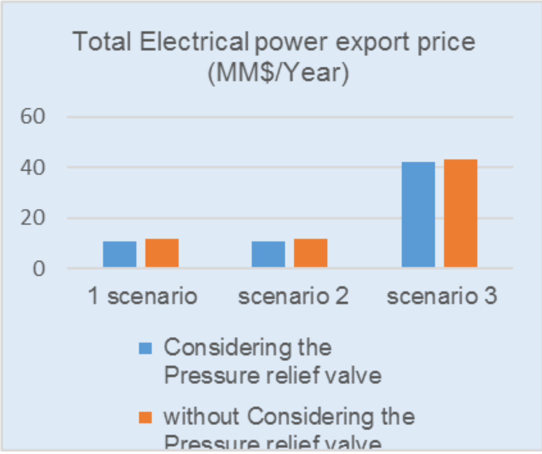

Figure 3a. Total Electrical power export price in the three scenarios (MM$/Year).

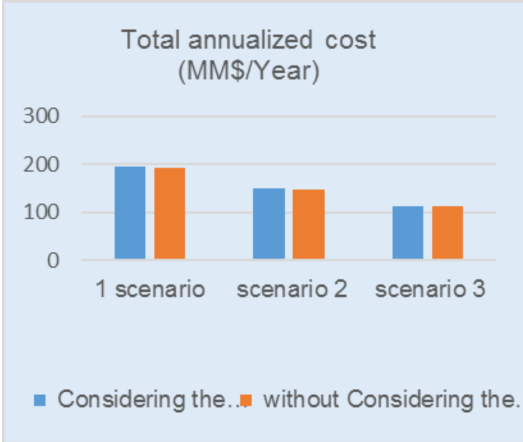

Figure 3b. Total annualized cost in the three scenarios (MM$/Year).

7. Conclusion

In this paper, exergetic, exergoeconomic, economic and emission modeling and analysis were conducted for a steam network of Tehran oil refinery simultaneously. In this regard, three scenarios were considered and evaluated. The first Scenario was a base case in which boiler efficiency was 67%. The second situation based on the boilers efficiency was 86%. The third scenario was the same as the base scenario except that one of the boilers had been removed from the site, and two gas turbines with heat recovery steam generator were proposed. After the simulation and optimization of steam network regarding Tehran oil refinery, scenario 3 was the best scenario regarding TAC and cost of power export.In addition, scenario 3 was the worst case given the emission pollution.

Nomenclature

bfw	Boiler Feed Water
boi steam	Steam Production in Boiler
d steam	Steam for Deaerator
cr	Condensate Return
vent	Steam Vent
tw	Treated Water
boi	Boiler
int	Intercept
is	Isentropic
max	Maximum
p	Product
F	Fuel
CI	Capital Investment
OM	Operation & Maintenance
$\dot{m}$	(kg.s-1) Mass flow
h	Specific Enthalpy
η	Efficiency
$\dot{W}$	(MW) Power

$\dot{E}$	(Kj.s-1) Exergy Flow
$\dot{C}$	($.s-1) Exergetic Cost Flow
T	(K) Temperature

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شبیه‌سازی و بهینه‌سازی شبکه بخار پالایشگاه نفت تهران و ارزیابی آن از لحاظ ترمودینامیکی، ترمواکونومیکی و زیست محیطی

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ترمواکونومیک

محیط زیست

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چکیده

به علت اهمیت بهینه سازی مصرف انرژی در شبکه بخار پالایشگاه، در این تحقیق به تحلیل و بهینه سازی شبکه بخار پالایشگاه تهران پرداخته شده است. در این مقاله با استفاده از مفاهیمی مانند قانون اول و دوم ترمودینامیک، مباحث ترمواکونومیکی، محیطزیستی و اقتصادی، سه سناریو پیرامون شبکه بخار پالایشگاه تهران بررسی شده است. سناریو اول، نمونه اصلی می‌باشد که راندمان بویلرها ۶۷٪ می‌باشد. سناریو ۲ مشابه با حالت اول است با این تفاوت که راندمان بویلرها ۸۶٪ می‌باشد. سناریو سوم مشابه با سناریو اول است، با این تفاوت که یک بویلر حذف می‌شود و جای آن دو توربین گازی و یک مولد بازیاب حرارتی جایگزین می‌شود و راندمان بویلر ۸۶٪ است. در نهایت میزان هزینه سالیانه در سناریو ۲ به میزان ۲۳ ٪ و در سناریو ۳ به میزان ۴۲ ٪ نسبت به سناریو اول (مبنا) کاهش یافته است. برای انجام مدل سازی ترمودینامیکی تجهیزاتی مانند توربین‌بخار، توربین‌گاز و بازیاب‌های حرارتی از نرم افزار استار استفاده شده‌است. در ادامه ارزیابی ترمواکونومیکی و محیط زیستی برای هر یک از سناریوها انجام شده و با یکدیگر مقایسه شده‌اند.