AN OPTIMIZATION APPROACH TO REFINERY STEAM MANAGEMENT WITH CONSIDERATION OF CO_2 EMISSION

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ABSTRACT

The importance of energy crisis and global warming necessitates presenting strategies in order to decrease the amount of emissions as well as fuel consumption in large and complex industries such as refineries and petrochemical industries. Generally, refinery steam networks are regarded as units which consume fuel enormously. In this paper, the steam network of Tehran Oil Refinery is considered as an industrial case study. Then, various scenarios are proposed to modify the network. In this regard, the network and suggested scenarios are initially modeled into STAR software environment. Next, they are simulated to estimate process parameters and costs. Afterwards, each scenario is separately optimized and, after comparison, the best scenario is chosen from the viewpoint of total annualized cost (TAC). The objective function of optimization is to minimize TAC. At the second stage, the amount of carbon dioxide production is calculated for all the proposed scenarios, before and after optimization. In addition, the tax of production (Kyoto Protocol) is added to the TAC of each scenario. Since in this version of STAR software, the effects of CO_2 emission have not been taken into account, a combination of the results of TAC in the software considering CO_2 and its effect on TAC has been considered as a new investigation. In fact, both economical and environmental issues are taken into account. Moreover, the scenarios are simultaneously compared with each other and the best scenario is chosen with considering carbon dioxide taxes.

Keywords: Retrofit, Steam Networks, CO_2, Economy, Optimization

INTRODUCTION

Refinery steam network is considered as a unit that greatly consumes energy. The main objective of the network is to produce the steam, which is required in different site processes. The amount of fuel consumption in steam networks is enormously high because of boilers and other fuel-consuming components. Furthermore, water consumption and treatment costs as well as maintenance cost have caused the amount of total operating cost to increase. Hence, the reduction of energy consumption significantly saves total operating costs. In addition, it is possible to reduce total annualized cost through introducing new scenarios, which improve the network performance.

Different approaches are proposed to optimize steam networks, which can be categorized as:

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(1) using renewable energy; (2) promoting the performance of the network components; (3) selling or buying the power exported or imported, which depends on political and geographical strategies of countries; (4) steam coupling between the networks and adjacent power plants; (5) using heat recovery steam generating systems and gas turbines instead of old boilers and so on. Figure 1 shows the opportunities of optimization in steam networks.

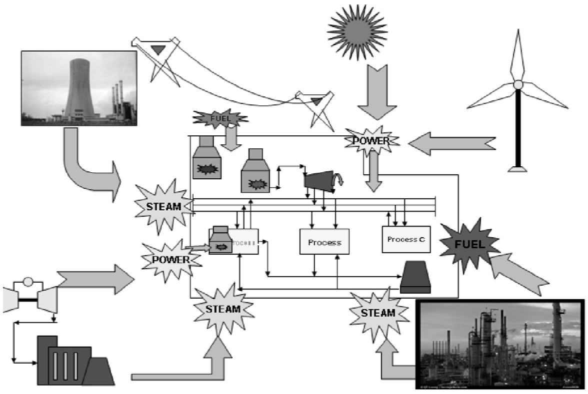

Figure 1: The opportunities of optimization in steam networks

MODELING

The multidisciplinary design optimization of system networks in large and complex industrial plants such as oil refinery and petrochemicals has been introduced by Smith [1]. Mavromatis et al. introduced a conceptual design and operation of industrial steam turbines considering superstructure models, which had been used as a main source of STAR software. The optimization techniques are simply facilitated by a mixed integer linear programming (MILP) formulation in this software [2,3]. Varabanov et al. used grand composite curves in order to extend the idea of the level analysis of steam networks [4]. Further investigations such as those by Smith et al. are also included in order to improve the software implementation in industrial case studies [5,6]. However, there is still some lack of data in terms of emissions. In this paper, by considering Tehran Oil Refinery steam network as a real case study, six scenarios have been introduced in order to achieve the minimum total annualize cost. Key information such as type of fuel consumed by boilers, steam turbine flow rates, and the amount of steam required and produced in different processes as well as the fuel prices were used as input data in the software [7,8]. Furthermore, an estimation of the reduction of CO_2 emissions from steam network devices used by Gadalla et al. [9], is applied to different six scenarios in order to consider emission and its effect on total annualized cost; however, due to the importance of emission, there is a need to use more accurate models in conjunction with the results of the simulation.

STAR Software Package

STAR is a software package for the design of site utility and cogeneration systems. The interactions between the processes on the site and the steam system, steam turbines, gas turbines (with auxiliary firing options), boiler house, local fired heaters, and cooling systems are all analyzed using STAR package. It can be used for reducing energy costs or planning infrastructure investment in situations where changes to operations on the site are anticipated or energy equipment needs to be replaced. The most effective capital investment strategy can be investigated. STAR package can also be used to investigate the reduction of flue gas emissions to meet tighter environmental regulations. A simulation of steam network in Tehran Oil Refinery considering different scenarios has been performed by using STAR in order to achieve the minimum total annualized cost; in addition, an estimation of CO_2 production and its effect on total annualized cost have been investigated [8].

In this regard, the steam network of Tehran Oil Refinery (northern site) has been considered as

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an industrial case study. Because the network is old, the amount of fuel is at a high consumption level. Additionally, since the boilers have no economizer, their exhaust temperature is high and their efficiency is low. These factors can consequently increase the amount of air pollutions especially CO_2. The networks are shown in Figure 2 [8,9]. The network consists of boilers, steam and process turbines, de-aerator, steam main headers at three levels, which are HP, MP, and LP, and two hot and cold condensate headers. The fraction of fuel consumption in boilers is generally 50 percent natural gas and 50 percent fuel oil.

Correlations and Models

Boilers

The correlations of boiler efficiency and blowdown stream have been mentioned below [1].

$$Efficiency = \frac{M}{\left[(1+B)M + AM_{Max}\right]} \quad (1)$$

where, M represents steam mass flow; M_{Max} is maximum steam mass flow and A and B stand for the coefficients of boiler efficiency (A= 0.0126, B = 0.2156).

The amount of boiler efficiency is estimated through a regression analysis. The analysis implements thermodynamic parameters such as temperature and saturated temperature, pressure, and the enthalpy of the steam supplied for HP header as well as the mass flow rate of the steam produced in the boiler; then, it plots the efficiency of the boiler versus the mass flow rate of the produced steam. Figure 3 represents the relationship between the efficiency of boiler and the mass flow rate of the steam produced.

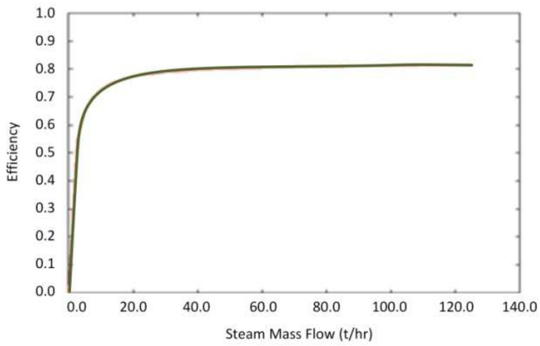

Figure 3: Efficiency of the boilers versus the mass flow rate of the steam produced

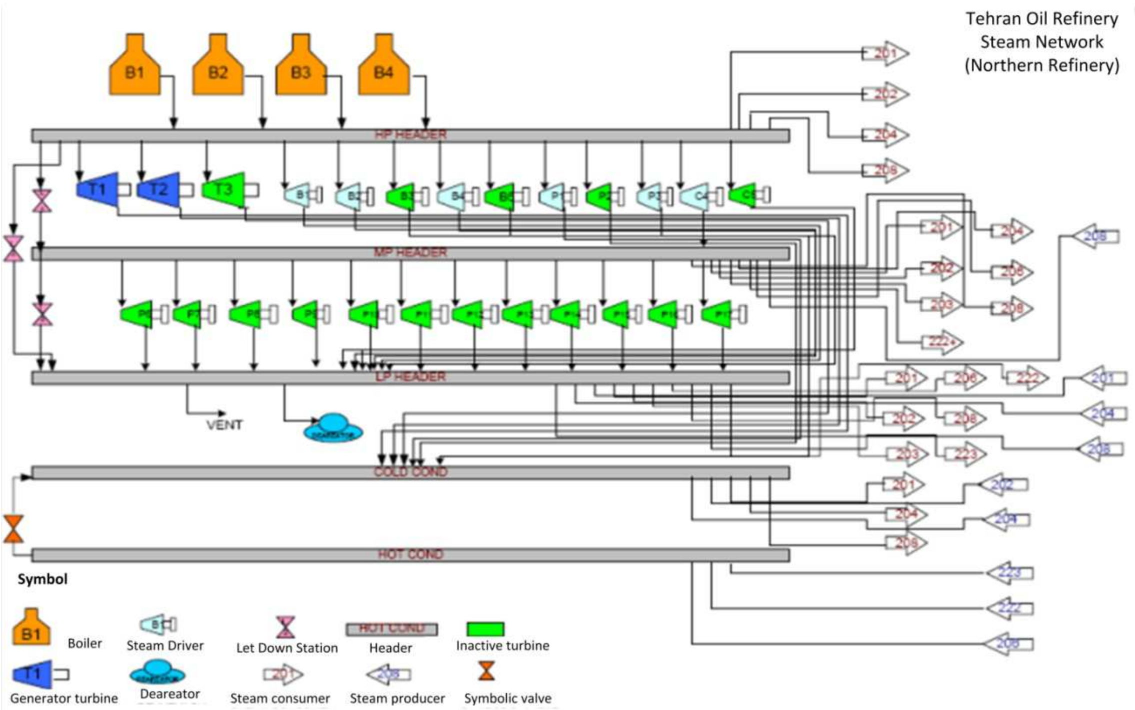

Figure 2: The steam network of Tehran oil refinery (Northern site) [10]

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Steam Turbine

The correlations that calculate shaftwork and the efficiency of steam turbines, which were initially introduced by Mavromantis [2,3], are mentioned below.

$$W = \frac{1}{\eta_{willan}}\left(\overline{\Delta H_{is}} - \frac{A}{m_{max}}\right)\left(m-(1-\eta_{max})\left(m-(1-\eta_{max})m_{max}\right)\right) \quad (2)$$

$$\eta_{is} = \frac{1}{\eta_{willan}B}\left(1-\frac{A}{\overline{\Delta H}.m_{max}}\right)\left(1-(1-\eta_{max}).\frac{m_{max}}{m}\right) \quad (3)$$

$$\eta_{willan} = \frac{W_{max}}{W_{max}+W_{loss}} \quad (4)$$

where, W is shaftwork; m represents steam flow rate and W_{loss} is internal losses. A and B are calculated as given by [3]:

$$A = 0.00423 \times \Delta T_{Sat} \quad (5)$$

$$B = 1.155 + 0.000538 \times \Delta T_{Sat} \quad (6)$$

In the power regression section, it is possible to estimate efficiency, shaftwork, outlet temperature etc. using HP header temperature and saturated temperature as well as steam turbine flow rate. Figure 4 represents the relationship between the shaftpower of turbine and its mass flow rate.

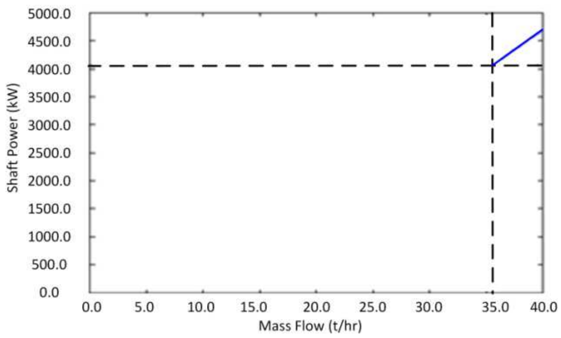

Figure 4: Shaftpower of steam turbine versus its mass flow rate

Gas Turbine

In this section, after specifying fuel type and the shaftpower of gas turbine, the software package determines exhaust temperature, mass flow rate, and heat load as well as fuel consumption and capital cost. Figure 5 shows the relationship between the efficiency of gas turbine and its shaftpower.

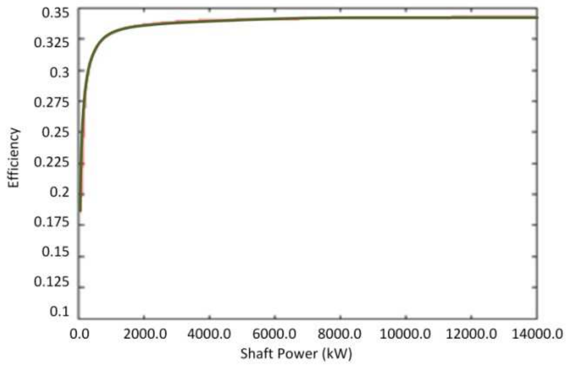

Figure 5: Efficiency of gas turbine versus its shaft power

Scenario Suggestion

Herein, different scenarios are proposed to improve the network as listed in Table 1. The scenarios 2 to 5 introduce HRSG and gas turbine under different conditions. Scenario 1 and 6 are the same, but the fuel ratio is 50% natural gas and 50% fuel oil in scenario 1, while it is 70% natural gas and 30% fuel oil in scenario 6. Generally, the fuel ratio in the proposed scenarios is fixed or variable during optimization. Since scenarios 2 to 5 introduce new equipment to the network, capital cost must be added to the total annualized cost. Figure 6 shows the steam network of Tehran Oil Refinery modified according to the new scenarios (2-5). The costs of fuels are based on the Persian Gulf zone costs, as listed in Table 2 [4].

Simulation of Tehran Oil Refinery Steam Network

After presenting the scenarios, the steam network is simulated in STAR software environ-

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ment. The simulation results such as total annualized cost, fuel heat load of all processes and equipment as well as unused heat load will be applied to the optimization phase. Figure 7 shows the simulation of the scenario 1 and 6. Figure 8 illustrates the scenarios 2 to 5 simulated by STAR software package.

Table 2: Cost of fuels based on the Persian Gulf zone costs [4]

Type of Fuel	Costs
Fuel Oil ($/ton)	348.245 ($/ton)
Natural Gas ($/ton)	209.204 ($/ton)
Imported Power ($/kWh)	0.06 ($/kWh)

Optimization of Tehran Oil Refinery Steam Network

Large and complex utility systems often have significant scope for optimization [1]. The objective function of optimization is to minimize total annualized costs. Some parameters can be limited during the optimization such as gas turbine power, the amount of the steam produced in HRSG, and fuel ratio. The optimization approach is based upon fixed header conditions such as temperature and pressure. The steam system model is first simulated and the pressures and temperatures of the steam main is remained fixed. The model is then optimized using a linear program with the temperatures of the mains remaining fixed. The re-simulation of the model then allows the temperature of the steam mains to be determined.

Table 1: The scenarios proposed to modify the steam network

Scenario	Boiler 1	Boiler 2	Boiler 3	Boiler 4	HRSG	Gas Turbine	Steam Turbine	Fuel Ratio
1 (Exist)	✓	✓	✓	✓	-	-	✓	Var. (50-50)
2	✓	✓	×	×	✓	✓	✓	Fixed
3	✓	✓	×	×	✓	✓	✓	Variable
4	✓	✓	×	×	✓	✓	×	Fixed
5	✓	✓	×	×	✓	✓	×	Variable
6	✓	✓	✓	✓	-	-	✓	Var. (70-30)

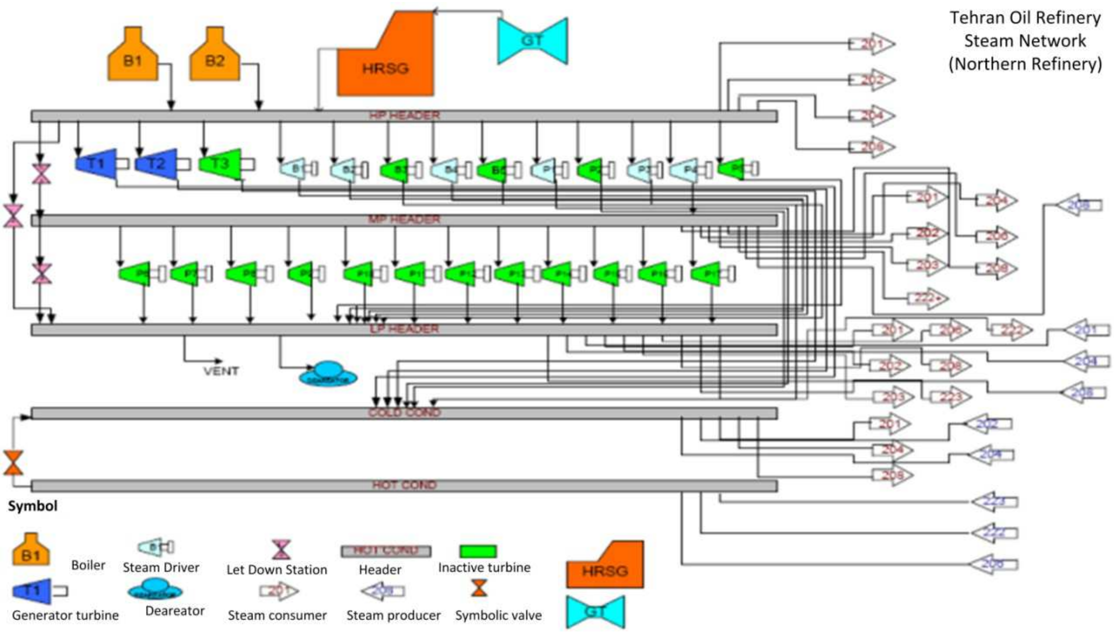

Figure 6: The steam network of Tehran Oil Refinery modified according to the new scenarios (2-5) [10]

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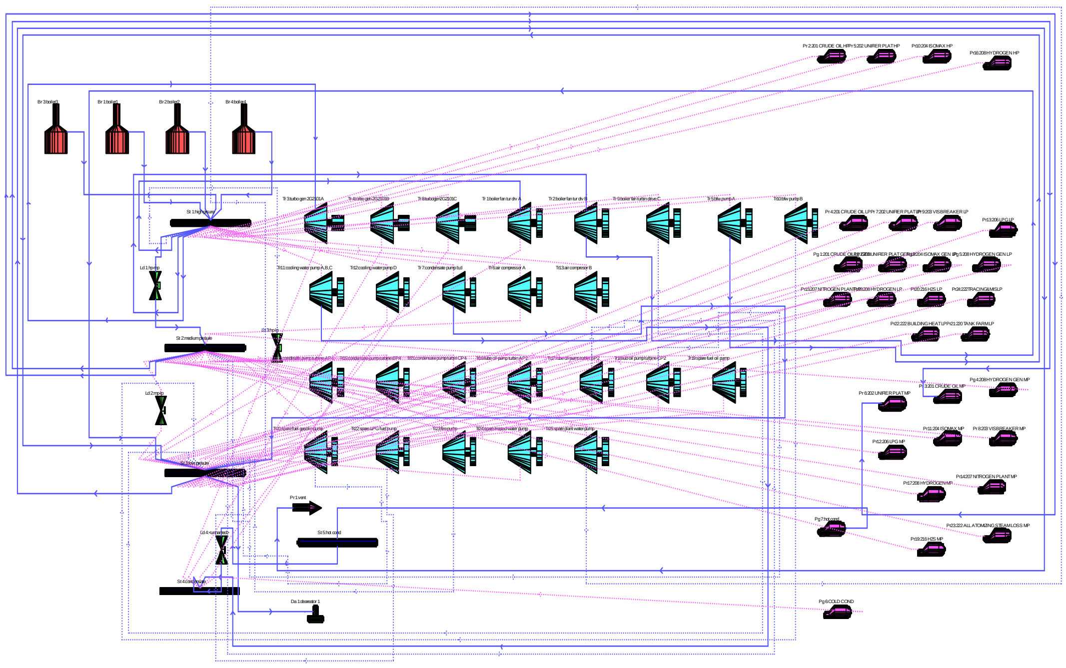

Figure 7: Simulation of the scenarios 1 and 6

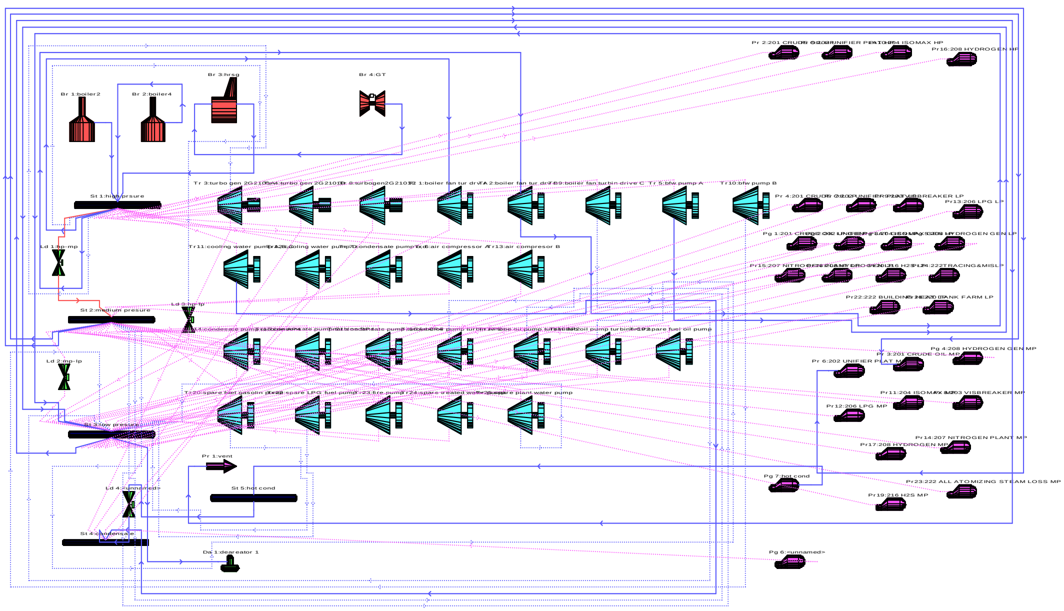

Figure 8: Simulation of the scenarios 2 to 5

These temperatures are then fixed, the model is re-optimized using a linear program and re-simulated, and so on until convergence is achieved [1,5]. During optimization, the amount of the steam consumed through the refinery units is fixed.

Let-down stations are used to increase degrees of freedom. It is not allowed to vary driver turbines power in order to directly connect them to a drive such as pumps and compressors.

The cost of steam is calculated according to the fuel cost and other costs of headers [1,5]. The cost of each steam level is the cost of the next highest level minus the value of the power generated from the expansion from the next highest level. If there are utility boilers generating steam into the lower pressure steam mains, then the cost of operating these boilers must also be added to the cost of steam at that level [1].

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Analysis of Tehran Oil Refinery Steam Network Considering CO_2 Emission

Carbon dioxide as a greenhouse gas plays a vital role in global warming. Studies show that it is responsible for about two-thirds of the enhanced greenhouse effect. In order to meet the environmental standards as agreed in the Kyoto Protocol, the chemical industries are challenged to reduce their greenhouse emissions, in particular CO_2 emissions [7,9]. Figure 9 shows carbon dioxide producing sources in steam networks. In this section, the steam network (the existing case and the proposed scenarios) in both simulation and optimization states, is analyzed from the viewpoint of CO_2 emission. The fuel is combusted when mixed with air, producing CO_2 according to following stoichiometric reaction [7]:

$$C_xH_y+\left(x+\frac{y}{4}\right)O_2\rightarrow xCO_2+\frac{y}{2}H_2O \qquad (7)$$

where, *x* and *y* denote the number of carbon (C) and hydrogen (H) atoms respectively present in the fuel compositions; the complete oxidation of carbon is assumed.

The amount of the CO_2 emitted is calculated according to the following equation:

$$M_{CO_2}=\left(\frac{Q_{fuel}}{NHV}\right)\left(\frac{C\%}{100}\right)\alpha \qquad (8)$$

where, α (equal to 3.67) is the ratio of molar masses of CO_2 and C; NHV (kJ/kg) represents the net heating value of a fuel with a carbon content of C% (dimensionless) [7,8].

Table 3 represents the net heating value of the fuel consumed together with carbon content. There are two approaches to computing Q_{Fuel}; the first is to use simulation and optimization results. The second approach is to implement the following formulas [7]:

A. CO_2 Emission for Steam Boilers

$$Q_{Fuel}=\frac{Q_{\text{Process}}}{\lambda_{\text{Process}}}\times (h_{Process}-7862)\times\frac{T_{FTB}-T_0}{T_{FTB}-T_{Stake}} \qquad (9)$$

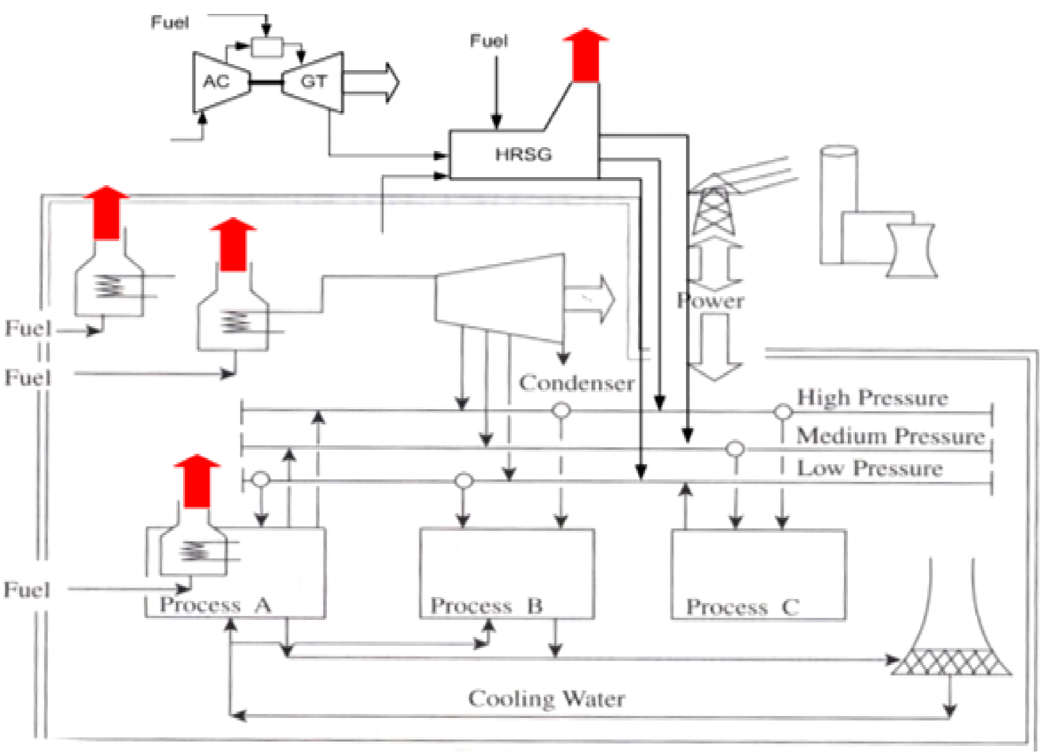

Figure 9: Sources producing carbon dioxide in steam networks [1,10,11]

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where, $\lambda_{Process}$ (kJ/kg) and $h_{Process}$ (kJ/kg) are the latent heat and enthalpy of steam delivered to the process respectively; TFTB (°C) is the flame temperature of the boiler flue gases.

Table 3: Data for heating fuels to determine CO_2 emissions [6-11]

	NHV (kJ/kg)	Carbon (%)
Fuel oil	40245	86.5
Natural gas	46151	75.4

B. CO_2 Emission for Gas Turbines

$$Q_{Fuel} = \frac{Q_{\text{Process}}}{\eta_{GT}} \frac{1}{1-\eta_c} \tag{10}$$

where, $Q_{Process}$ is the amount of fuel burnt; η_{GT} represents the efficiency of a gas turbine (dimensionless) and η_c stands for the Carnot factor (dimensionless).

$$\eta_C = \frac{T_{inlet} - T_{outlet}}{T_{inlet} + 273} \tag{11}$$

where, T_{inlet} (°C) is the temperature at the inlet of the gas turbine (combustion temperature) and T_{outlet} (°C) is the temperature at the outlet of the gas turbine (flue gas temperature).

$$Q_{Fuel\,,\,HRSG} = Q_{Fuel\,,\,Gas\ Turbine} + Q_{Fuel\,,\,Supplimmtry\ Firing} \tag{12}$$

RESULTS AND DISCUSSION

Simulation and Optimization Results without Considering CO_2 Tax

The simulation and optimization results in different scenarios are listed in Table 4. The difference between the total annualized cost of different cases in the base and optimum states are shown in Figure 10. In scenario 5, the deference between TAC in the simulation and optimization states is greater than the other scenarios. In fact, the optimum state of scenario 5 is the best from the viewpoint of TAC. Figure 11 shows the amount of fuel consumption in the proposed scenarios in both simulation and optimization states. Tables 5 and 6 show the total amount of steam production (ton per hour) in different scenarios in both simulation and optimization scenarios.

Table 4: Simulation and optimization results of different scenarios

Total Annualized Cost ($/yr)			
Scenario	**Base**	**Optimum**	**Differences**
1 (Exist)	0.572727×10^8	0.474677×10^8	-0.980502×10^7
2	0.647052×10^8	0.612986×10^8	-0.340663×10^7
3	0.538791×10^8	0.468572×10^8	-0.702188×10^7
4	0.556996×10^8	0.431071×10^8	-0.125926×10^8
5	0.556996×10^8	0.391577×10^8	-0.165420×10^8
6	0.514120×10^8	0.474677×10^8	-0.394431×10^7

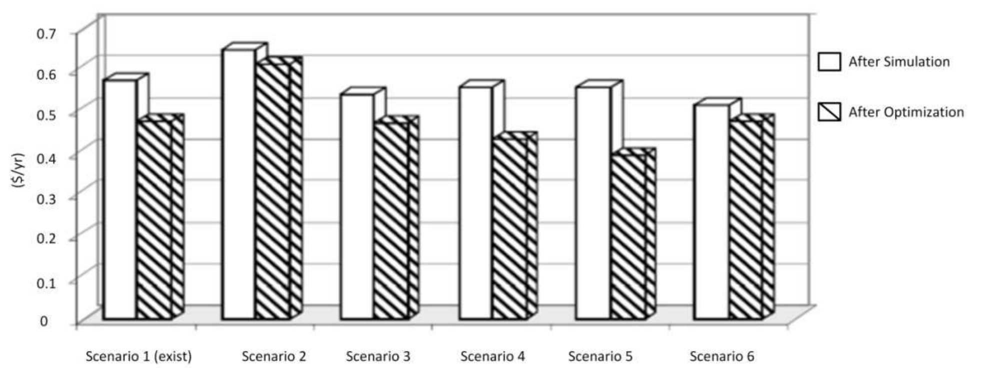

Figure 10: Difference between the total annualized cost of the proposed scenarios in the base and optimum states

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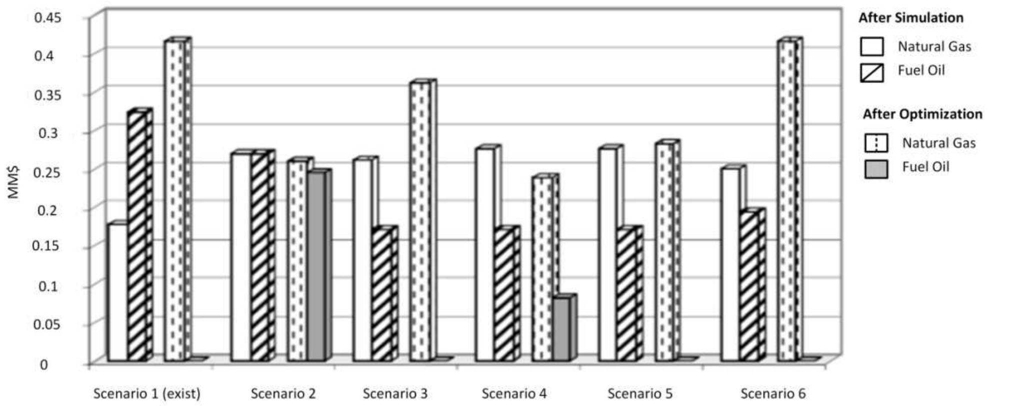

Figure 11: The amount of fuel consumption in the proposed scenarios in both simulation and optimization states

Table 5: The amount of steam production in different scenarios (simulation state)

Model	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Boiler 1	66.6	0	0	0	0	66.6
Boiler 2	66.6	85	66.6	66.6	66.6	66.6
Boiler 3	66.6	0	0	0	0	66.6
Boiler 4	66.6	86	66.6	66.6	66.6	66.6
HRSG	0	120	133.4	133.4	133.4	0
Total	266.4	291	266.6	266.6	266.6	266.6

Table 6: The amount of steam production in different scenarios (optimization state)

Model	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Boiler 1	125	0	0	0	0	125
Boiler 2	62.044	30.669	10.66	64.669	64.669	62.044
Boiler 3	0	0	0	0	0	0
Boiler 4	125	125	125	0	0	125
HRSG	0	120	140	140	140	0
Total	312.04	275.69	275.66	204.669	204.669	312.044

Table 7: Simulation and optimization results in different scenarios considering CO_2 tax

Total Annualized Cost with CO_2 Tax ($/yr)		
Scenario	**Base**	**Optimum**
1 (Exist)	63.912×10^8	52.580×10^8
2	71.846×10^8	67.602×10^8
3	60.412×10^8	51.146×10^8
4	62.510×10^8	47.556×10^8
5	62.510×10^8	42.611×10^8
6	56.300×10^8	52.580×10^8

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Table 8: The amount of CO_2 produced in different scenarios in both simulation and optimization state (ton/hr)

Scenario	Base	Optimum
1 (Exist)	50.53	38.91
2	54.34	47.97
3	49.58	32.64
4	51.83	33.86
5	51.83	26.28
6	37.05	38.91

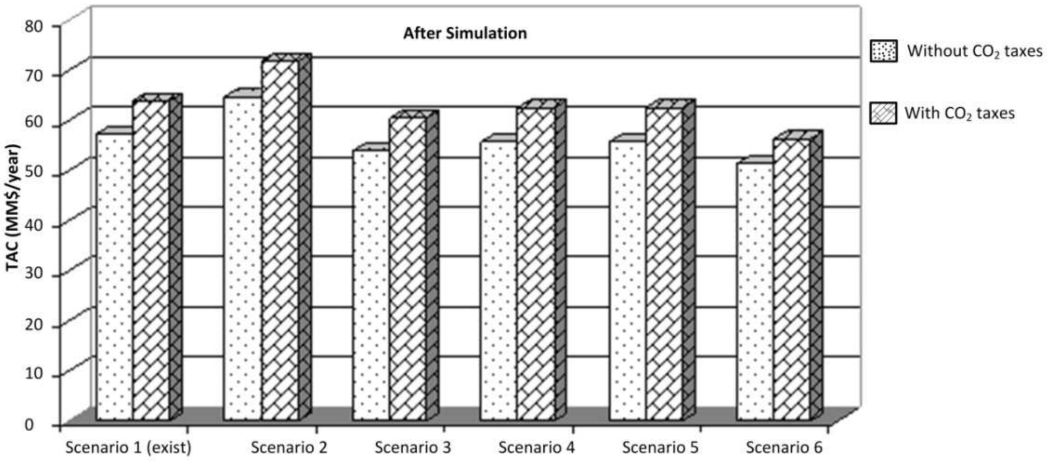

Figure 12: Total annualized cost of the proposed scenarios after simulation

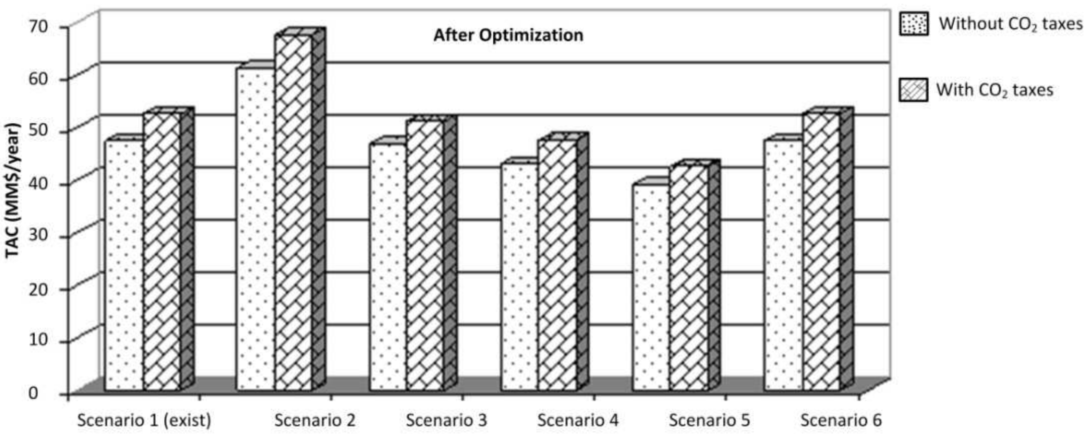

Figure 13: Total annualized cost of the proposed scenarios after optimization

As shown in Figure 11, the natural gas consumption is increased in the optimum state of the existing case. It should be kept in mind that the fuel ratio in the existing case is 100% natural gas. It is acceptable because TAC with (and without) CO_2 tax and production are significantly reduced, although the natural gas consumption is obviously increased during optimization.

Simulation and Optimization Results with Considering CO_2 Tax

After calculating the amount of CO_2 production for the components of Tehran Oil Refinery steam network, total annualized cost considering CO_2 production tax is calculated for all the proposed scenarios in both simulation and optimization states as shown in Table 7 [7,10,

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12]. In addition, the amounts of CO_2 production are shown in Table 7. Tables 7 and 8 show that scenario 5, which has been optimized, is the best scenario from the viewpoint of CO_2 production as well as TAC considering CO_2 tax.

Finally, the comparison between the results obtained from the simulation and optimization in different scenarios (with and without CO_2 tax) is shown in Figures 12 and 13. The results of the simulation (Figure 12) and the optimization (Figure 13) indicate that the amount of TAC with and without CO_2 tax is dramatically reduced after optimization in all the proposed scenarios. Scenario 5 is the best from the viewpoint of TAC (with and without CO_2 tax).

CONCLUSIONS

After the simulation and optimization of Tehran Oil Refinery steam network, the following results were obtained for the proposed scenarios. Scenario 5 was selected as the best-optimized scenario. After that, the optimized results of scenario 5 were compared with the present steam network. The comparison showed that the amount of TAC was reduced by 31%, without considering carbon dioxide tax. In addition, when the carbon dioxide tax was taken into account, the amount of TAC was decreased by 33%. Besides, scenario 5 remarkably reduced the amount of carbon dioxide production by 97% in comparison with the existing network. Therefore, it was deduced that scenario 5 was feasibly the best proposed scenario from the viewpoint of TAC as well as the amount of greenhouse gas emissions.

NOMENCLATURE

COND	Condensing header
GT	Gas turbine
HBFW	Specific enthalpy of boiler feed water
HCR	Specific enthalpy of condensate rate
HP	High pressure steam
HRSG	Heat recovery steam generator
HSTEAM	Specific enthalpy of steam
HVENT	Specific enthalpy of steam vented
HTW	Specific enthalpy of treated water
LP	Low pressure steam
M	Mass flow rate
MBFW	Boiler feed water flow rate
MCR	Steam condensate flow rate
MP	Medium pressure steam
MSTEAM	Steam flow rate
MTW	Treated water flow rate
Q	Heat load

Greek Symbols

α	Proportion of deareation steam rated
η_c	Carnot factor efficiency

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