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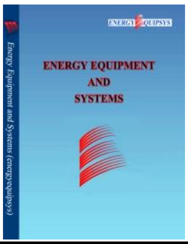

Simulation and economic evaluation of heat and power generation from flare gases in a combined cycle power plant

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ABSTRACT

In recent decades, the release of flare gases from different units of chemical industries into the atmosphere has become a substantial environmental problem all around the world. Therefore, recovery or use of flare gases has become much more critical. Combined heat and power generation from flare gases is one of the most economical methods for recovering flare gases. Two power generator gas cycle power plant or a combined cycle power plant can be used to generate heat and power. In this research, simulation and economic evaluation of heat and power generation from flare gases in a gas cycle power plant and combined cycle power plant using PRO/II v.10 software. Finally, by changing the effective operating parameters such as air to treated flare gas ratio, the outlet pressure of compressors, outlet pressure of steam and gas turbine, outlet pressure of pumps and adiabatic efficiency steam and gas turbine, heat and power generation and total capital and operating cost were investigated and analyzed. The results of simulation and sensitivity analysis showed that the use of flare gas with a mass flow rate of 9700 kg/h (mole fraction of CH_4: 0. 84) could be used to construct a combined cycle power plant with a capacity of 115 MW with an investment cost of 100 M$. This value of energy surpasses the need for an average community with 85000 families, and the excess can be sold to the national grid.

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1. Introduction

According to increasing global populations and living standards, especially in developing countries, greenhouse gas emissions have increased in recent years. To do the ever-increasing global demand for oil and gas, great quantities of co-produced gas are flared as a waste by-product, and large provisions of gas have emerged. Although this process ensures the safety of the equipment by decreasing the pressure in the system resulting from gas liberation, it is very harmful to the environment [1]. In 2015, Iran was second among regional countries, with flaring 35 million cubic meters per day of flare gas. The subject of flare gases is important from two points of view. First of all, these gases have significant economic value since they have valuable components and high energies, and

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second of all, flaring those results in destructive effects on the environment. There are several methods to recover flare gases such as: gas compression, enhanced oil recovery and using flare gases to produce gasoline and power generation [2]. The solution to using flare gas for heat and power generation is, in fact, a special case of gas consumption (treated gas flare) as fuel gas. Due to the importance and attractiveness of this solution, especially in locations away from the main electrical grid, such as offshore platforms or high-power units, the power generation from flare gas is proposed as an innovative solution [3]. The gas flow into the power plant for power generation is 80 percent methane (mole fraction). Therefore, power generation from flare gas in the oil refinery is not economically feasible, as the percentage of methane of flare gas in the oil refineries is about 15-30 percent. In fact, power generation from flare gases containing a significant percentage of methane (80-90%) can be considered as a significant strategy. Because the higher the amount of methane, the greater the amount of electricity produced. The idea of using flare gases to power generation is a specific case of using natural gases as fuel gas. Since using flare gases to generate electricity can be very important and appealing, it is proposed as an approach to power generation, especially in areas far from the main electrical grid like offshore platforms or desalination units. So, using flare gases in combined heat and power (CHP) plants has drawn much attention due to its environmental, social, and economic advantages [4].

In 2012, Rahimpour et al. studied the gas refinery of Asalloyeh with a specific volume of flare gas. In that investigation, three methods of converting flare gas to liquid using GTL, electricity generation, and compression were studied. The results showed that the return on investment (ROI) was higher in the case of electricity generation compared to the two other methods [5]. In 2016, lora et al. Studied the reduction of flare gas through power generation. This article analyzed the possible energy recovery from rather small quantities of flare gas (<2000 m^3/h), where the on-site power generation within the oil extraction field may represent a cost-effective solution as an alternative to flare combustion. The results show that by adopting a scheme with combustion engines fed by treated gas, the most cost-effective result was obtained, showing a payback time of about five years [6].

In 2016, Heidari et al. developed and analyzed two novel methods of power generation from flare gases. This study is aimed to develop two possible scenarios to reuse flare gases. The first scenario is burning the mixture of the flare gas and conventional fuel, while the second one is sending the flare gas to an intermediate stage of a gas turbine after burning it in a combustor. The results show that the first scenario is preferable from technical and economic aspects for all of the flare and natural gas flow rates except when the amount of flare flow rate in the plant is lower than 0.8 kg/s [7]. In 2017, Zolfaghari et al. studied the Technical characterization and economic evaluation of recovery of flare gas in various gas-processing plants**.** In this paper, three methods, including gas to liquid (GTL), gas turbines generation (GTG), and gas to ethylene (GTE) are introduced and compared with the best method from the economic point of view being identified. The results showed that the power generation from flare gas is very economical and with a higher annual profit than other methods [8].

In 2018, Okullo et al., studied the power generation from excess gas for Ugandan Rural Community. This paper proposes the utilization of excess gas to generate off-grid power for the rural community. A simulation of power generation from excess gas for the Ugandan rural community using Aspen HYSYS V8.8 for computational modeling was developed on thermodynamic concepts. Two systems were considered; a gas-turbine only system and a GT-with steam turbine in the bottom cycle, based on 71% CH_4 - 29% CO_2 as inlet excess gas composition. The results showed that it is possible to obtain 2.5MW of power using a gas turbine only system and an additional 1MW when a combined cycle system is considered. The results showed that this amount of energy surpasses the need for an average community with 5000 households, and the excess can be sold to the national grid to supplement deficiencies [9].

We aimed in this work, evaluate the potential of huge amounts of wasted flare gases for energy recovery in Iran. Therefore, this research studied the technical and economic analysis of heat and power generation at the gas cycle power plant and combined cycle power plant from flare gases. One of the most important goals of this paper is to convert 95% of the released heat at the gas cycle power plant into power, and its economic evaluation is based on different operational parameters. Table 1 shows the place of Iran in terms of power consumption in comparison with some other countries and ' 'world's average. This list helps to see how many people or families can use power with this amount of power generation by the power plant [10]. For example, every person in Iran consumes 300 watts of power (electricity) (1200 watt per family).

2. Materials and Methods

Asalloyeh is one of the biggest gas fields in Iran with the largest oil and petrochemical sites and significant sources for gas flaring [8]. The gas is sent to the refinery plant, and then the surplus gas is transferred to the flare system. The study has been done in this paper on a flare gas sample taken from the Asalloyeh refinery plant. Since this gas is composed mainly of methane, it was supposed that trace components of accompanying other gases were petty, and the performance using flare gas purity of 84% CH_4 and 16% CO_2, H_2S, N_2, and other hydrocarbons were analyzed. Given the nature of the flare gas commonly collected, two systems for heat and power generation are used in the simulation; a gas-turbine (GT) only system and a GT-with 10 number of the steam turbine (ST) were considered. PRO/II v.10 was used for computational modeling. PRO/II is a steady-state process simulator for process design and operational analysis for process engineers in the chemical, petroleum, natural gas, solids processing, and polymer industries. It includes a chemical component library, thermodynamic property prediction methods, and unit operations such as distillation columns, heat exchangers, compressors, and reactors, as found in the chemical processing industries. It can perform steady-state mass and energy balance calculations for modeling continuous processes. An important characteristic of PRO/II is the ability to couple with other main software such as MATLAB, Aspen HYSYS, Aspen Process Economic Analyzer, Excel, etc. In the current research, the Peng-Robinson fluid package is used for the simulation, as the most enhanced model in PRO/II v.10. The Peng-Robinson equation of state (PR) is a modification of the Redlich-Kwong equation of state and was published by Peng and Robinson in 1976 [11]. Estimation of the total capital and operating costs were performed using Aspen Process Economic Analyzer (APEA) (Version 10, 2016 pricing basis).

Table 1. Average power and electrical energy consumption in Iran compared with other countries in the year 2016 [10].

Country/Region	Electrical energy consumption (kW.h per person per year)	Power consumption (watts per person)
Word	2674	309
Iran	2632	300
China	4475	510
United States	12071	1377
India	1122	128
Russia	7841	854
Japan	7371	841
Brazil	2516	287
France	6448	736
Turkey	2578	445

2.1. Simulation process

In this section, simulation of heat and power generation from the flare is studied through PRO/II v.10 software. A gas cycle power plant (GT- only system) and combined cycle power plant (GT-ST system) are considered in this study. The goal is to refine the flare gas, separate the toxic and dangerous gas of H_2S and CO_2, and bringing the concentration of these gases to a standard and acceptable level. The treated flare gas for the generation of heat and power in the first step enters the gas station's power plant. The specifications of flare gas are tabulated in Table 2.

Flare gas [12] enters the compressor (K-100) at a temperature of 50 °C and pressure of 1 bar, so its pressure is increased to 11 bar, then it enters the heat exchanger (E-100), and its temperature is decreased to 35 °C, and after that, it goes to the membrane treatment unit. The common membranes used for natural gas sweetening have polymer structures such as polyphosphazene, polyamide, cellulose acetate, poly (ether urethane), poly (ether urethane urea), polyamide-polyether copolymers, and polyvinylidene fluoride [13]. Among the membranes studied in previous papers, PN7 and PN8 membranes from polyphosphazene type, PU4 membrane from polyurethane urea type, and Pebax 1074 and Pebax 4011 from polyamide-polyether copolymers 'membranes' type have the highest permeability and selectivity [13]. In the membrane separation unit, H_2S will be removed from flare gas down to 5 ppm. Considered parameters and characteristics for simulation of membrane unit such as the thickness of the membrane, permeability of all components are presented in Table 3.

On the other hand, the schematic diagram of the membrane unit is shown in Fig.1. In this research, the series arrangement of the membrane has been used in 7 stages. The total number of the selectivity and desired purity level for upper and lower products. Because H_2S selectivity is greater than other components in this PU4 membrane, only the stripping parts are present in this arrangement. At each part of the membrane stage, the goal is to maximize methane separating in the permeate stream so that no acid gas enters the retentate stream.

Table 2. The specifications of the flare gas and air in a membrane unit and GT-system as the input flows for simulation in PRO/II [12].

Composition	Flare gas (mole fraction)	Air (mole fraction)
Methane	0.8458	0.00
Ethane-Hexane	0.0940	0.00
H_2S	0.0052	0.00
CO_2	0.0202	0.00
N_2	0.0353	0.79
O_2	0.0000	0.21
Properties	**Flare Gas**	**Air**
Temperature (^{0}C)	50	25
Pressure (bar)	1	1
Mass flow (kg/h)	9690	164200

Table 3. Polyurethane urea (PU4) membrane specifications [14].

Specification	value
Temperature (C)	35
Pressure (bar)	10
Membrane thickness (μm)	70
Permeability of Components (Barrer)	**value**
H_2S	123
CO_2	25.4
N_2	2.31
CH_4	1.29
C_2H_6	0.12
C_2^+	0.01

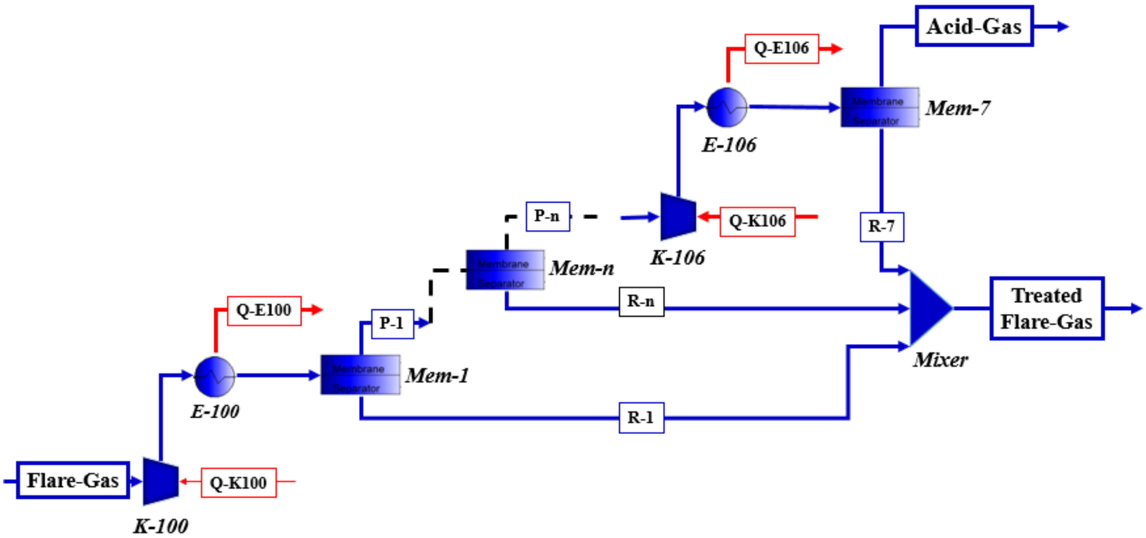

Fig.1. Simulation schematic of the membrane treatment process of flare gas [15].

The GT-system was developed basing on the Brayton cycle [16]. Where in both expansion and compression occurred in the same rotating movers (Fig.2). The GT-system consists of three main sections; the combustion chamber, compressors, and gas turbine-generator. The treated flare gas enters the compressor (K-107) after being treated in the membrane separation unit, and its pressure is increased up to 12 bar. Air is drawn in by the air compressor and delivered to the combustion chamber. The air at the temperature of 25 °C, the pressure of 1 bar, and other properties listed in table 1 enter the air compressor and its pressure is increased up to 12 bar. Outlet flows of the compressor (K-107) and air compressor enter the combustion chamber with equal pressures. Flare gas is fed to the combustion chamber as fuel where it is supposed to burn to completion. In this furnace, hydrocarbons are oxidized completely and are converted to CO_2 and H_2O. The combustion chamber outlet is mainly CO_2, H_2O, and N_2 with high temperature and pressure. To power generation, this flow enters a gas turbine, and its pressure reduces to 0.5 bar. The waste exhaust gases from the GT-system are captured by a heat recovery steam generator (HRSG) made of an economizer, superheater, and evaporator. Figure 2 shows a simulation schematic of combined heat and power (CHP) generation using a gas turbine power plant with flare gas as fuel.

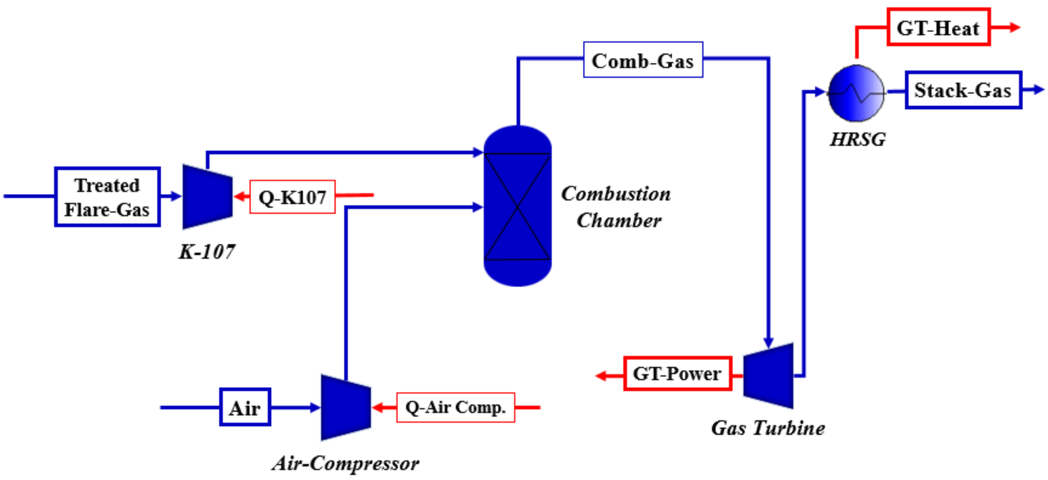

Fig. 2. Simulation schematic of combined heat and power (CHP) generation process in a GT-system [16].

Outlet combusted gas flow from the gas turbine enters the first stage of steam cycle to generate heat and power after passing the heat exchanger and generating steam (heat). The HRSG heats water in a boiler to store steam to the steam cycle which is based on the steam Rankine model. The steam expands in the steam turbine to produce power (ST power) [16]. In this step, a determined amount of net power is generated, and the heat generated in this step is used to generate steam in the next step. In this simulation, 10 steam cycles power plants are used to convert the released heat to power. Figure 3 demonstrates one stage of the steam cycle power plant. To generate power from heat, in the first step, the heat released from the combustion chamber is used, and in the next steps, the heat released from the steam condenser will be used. In Fig.4, a simulation of the process of the combined cycle power plant is shown with a gas cycle power plant and a 10-step steam cycle power plant.

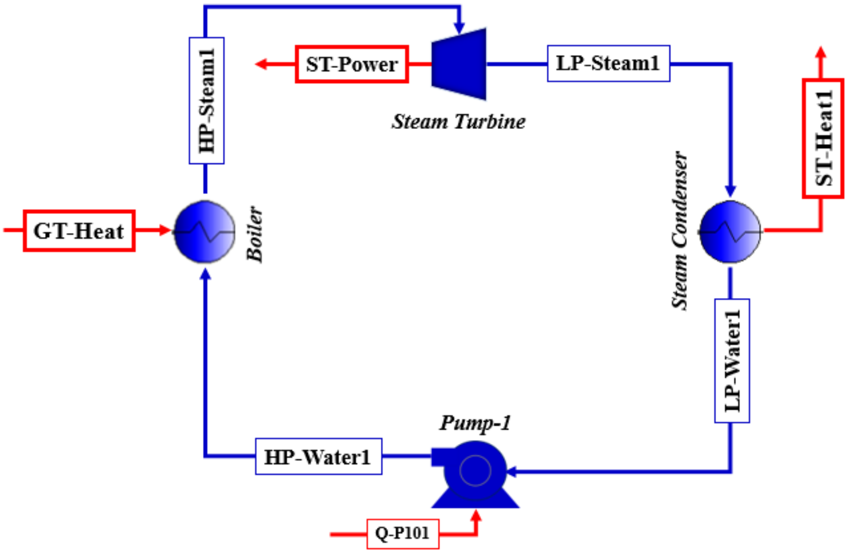

Fig.3. Schematic of one stage of ST-system [16].

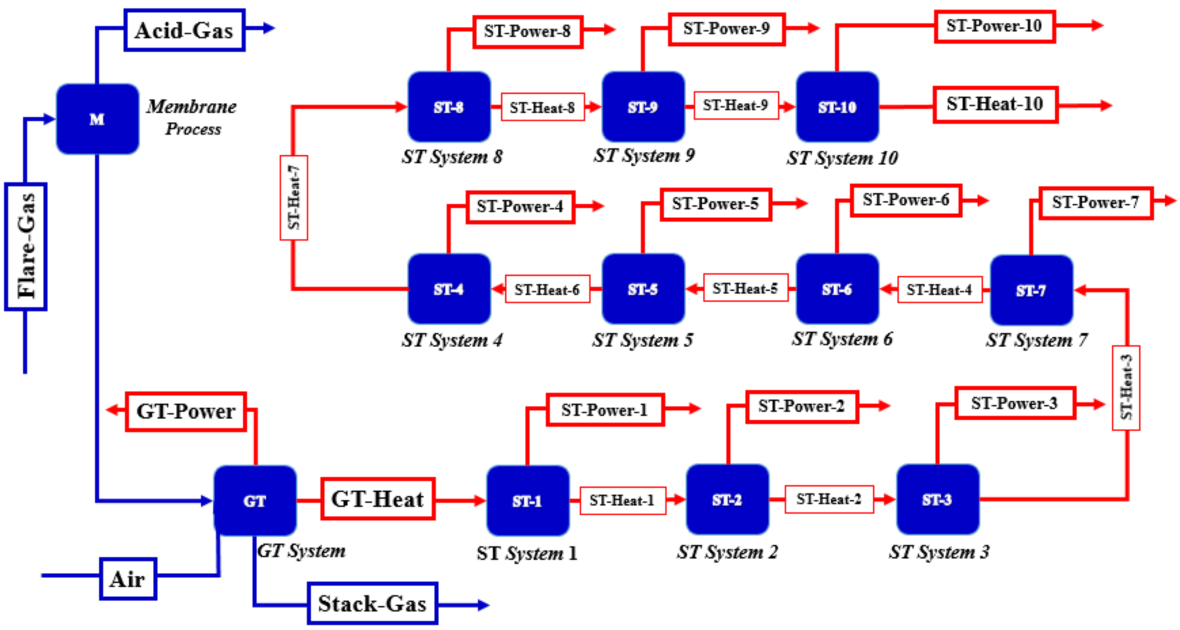

Fig.4. Simulation of combined cycle power plant (one stage of gas cycle with ten stages of the steam cycle) along with membrane treatment plant

2.2. Economic evaluation

Aspen Process Economic Analyzer uses the equipment models contained in the Icarus Evaluation Engine a knowledge base of design, cost, and scheduling data, methods, and models to generate preliminary equipment designs and simulate vendor-costing procedures to develop detailed Engineering-Procurement-Construction (EPC) estimates [17]. During the conceptual design stage, 80% of total capital costs are determined, and 95% of your total operating costs are determined at this stage. Total operating costs are typically 2-3 times the amount of total capital costs. Of course, since we have utility generation (heat and power generation) and consumption and cost of cooling water are very low, here the total operating is lower than total capital cost [18]. In economic evaluation of a chemical process, some cases such as total capital cost, total operating cost, total product sales, total utility cost, equipment cost, total installed cost, and desired rate of return are obtained. The following is a list of some of the commonly used terminology in economic evaluation with its description:

- **Installed cost** represents the total direct material and labor cost.
- **Equipment cost** represents the bare equipment cost associated with the project component.
- **The Operating Cost**: Indicates, by period, the total expenditure on the following items necessary to keep the facility operating: raw materials, operating labor cost, maintenance cost, utilities, operating charges, plant overhead, subtotal operating costs, and G and a costs (general and administrative costs incurred during production. This is calculated as a percentage of the subtotal operating costs.).
- **Total Capital Cost:** The capital needed to supply the necessary manufacturing and plant facilities is called the fixed-capital cost, while that necessary for the operation of the plant is termed the working capital. The sum of the fixed-capital cost and the working capital is known as the total capital cost. An economic evaluation of a chemical process in APEA software includes the following steps [17]:
  1. Process Simulation
  2. Adding the cost of feed and product streams (Because the purpose here is to obtain total capital and operating cost, there is no buying and selling price.)
  3. Specify the utility type
  4. Mapping unit operations to constituent equipment
  5. Sizing equipment
  6. Evaluating equipment for cost based on the sizing

The next step is the determination of the equipment. In Table 4, a list of equipment and their type is provided to estimate their equipment cost.

3. Results and discussion

In this study, simulation of heat and power generation from flare gases in a combined cycle power plant with one membrane

Table 4. A list of unit operation and equipment description

Unit operations	Description
Coolers (E-100, E-101, and E-103)	TEMA shell and tube heat exchanger
Compressor (K-100, …, K-106)	centrifugal-integral gear
Membrane (Mem-1, …, Mem-7)	Polymeric membrane (define at APEA)
Compressors (K-107 and air compressor)	centrifugal-integral gear
Conversion Reactor and Gas turbine	Gas turbine with combustion chamber
Pumps (P-100, …, P-109)	centrifugal single or multi-stage pump
Condensers (Steam Condenser-1, …, Steam Condesnser-10)	TEMA shell and tube heat exchanger
Boilers (Boiler-1…, Boiler-10)	TEMA shell and tube heat exchanger
Steam Turbine (Steam turbine-1, …, Steam Turbine-10)	Steam Turbine driver, non-condensing

treatment plant, one plant of gas cycle power plant (GT-System), and ten plants of steam cycle power plant (10 ST-systems) was carried out in the PRO/II v.10 software. Treated flare gas flow is sent to the GT-system after exiting the membrane treatment plant. Also, separated acid gas, due to the importance of the environment, should be sent to the SRU unit. Specifications of treated flare gas stream, acid gas, and stack gas stream are shown in Table 5. Outlet combusted gas flow from the gas turbine at the temperature of 1220 ℃ enters the heat exchanger (HRSG) to generate heat (steam).

As presented in table 6, 58.38 MW of power was generated in the gas turbine. 3.81 and 18.82 MW of power were consumed for the compressors of membrane treatment unit and air and treated flare gas compressor, respectively. So, in this capacity of treated flare gas, the designed gas cycle power plant generates 35.75 MW of net-power and 81.30 MW of heat. The net-power generation in the GT is derived from the subtraction of the power generation by the gas turbine from the power consumption of compressors in the membrane and GT unit.

In the GT-system or even combined cycles power plant, there is a high amount of heat release. The higher the use of this thermal energy, the higher the efficiency, profit, and return on investment (ROI). The released heat of these processes can be used for thermal uses, steam generation in different levels, drying processes, crystallization, and even increasing power generation using steam turbines. The high heat generated in GT-system, which is 81.30 MW, is a great opportunity to generate power using a steam turbine cycle power plant. As shown in Table 7, this amount of heat can be generated in the 10 ST-system to 77.43 MW of power. Therefore, this 10-ST system, along with the gas turbine cycle, can produce 113 MW of power. Finally, Table 8 shows the net heat and power generation in a combined cycle power plant (GT-system and 10 ST-system).

Table 5. Specification of treated flare gas and acid and stack gas in the membrane unit and GT-system.

Composition	Treated flare gas (mole fraction)	Acid gas (mole fraction)	Stack gas (mole fraction)
Methane	0.8693	0.2425	0.00
C2-C6	0.097	0.00	0.00
H2S	0.000	0.1389	0.00
CO2	0.0002	0.5358	0.0842
N2	0.0335	0.08228	0.7281
O2	0.0000	0.00	0.0337
H2O	0.000	0.00	0.1540
Properties			
Temperature (°C)	34	27	17.85
Pressure (bar)	11	1	0.5
Mass flow (kg/h)	9054.7	635.3	173300

Table 6. Generation and consumption of heat and power in the membrane unit and GT system.

Generation or consumption of heat and power	value	unit
Power consumption of compressors in the membrane unit	3.81	MW
Power consumption of compressors in the GT-system	18.82	MW
Power generation of the gas turbine in the GT-system	58.38	MW
Heat generation in the GT-system	81.30	MW
Net-power generation in the GT-system	35.75	MW

Table 7. Generation and consumption of heat and power in 10 ST system.

Generate or consume heat and power	value	Unit
Power consumption of Pump in the 10 ST unit	0.27	MW
Power generation of steam turbine in the 10 ST unit	77.70	MW
heat consumption in the 10 ST unit	77.43	MW
Net-power generation in the 10 ST unit	77.43	MW
heat remains in the 10 ST unit	3.87	MW

Table 8. Generation and consumption of heat and power in GT& 10ST-system.

Generate or consume heat and power	value	Unit
Net-power generation in the 10 ST and GT unit	113.16	MW
Net-heat generation in the 10 ST and GT unit	3.87	MW

In Table 9, a summary of the economic evaluation of membrane units, GT-system, and 10 stages of the ST-system are reported separately. This table shows that there is only a utility cost in the membrane unit because cooling the outlet gases from the compressors requires cooling water. Since the power consumption in the membrane unit is supplied from the gas cycle power plant, the utility cost at the membrane unit is very low. In other units, there is no utility cost, and energy is provided by the power plant itself. On the other hand, according to the table, the total capital and operating cost for the construction of this combined cycle power plant (membrane Unit+GT-system+10 ST-System) is 98 MUSD and 22 MUSD/year, respectively.

In Table 10, the values of operating parameters affecting heat and power generation, as well as the amount of total capital and operating cost and the range of changes, are presented. In the following, and Figs. 5-22, the results of variations in the effective operational parameters the power generation and total capital and operating cost have been investigated.

Table 9. Summary of the economic evaluation of membrane and combined cycle power plant unit

	Equipment Cost (MUSD)	Total Utilities Cost (MUSD/year)	Total Capital Cost (MUSD)	Total Operating Cost (MUSD/year)
Membrane Unit	6.58	0.02	19.62	2.61
GT-System	27.95	0.00	43.58	5.39
10 ST-System	15.20	0.00	34.54	13.46
Total	49.73	0.02	97.74	21.46

Table 10. A list of effective operational parameters

Effective operational parameters	Value	range	Unit
Air/Treated FG	12	7-19	
Outlet Pressure of K-107	12	1-19	Bar
Outlet Pressure of Air Compressor	12	1-19	Bar
Outlet pressure of Gas Turbine	0.5	0.2-1	Bar
Adiabatic efficiency of Gas Turbine	75	50-100	%
Outlet pressure of Steam Turbine	0.02	0.02-5	Bar
Outlet pressure of pump	20	1-20	Bar

Figure 5a shows the ratio of power-ST generation to the amount of Heat-GT vs. the increase in the number of ST-system. Increasing the number of steam turbine 'cycles' stages from 1 to 10 leads to the increment of this ratio from 26% to 95%. For example, in Fig.5b, any amount of heat-GT enters the 10 stages of the ST-system, 95% of this heat is converted to power.

Figure 6a shows heat and power generation changes vs. the increase in the number of ST-System. Increasing the number of ST-System from 0 to 10 leads to the increment of power generation from 35.74 MW to 113.16 MW and decrement of heat from 81.30 MW to 3.87 MW. Figure 6b shows total capital and operating cost changes vs. the increase in the number of ST-System. Increasing the number of steam turbine 'cycles' stages from zero to ten leads to the increment of total capital cost from 63.20 M$ to 97.74 M$ and total operating cost from 8.01 M$/year to 21.46 M$/year.

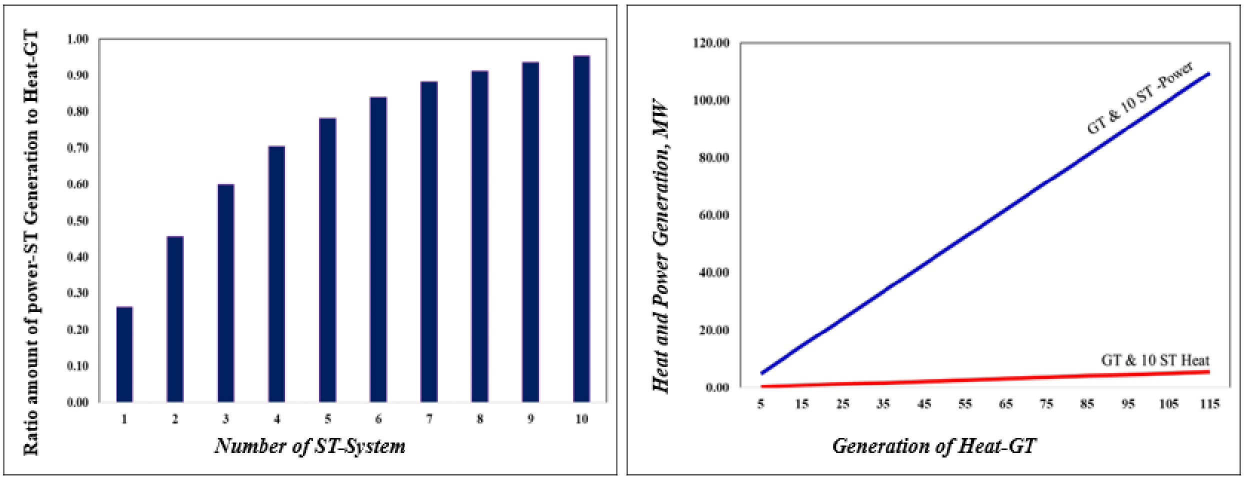

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Fig. 5. a) Ratio amount of power-ST Generation to Heat-GT versus the increasing number of ST-system, b) Heat and power generation versus increasing generation of Heat-GT

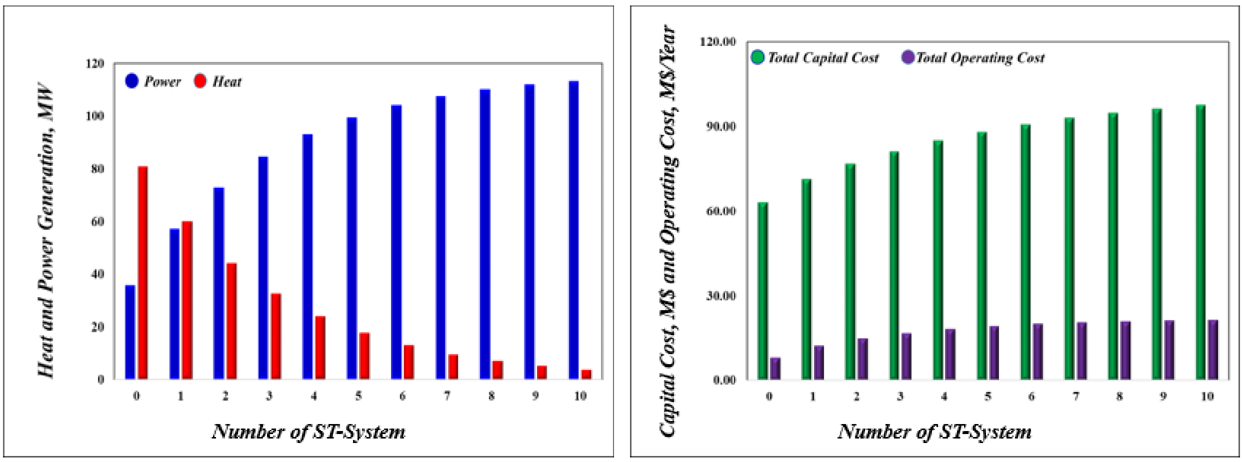

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Fig.6. a) Heat and power generation, b) Total capital and operating cost versus increasing number of ST-system

Figure 7a shows the changes in molar rate ratios of air to the treated flare gas (molar ratio) vs. heat and power generation in two layouts of the GT-only system (with no steam turbine cycles) and GT&10 ST system (gas turbine cycle along with ten cycles of steam turbines). GT-Power and GT-Heat curves are representatives of power and heat generation in the gas turbine cycle, respectively. GT&10 ST-power and GT&10 ST heat curves show power and heat generation in the combined cycle, respectively. This curve shows that by increasing molar rate ratios of air to the treated flare gas from 7 to 1۳, the amount of power generation in the GT-system is 23.55 to 35.73 MW, and the heat generation rate increased from 58.26 to 80.48 MW. In ratios higher than 13, The amount of heat and power generation will remain constant. Also, increasing this ratio from 7 to 13, the amount of power generation in the GT&10 ST-system increased from 100 to 113.15 MW. In ratios higher than 13, The amount of heat and power generation will remain constant.

Figure 7b shows that by increasing molar rate ratios of air to the treated flare gas, from 7 to 19, the total capital cost in the GT-system is 50.71 to 64.46 M$ and total operating cost increased from 6.74 to 8.63 M$/year. Also, increasing this ratio from 7 to 19, the total capital cost in the GT&10 ST-system is 78.72 to 101.51 M$, and the total operating cost increased from 16.41 to 21.85 M$/year.

Figure 8a demonstrates the changes in outlet pressure of the air compressor against heat and power generation in two layouts of gas and combined cycle power plants. This curve shows that by an increase in the outlet pressure of the air compressor from 1 to 40 bar, the amount of power generation in the GT-system is 10.96 to 38.13 MW, and the heat generation rate decreased from 105.52 to 78.35 MW. With an increase in the outlet pressure of the air compressor in the GT&10 ST-system, the amount of heat and power generation in 3.5 and 113 MW remains constant approximately. Figure 8b shows that by increasing outlet pressure of air compressor from 1 to 19, the total capital cost in the GT-system is 32.97 to 68.48 M$ and total operating cost increased from 4.44 to 8.64 M$/year. Also, increasing pressure from 1 to 19, the total capital cost in the GT&10 ST system is 73.31 to 101.72 M$, and the total operating cost will remain constant.

Figure 9a shows the gas turbine outlet pressure alterations vs. heat and power generation in two layouts of gas and combined cycle power plants. This curve shows that by increasing the outlet pressure of the gas turbine from 0.2 to 1 bar, the amount of power generation in the GT-system is 64.85 to 91.96 MW and the heat generation rate decreased from 46.33 to 26.13 MW. Also, an increase in outlet pressure of the turbine in the GT&10 ST system has no significant effect on power and heat generation, and the amount of heat and power generation in 3.5 and 113 MW remains

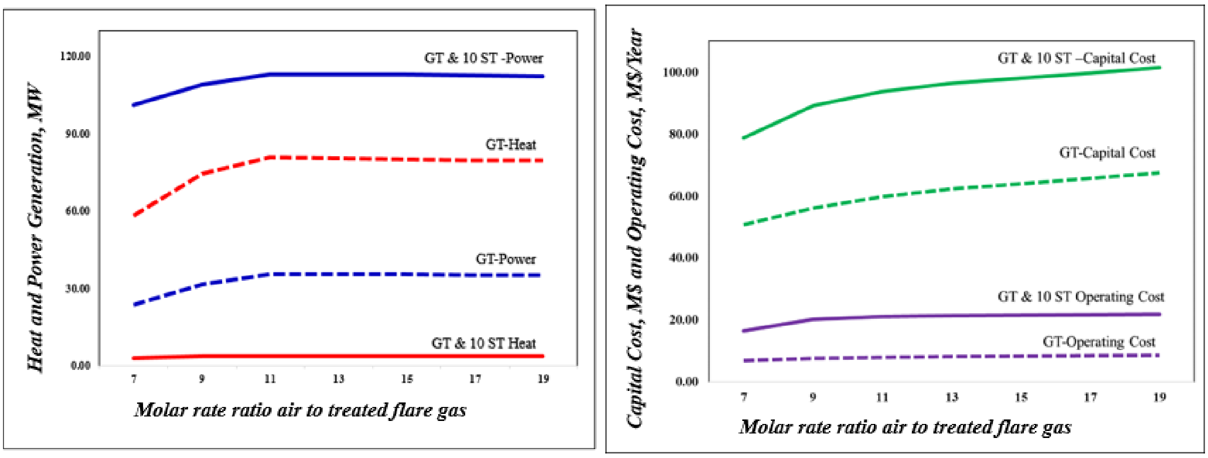

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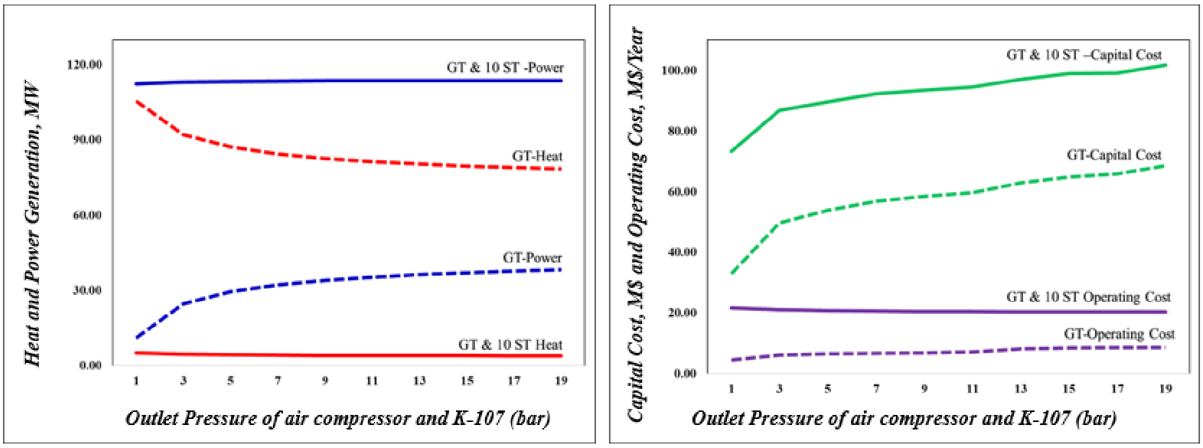
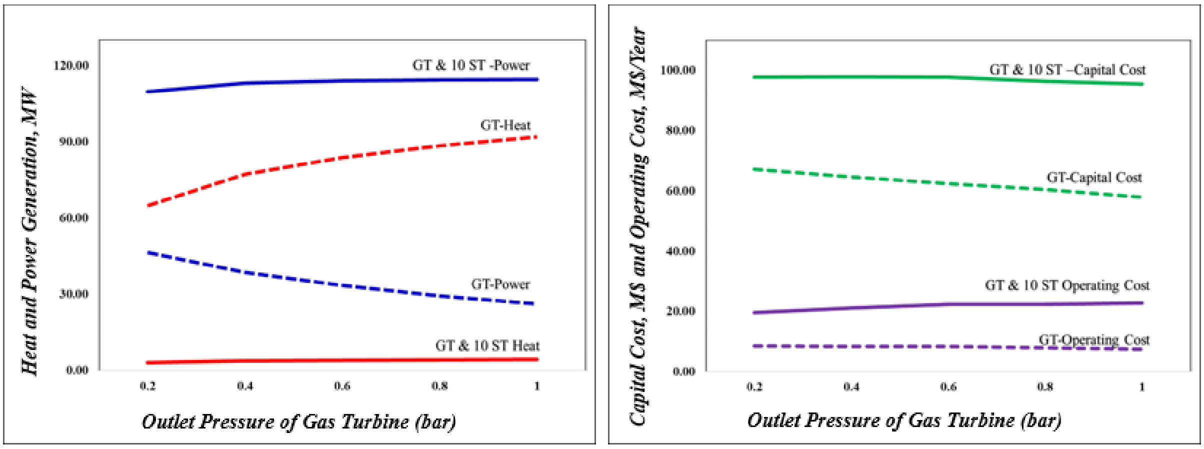
Fig.7. a) Heat and power generation, b) Total capital and operating cost versus molar rate ratio air to treated flare gas



a *b*

Fig.8. a) Heat and power generation, b) Total capital and operating cost versus increasing outlet pressure of air compressor and K-107

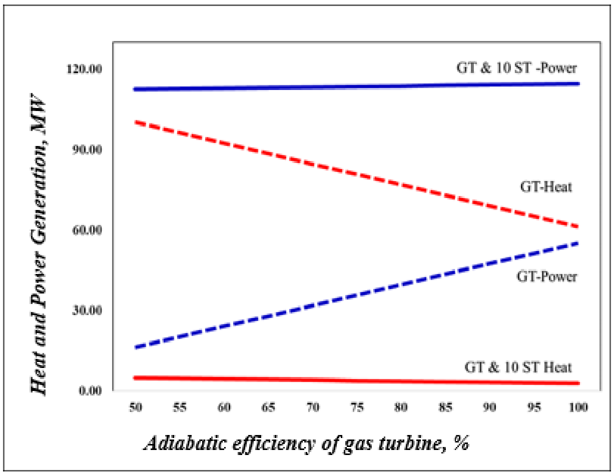


a *b*

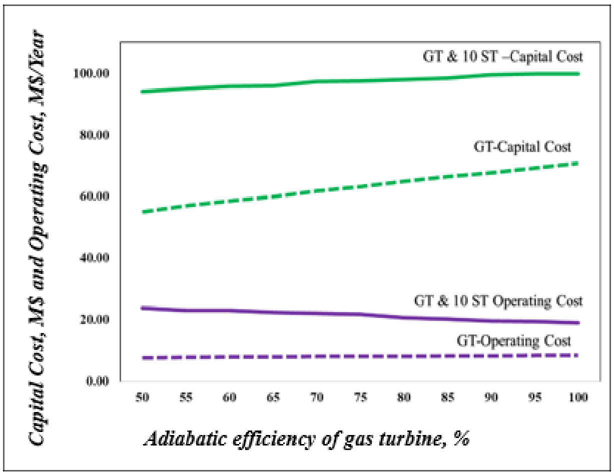
Fig.9. a) Heat and power generation, b) Total capital and operating cost versus increasing outlet pressure of gas turbine

constant approximately. Figure 9b shows that by increasing outlet pressure of gas turbine from 0.2 to 1, the total capital cost in the GT-system is 67.20 to 57.69 M$ and total operating cost decrease from 8.56 to 7.50 M$/year. Also, increasing pressure from 0.2 to 1, the total capital cost in the combined cycle power plant is 97.73 to 95.39 M$, and the total operating cost remains constant.

Figure 10a presents adiabatic efficiency changes of gas turbine vs. heat and power generation in two layouts of gas and combined cycle power plants. This curve shows an increase in the efficiency from 50% to 100%, the amount of power generation in the GT-system is 16.28 to 55.20 MW, and the heat generation rate decreased from 100.21 to 61.29 MW. Also, by increasing outlet pressure of air compressor in the GT&10 ST-system, the amount of heat and power generation in 3.5 and 113 MW stay unchanged approximately. Figure 10b shows that by increasing adiabatic efficiency changes of the gas turbine, from 50% to 100%, the total capital cost in the GT-cycle is 55 to 70.75 M$ and total operating cost decrease from 7.51 to 8.32 M$/year. Also, increasing adiabatic efficiency changes in the gas turbine, from 50% to 100%, the total capital cost in the GT&10 ST-system is 94 to 99.85 M$, and the total operating cost will remain constant.



a

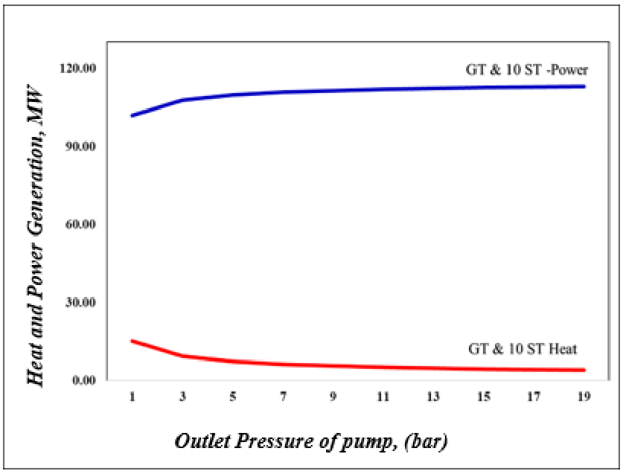


b

Fig.10. a) Heat and power generation, b) Total capital and operating cost versus increasing adiabatic efficiency of gas turbine

In Fig. 11, heat generation, power generation, total capital cost, and total operating cost, against the outlet pressure of pumps in the combined cycle power plant. They suggest that by increasing the outlet pressure of pumps from 1 to 19 bar, heat generation changes from 15.96 to 4 MW, power generation changes from 100 to 113 MW, total capital cost at 97 M$, and total operating cost at 21 M$/year stays unchanged.

In Fig. 12, heat generation, power generation, total capital cost, and total operating cost, against the outlet pressure of steam turbine in the combined cycle power plant. They suggest that by increasing the outlet pressure of steam turbines from 0.02 to 5 bar, heat generation changes from 3.87 to 32.35 MW, power generation changes from 113 to 85 MW, total capital cost at 97 M$ stays unchanged, and total operating cost changes from 21.47 to 31 M$/year.



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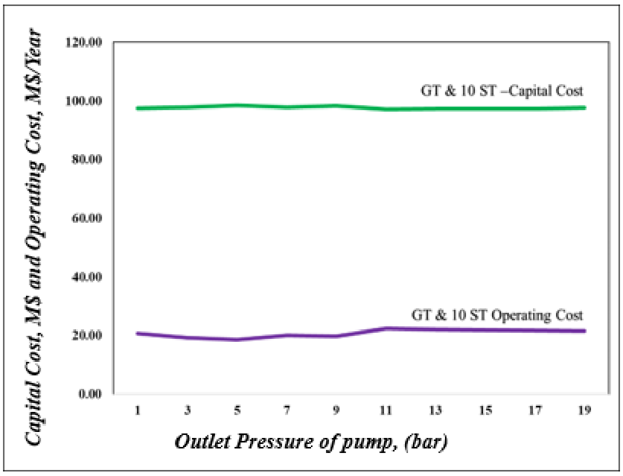
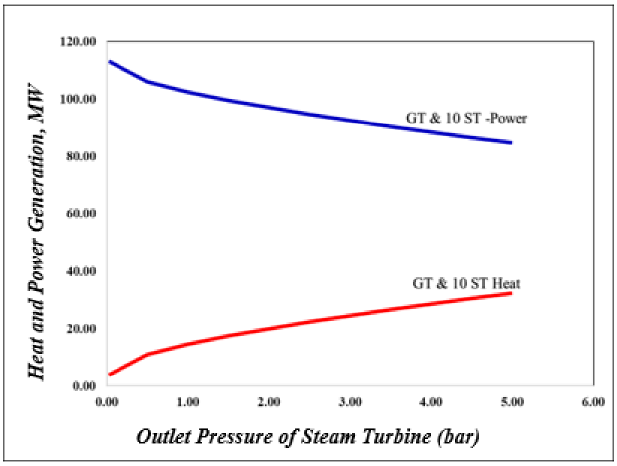


b

Fig.11. a) Heat and power generation, b) Total capital and operating cost versus increasing outlet pressure of the pump



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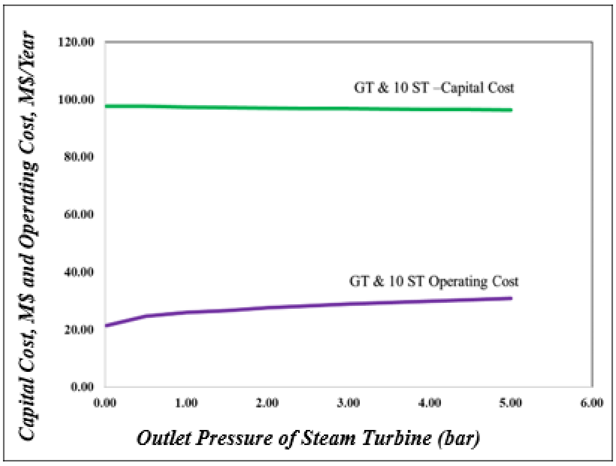

b

Fig.12. a) Heat and power generation, b) Total capital and operating cost versus increasing outlet pressure of steam turbines

4. Conclusions

A simulation of heat and power generation from flare gases was conducted for use in the cities near to the refinery as well as the refinery itself using PRO/II. The economic evaluation of this simulation was also done in the Aspen Process Economic Analyzer. In this study, flare gas was used as an alternative fuel for natural gas to simultaneously generate heat and power in a combined cycle power plant. Since the flare gases of some regions, petrochemical complexes, and refineries have toxic acidic components like hydrogen sulfide that are harmful to the environment, humans, and equipment, these flare gases must be treated before use. Membrane treatment technology is a very desirable method for treating flare gases and has advantages such as: being cost-effective, environmentally friendly, safe, and having low energy and utility use. Utility and energy uses in the membrane treatment process include cooling water of heat exchangers and electricity uses of compressors. The whole required power of compressors of the membrane treatment unit is supplied by the power generated in a gas turbine in the combined power and heat system of flare gases. Therefore, the utility and energy costs of the membrane treatment unit are limited to the cooling water use only and are very cost-effective. The net power generated in the combined cycle power plant is the difference of (power generation in gas and steam turbines) and (power consumption of membrane unit compressors, air compressors, and sweetened flare gas compressors and pumps).

The proposed utilization of flare gases for power generation in this study is done basing on a target to generate at least 100 MW of power. For a treated flare gas with a gas flow rate of 9055 kg/h (1075 m^3/h) for a single gas turbine GT-system (Considering the supply of membrane unit compressors), the net power obtained from the system is 36 MW, which is available for use by the community. To increase power generation, the heat generated by the GT-system can be used. To generate more power, the number of steam turbine cycles can be increased so that a 10-stage turbine cycle can be used to convert 95% of the heat to power. For a combined cycle power plant (GT-10 ST) system, an extra 77 MW can be generated for the community to give a total net of 113 MW. This amount of energy surpasses the need for an average community with 85000 families, and the excess can be sold to the national grid to supplement deficiencies. The results of the economic evaluation showed that for the generation of every 1 MW of power, a total capital cost of about 1 M$ is required. The results show that with the increase of the outlet pressure of compressors, pumps, adiabatic efficiency of gas (or steam) turbine and a decrease in outlet pressure of steam turbines in the GT-only system (without a steam cycle power plant), power generation will increase and heat generation will decrease. But here, a GT&ST-system (a gas cycle along with a steam cycle) is used and the results show that any further increase in the mole ratio of air to treated flare gas from 10, ' 'compressor's outlet pressure increase and gas and steam 'turbines' outlet pressure decrease has no sensible effect in heat and power generation. Since the 10 ST-system converts about 95% of the heat to power, the amount of heat generation in the GT-system will decrease or increase until the amount of power generation remains constant.

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