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Techno-Economic Assessment of Different Inlet Air Cooling Systems in Warm Dry & Wet Climate Stations

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Abstract

Performance of a gas turbine mainly depends on the inlet air temperature. The power output of a gas turbine depends on the flow of mass through it. This is precisely the reason why on hot days, when air is less dense, power output falls. The objective here is to assess the advanced systems applied in reducing the gas turbine intake air temperature and examine the merits from integration of the different air-cooling methods in two 25 MW gas-turbine-based gas pipeline stations. Four different intake air-cooling systems are applied in two pipeline gas stations. The calculations made on annual basis of operation.

The techno-economic and exergoeconomic analysis of heat recovery of gas exhaust is assessed for Turbo-compressor Station through this proposed inlet air cooling system. Modifications are applied on a MAPNA 25 MW gas turbine in compressor station. The configuration of gas turbines in compressor station is based on (3+1) arrangement. In this context, a heat recovery steam generator and a steam turbine are added for three gas turbines as a proposed combined cycle.

The case study is run on Assaloyeh and Qom pipeline gas stations in Iran Gas Trunk line 8. Thermodynamic simulation, mechanical design and economic analysis are run in Thermoflow (GT PRO module) software. The thermodynamic, economics and exergoeconomic parameters from integration of different cooling systems in this proposed combined cycle are calculated and compared.

Keywords
Integration, Gas-to-liquid, Fischer – Tropsch, Exergy

1. Introduction

Gas turbines are designed to operate with a constant air volume flow in the compressor. Due to the inverse relation between air density and temperature, the performance and power output of a gas turbine decrease as the ambient temperature increase. Cooling the inlet air to the compressor of a gas turbine system is a low-cost option for preventing a loss of power or even increase in its power output. There exist several methods for reducing gas turbine inlet temperature. Cooling the turbine inlet air of gas turbine even by a few degrees can increase power output in a significant manner. This is because the cooled air is denser, giving the turbine a high mass-flow rate while the work required to compress air is directly proportional to the air temperature that is, a reduction in inlet air temperature would reduce the work of compression and lead to an increase in turbine power output and efficiency.

Energy systems are involved in a large number and various types of interactions with the world outside their physical boundaries. The system designer must, face many issues, which deal primarily with the energetic and

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economic aspects of the system. Thermodynamic laws which govern energy conversion processes, costs involved in obtaining the final products and the effects of undesired fluxes to the ambient must be assessed in order to answer environmental concerns.

The second law analysis is widely applied in the last several decades by many researchers. Exergy analysis usually predicts the thermodynamic performance of an energy system and the efficiency of the system components by accurately quantifying the entropy generation of the components [1]. Furthermore, exergoeconomic analysis estimates the unit cost of products like the electricity, steam and quantifies monetary loss due to irreversibility. This analysis provides a tool for the optimum design and operation of complex thermal systems (Ahmadi & Toghraie, 2016; Lugo-Leyte et al., 2016; Saeidi, Mahmoudi, Nami, & Yari, 2016).

The objective here is to review the contemporary applications in reducing gas turbine intake air temperature and examine the merits from integration of the different air-cooling methods in 25 MW gas-turbine-based pipeline gas stations (Mazhari, Khamis Abadi, Ghalami, Khoshgoftar Manesh and Amidpour, 2012). Four different intake air-cooling methods are applied in two pipeline gas stations. The calculations are performed on an annual operation basis.

The Assaloyeh and Qom pipeline gas stations in Iran Gas Trunk line 8 are the subjects of this case study. The simulation is run in Thermoflow (GT PRO module) Software.

Thermoflow is one of the best software in simulating processes concerned with power and heat (e.g. power plants). This software was introduced in 1987 and it has become the most popular simulator of power producing process. Thermoflow has various modules like GT-PRO, STEAM-PRO, PEACE, THERMOFLEX etc. These modules are capable to meet any necessity in power producing matters by applying different methods of analysis like thermodynamic and exergy analysis and real and reliable data banks gathered from famous corporations.

Module GT PRO automates the process of designing a combined cycle or gas turbine cogeneration plant and is particularly effective for introducing new designs finding their optimal configuration and design parameters. The user feeds the design criteria to assumptions and the program and the latter computes the heat and mass balance, system performance, and component sizing. The scope and level of the details in GT PRO has enjoyed continuous growth since 1988, to the point that its 2008 version has over 3000 user-adjustable inputs. Most key inputs are developed through intelligent design procedures which assist the user identify the best design with the least time and effort, while allowing flexible changes or adjustments. GT PRO is easy to use, and requires only a few minutes to come up with a new plant design. It normally computes a heat balance and simultaneously designs the required equipment within five seconds. When run in conjunction with the optional PEACE module, the programs provide extensive engineering and cost estimation details (THERMOFLOW, 2014). The mechanical design and cost estimation of power plant can be performed through Thermoflow (GT PRO module).

The Matlab code is developed for exergoeconomic analysis of each case. Finally, the thermodynamic, economics and exergoeconomic parameters from integration of the different cooling systems are calculated and compared.

2. Process Description

The lengths of gas transporting pipelines are almost thousands of kilometers making, a number of compressor stations, which consume a significant amount of energy necessary along the path.

In this article, two such stations are of concern: the Assaloyeh and Qom gas stations in Iran Gas Trunk line 8. Power generation by integrating three 25 MW gas turbines with a HRSG and a steam turbine are proposed. To improve the efficiency of the compressor stations, four different intake air-cooling methods are adopted in both the stations. Here, the following cooling technologies are assessed for intake air-cooling:

1. Evaporative cooling
2. Fogging
3. Electric chiller
4. Absorption chiller

The schematic of this proposed cycle with inlet air cooling systems, Heat Recovery Steam Generator (HRSG), steam turbine and air cooled condenser are illustrated in Fig. (1). The calculations are run on an annual operational basis. The simulation is run in Thermoflow Software. Technical characteristics of the Qom and Assaloyeh pipeline gas stations and these proposed cycles are tabulated in Table 1.

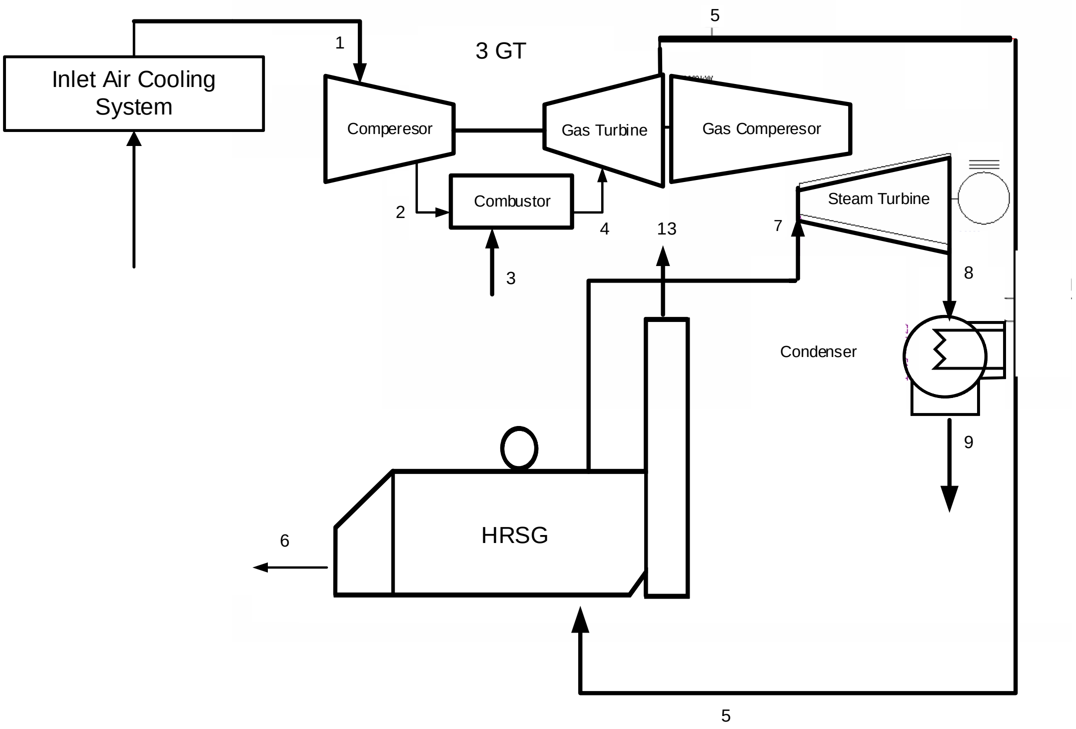

Figure 1. The Schematic of this Proposed Combined Cycle

Table 1. Specifications of the Gas Station Power Plant System

Parameter	***Unit***	***Value***	
		Qom	**Assaloyeh**
Site Level	*m*	*929*	*5*
Air Compression ratio	-	*20*	*20*
Gas transport Capacity	*MMSCMD*	*110*	*110*
Station Suction Pressure	*Psig*	*980*	*970*
Station Discharge Pressure	*Psig*	*1305*	*1305*
Station Inlet Temperature	*°C*	*42*	*40*
Station Outlet Temperature (Max.)	*°C*	*50*	*50*
Gas turbine efficiency	*%*	*87*	*87*
Inlet water temp	*°C*	*15*	*15*
Compressor power consumption	*MW*	*50.5*	*52.3*

The proposed algorithm for techno-economic and exergoeconomic assessment is presented in Fig. (2) the first step by considering the operating condition, plant criteria, gas turbine selection, combined cycle configuration and equipment's characteristics, the thermodynamics simulation and performance analysis are obtained and in second step, information derived from first step is applied in calculating the amount of exergy destruction of each equipment.

In the third step, the equipment costs are extracted from GT-PRO's data banks. The update cost index parameters

(Chemical Engineering Economic Indicators, (2017)) is applied to update equipment costs for each case. In addition, the cost input data of fuel, water and interest rate must be feed to the GT PRO economic input. The cost estimation and economic analysis are run in PEAC of GT PRO.

In the fourth step, through the information obtained from second and third steps and exergoeconomic modeling in Matlab, exergy product cost is calculated.

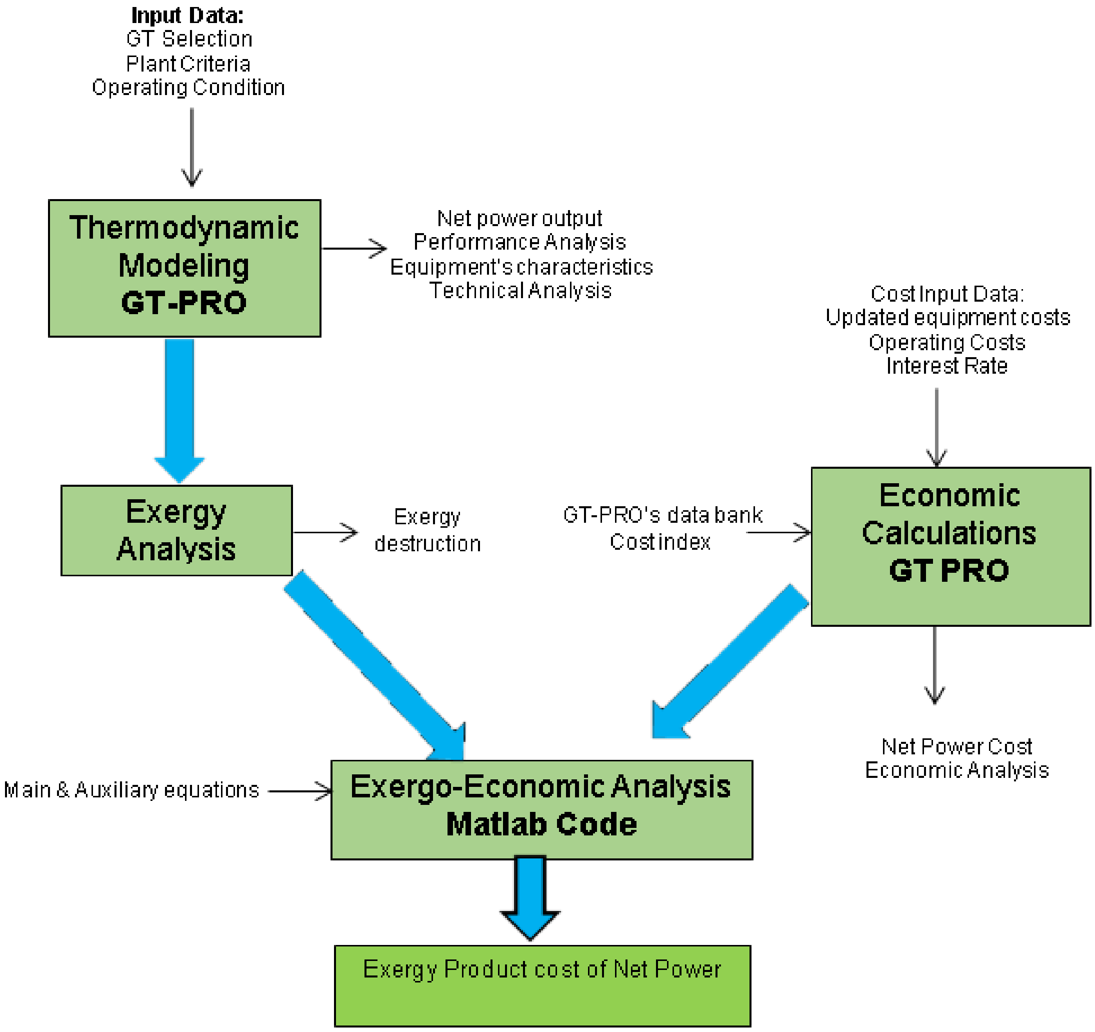

Figure 2. Algorithm of Techno-Ecnomic & Exergoeconomic Evaluation

3. Exergy and Exergoeconomic Analysis

Exergy is the maximum theoretical approach attainable from an energy carrier subject to conditions imposed by an environment at given pressure $P0$ and temperature $T0$, together with given amounts of chemical elements (Bejan, Tsatsaronis, & Moran, 1996). The purpose of an exergy analysis, in general is to identify the location, the source, and the magnitude of true thermodynamic inefficiencies in thermal systems.

By not considering the kinetic and potential energy changes the specific flow exergy of a fluid at any cycle state is expressed by:

$$e = h - ho - To(s - so) \quad (1)$$

The reversible work, as a fluid goes from an inlet state to an outlet state, is determined by the exergy change between these two states:

$$e2 - e1 = h2 - h1 - To(s2 - s1) \quad (2)$$

where, the subscripts 1 and 2 represent the inlet and outlet states for a flowing fluid.

All plant operating costs depend on the type of financing, the required capital, component life expectancy etc. The annualized (levelized) cost method of Moran is applied in estimating the capital cost of system components in this study. The amortization cost for a particular plant component is expressed as:

$$PW = Ci - SnPWF(i, n) \quad (3)$$

$$CC\ (\$/\ Year) = PW \times CFR(i, n) \quad (4)$$

The present worth of the component is converted in to annualized cost through the capital recoveryfactor CRF(i,n), (Kwak, Kim, & Jeon, 2003). Dividing the levelized cost by 8000 annual operating hours, obtain the following capital cost for the k^{th} component of the plant is obtained.

$$Zk = \Phi k\ CkC\ /(3600 \times 8000) \qquad (5)$$

The maintenance cost *factor* for each plant component the life expectancy of which is assumed to be 15 years determined through $\Phi k = 1.06$ (Kwak et al., 2003).

The results obtained from an exergy analysis constitute a unique base for exergoeconomics, an exergy-aided cost reduction method. A general exergy-balance equation, applicable in any component of a thermal system may be formulated by applying the first and second law of thermodynamics (Peng, Wang, Hong, Xu, & Jin, 2014; Sharma & Singh, 2016; Wang, Wu, Yang, Yang, & Fu, 2014; Zare & Hasanzadeh, 2016; Zhang, Wang, Zheng, & Lou, 2006).

The cost balance expresses the cost rate associated with the product of the system (CP); the cost rates that equal to total rate of expenditure made to generate the product, namely the fuel cost rate (CF), the cost rates associated with capital investment (ZCI), operating and maintenance (ZOM) (Bejan et al., 1996).

In a conventional economic analysis, a cost balance is usually formulated for the overall system (subscript tot) operating at steady state [11]:

$$C\,P\,,tot = C\,F\ \,,tot + C\,L\,Z\,tot \qquad (6)$$

Accordingly, for a component receiving a heat transfer and generating power, the following relation by (Bejan et al., 1996) is expressed:

$$\sum \dot{C}_{\mathrm{in},k} - \sum \dot{C}_{\mathrm{out},k} + \dot{C}_{\mathrm{W},k} + \dot{C}_{\mathrm{Q},k} + \dot{Z}_k \qquad (7)$$

To solve the unknown variables, it is necessary to develop a system of equations by applying Eq. (6) to each component, and it some cases if necessary apply some additional equations, to make the number of unknown variables fit the number of equations (Arriola-Medellín, Manzanares-Papayanopoulos, & Romo-Millares, 2014; Cziesla & Tsatsaronis, 2002; Khoshgoftar Manesh & Ameryan, 2016; Khoshgoftar Manesh et al., 2014).

In application of the cost balance equation Eq. (8) application, there usually exist more than one inlet outlet streams for some components. In this case the number of unknown cost parameters is higher than the number of cost balance equations for that component. Auxiliary exergoeconomic equations (according to rules P and F) are developed to solve this problem.

4. Results and Discussions

In this article, the simulation is run in Thermoflow (GT Pro module) Software for thermodynamic simulation and analysis of Qom and Assaloyeh pipeline gas station with different inlet air cooling systems. The Monthly Net extra Electric Energy Production of Qom pipeline gas station without any inlet air cooling systems is shown in Fig. (3).

Both Qom and Assaloyeh are arid zones in Iran; therefore, the inlet water cost in these areas is considered in techno-economic assessments. Consequently, the inlet water to air cooling systems can specified in GT-PRO and also in the exergo-economic equations in Matlab.

The effect of cooling technology on the net power capacity enhancement for the plant is shown in Figure 4, where the air is cooled through its ambient dry bulb temperature up to 10°C by Chillers and the Lowest Possible Temperatures with Evaporative Cooling (85%) and Fogging (98%) aapproaches**.**

Assessing the results obtained through Thermoflow (GT PRO) software, it is revealed that excessive cooling the inlet air of compressor is not only useless but it decreases the plant efficiency and net power output and increases the produced electricity cost.

Moreover, using the chiller type for inlet air cooling system enhances the net power output, while reduces the plant efficiency and increases the produced electricity price.

By checking out the results concerned with Assaloyeh, it is found that evaporative and fogging types for inlet air cooling are not feasible in this station, since the temperature drop in this cases is not significant. This phenomenon can be due to Assaloyeh's high HR rate.

Comparing the results obtained from Assaloyeh and Qom stations with it can be deduced that the plant efficiency in Qom is more than Assaloyeh, but net power output in Assaloyeh is more and this is because Qom is located at high MSL.

Moreover, Qom power plant electricity price is less than that of Assaloyeh.

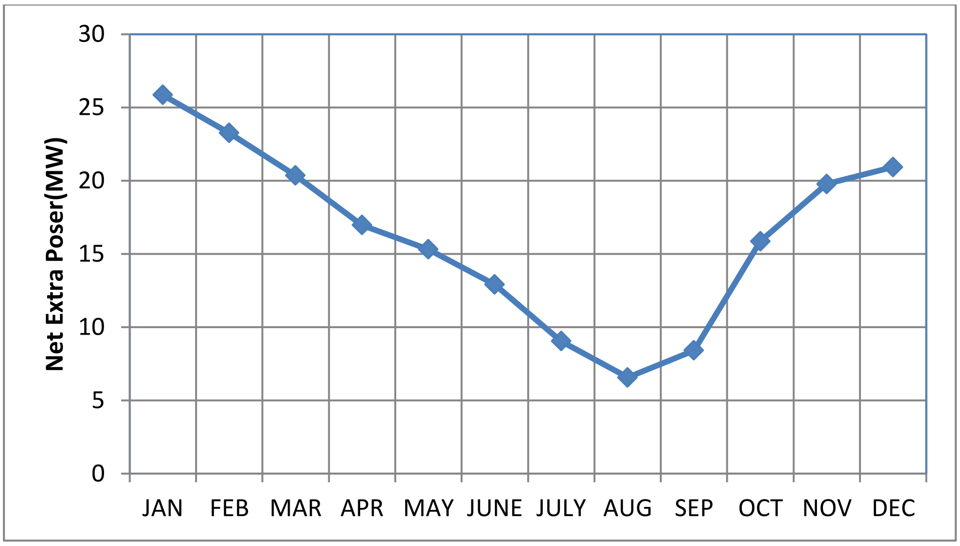

Figure 3. Monthly Net Electric Energy Production of Qom Pipeline Gas Station without any Intake Air Cooling Systems

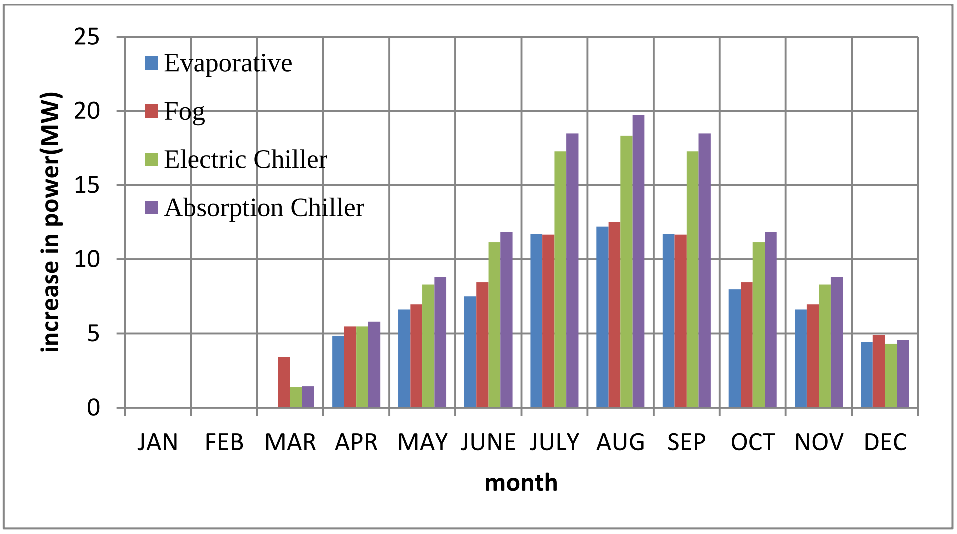

Figure 4. Effect of Cooling Technology on Monthly Net Increase in Electric Energy Production in Qom Gas Stations

When the Inlet Air is cooled to 10ºC by Chillers and to the Lowest Possible Temperatures through Evaporative Cooling (85%) and Fogging (98%) approaches, the intake air cooling systems with chiller achieve greater power capacity enhancement than those achieved through evaporative cooling and fogging on eleven months specially on warm months because

chillers can reduce the inlet temperature to 10°C, which is much lower than that of the same accomplished through evaporative cooling and fogging. Absorption chiller produces higher enhancement than the electric chiller because of its lower operating power needs.

The Monthly Net Electric Energy Production of Assaloyeh pipeline gas station without any intake air cooling systems is diagramed in Fig. (5). The effect of cooling technology on the net power capacity enhancement for the plant is shown in Fig. (6).

Figure. 5. Monthly Net Electric Energy Production of Asaluyeh pipeline gas station without any intake air cooling systems.

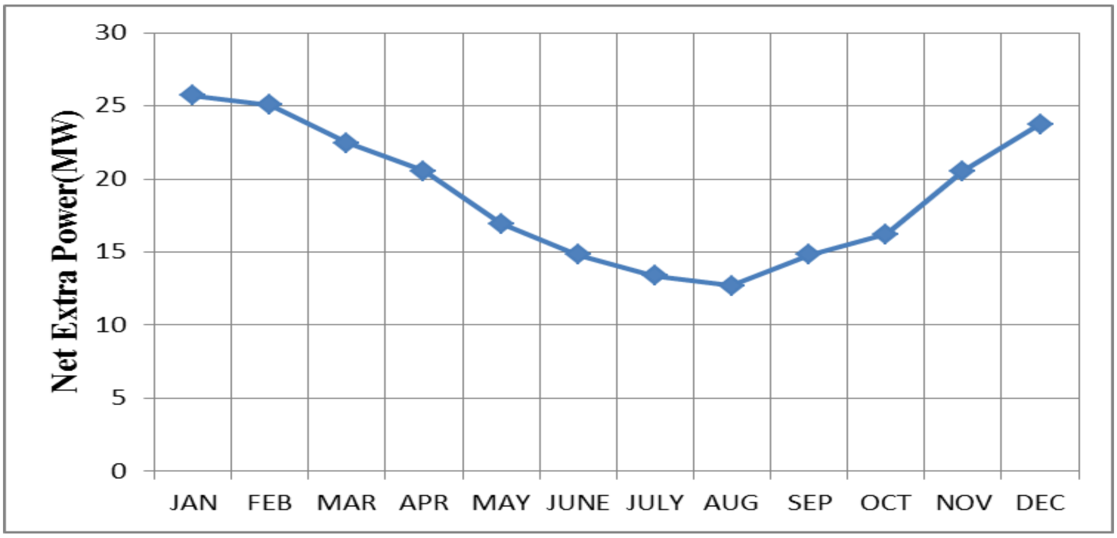

Figure 5. Monthly Net Electric Energy Production of Asaluyeh Pipeline Gas Station without any Intake Air Cooling Systems

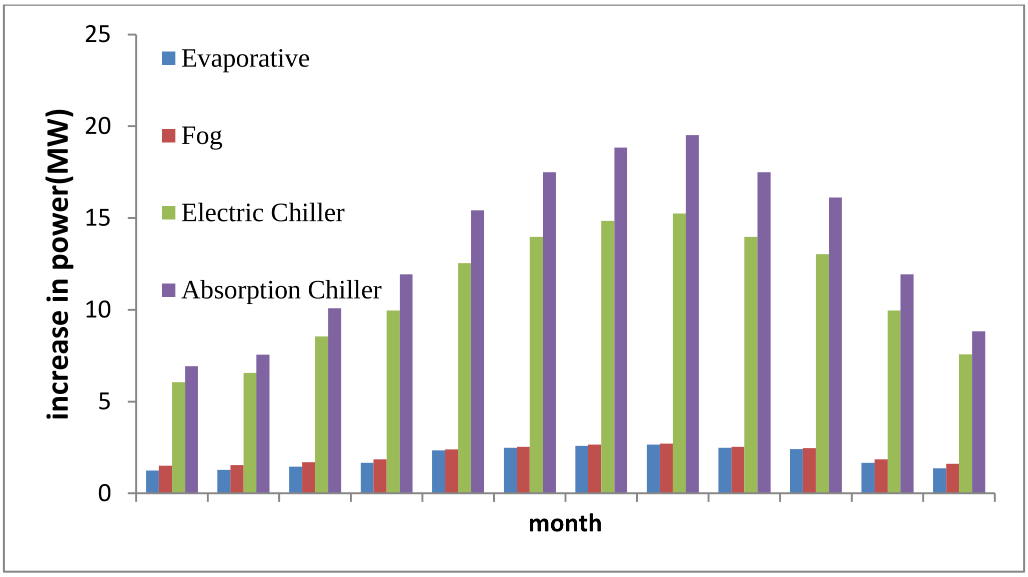

Figure 6. Effect of Cooling Technology on Monthly Net Increase in Electric Energy Production in Assaloyeh Gas Stations

When Inlet Air is cooled from its Ambient Temperature to 10°C by Chillers and to the Lowest Possible Temperatures with Evaporative Cooling (85% Approach) and Fogging (98% Approach) intake air cooling systems with chiller achieve greater power capacity enhancement than those using evaporative cooling and fogging on nine months especially on warm months because chillers can reduce the inlet temperature to 10 °C, which is much lower than is possible with evaporative cooling and fogging. Absorption chiller produces higher enhancement than the electric chiller because of its lower operating power needs. After modeling and simulating the Qom and Assaloyeh pipeline gas stations with different intake air cooler systems and exergoeconomic analysis of each case, many of results are obtained. The exergy components and cost flow of various streams in Qom and Assaloyeh pipeline gas station with Evaporative air cooler system are tabulated in Table 2.

The exergy destruction of Qom gas station with Evaporative air cooler system is shown in Fig. (7) and the same exergy for Assaloyeh gas station is shown in Fig. (8).

Table 2. The Exergy and Cost Flow of Various Streams in Qom and Assaloyeh Pipeline Gas Station with Evaporative Air Cooler System

Stream	***Qom***			***Assaloyeh***		
	Exergy(KW)	**c($/MJ)**	**C($/s)**	***Exergy(KW)***	**c($/MJ)**	**C($/s**
Air in	*0*	0	0	*0*	0	0
Water in	*62*	0.0596	0.0037	*62*	0.0596	0.0037
Compressor inlet	*-775*	-0.0059	0.0046	*-50.28*	-0.0859	0.0043
Fuel in	*58736*	0.0047	0.2761	*60893*	0.0047	0.2862
Turbine exhaust	*14335*	0.0041	0.0585	*16629*	0.0043	0.0066
Net power output	*18886*	0.0154		*18658*	0.0155	

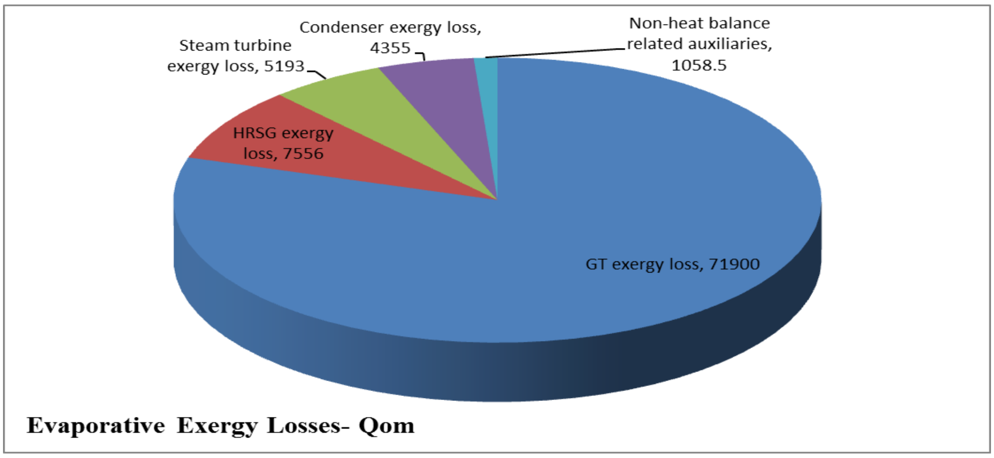

Figure 7. Exergy Destruction of Qom Gas Station with Evaporative Air Cooler System (kW)

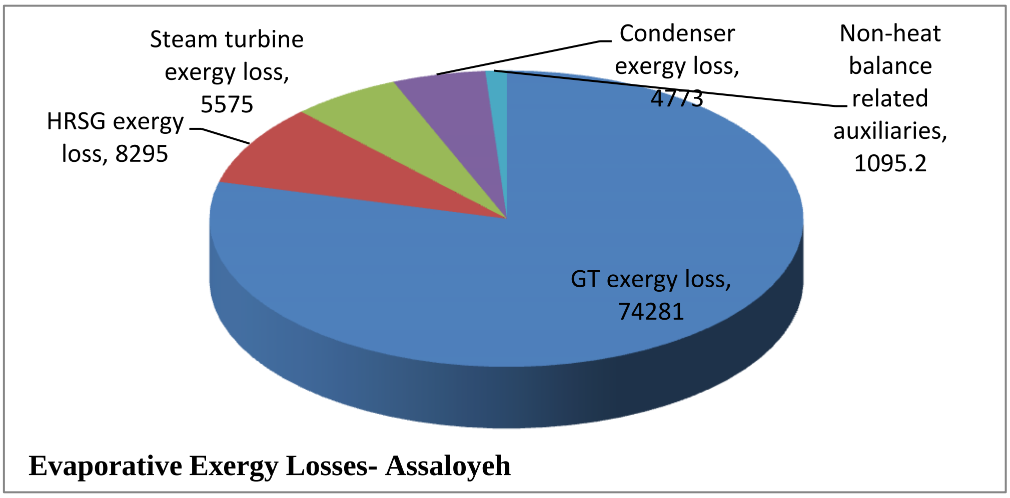

Figure 8. Exergy Destruction of Assaloyeh Gas Station with Evaporative Air Cooler System (kW)

The exergy components and cost flow of various streams in Qom and Assaloyeh pipeline gas station with fogging inlet air cooling system are tabulated in Table 3.

The exergy destruction of Qom gas station with Fog air cooler system is shown in 9 and the same for Assaloyeh gas station is shown in Fig. (10)

Table 3. The Eexergy and Cost Flow of Various Streams in Qom and Assaloyeh Pipeline Gas Station with Fogging Intake Air Cooling System

Stream	***Qom***			***Assaloyeh***		
	Exergy(KW)	**c($/MJ)**	**C($/s)**	***Exergy(KW)***	**c($/MJ)**	**C($/s)**
Air in	*0*	0	0	*0*	0	0
Water in	*62*	0.0596	0.0037	*62*	0.0596	0.0037
Compressor inlet	*-776*	-0.0056	0.0046	*-51.82*	-0.0769	0.0040
Fuel in	*59816*	0.0047	0.2761	*61123*	0.0047	0.2873
Turbine exhaust	*14447*	0.0040	0.0585	*16653*	0.0043	0.0715
Net power output	*19340*	0.0153		*18765*	0.0154	

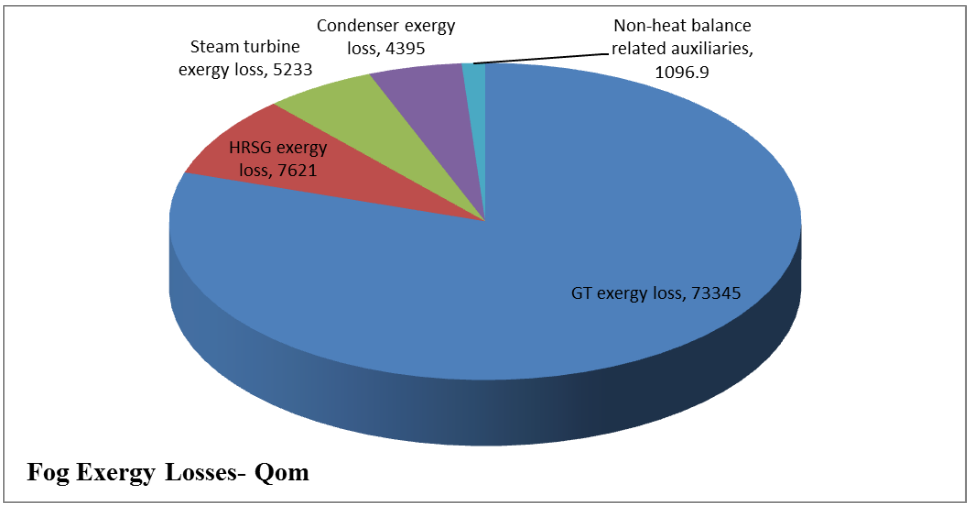

Figure 9. Exergy Destruction of Qom Gas Station with Fog Air Cooler System (kW)

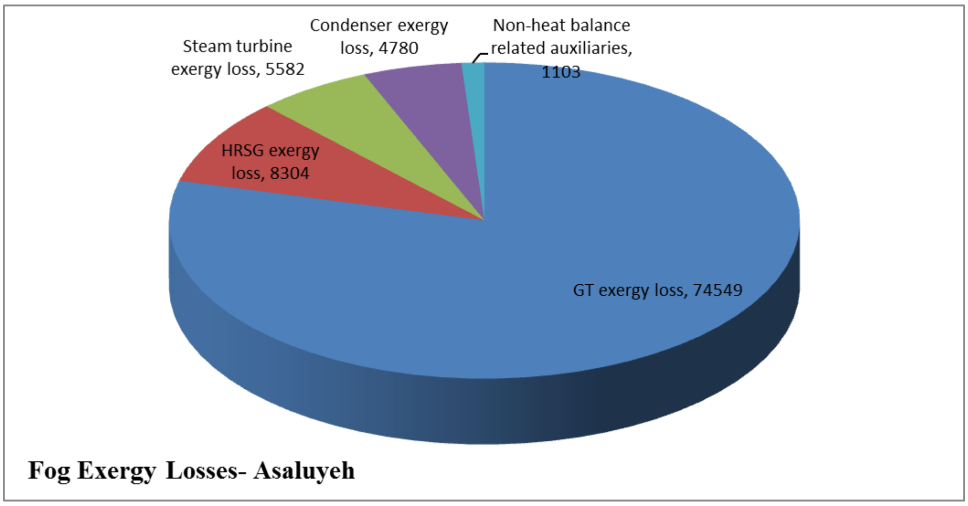

Figure 10. Exergy Destruction of Assaloyeh Gas Station with Fog Air Cooler System (kW)

The exergy components and cost flow of various streams in Qom and Assaloyeh pipeline gas station with electric chiller system are tabulated in Table 4.

The exergy destruction of Qom gas station with electric chiller system is shown in Fig. (11) and the same for, Assaloyeh gas station is shown in Fig. (12).

Table 4. The Exergy and Cost flow of Various Streams in Qom and Assaloyeh Pipeline Gas Station with Electric Chiller Intake Air Cooling System

Stream	***Qom***			***Assaloyeh***		
	Exergy(KW)	**c($/MJ)**	**C($/s)**	***Exergy (KW)***	**c($/MJ)**	**C($/s)**
Air in	*0*	0	0	*0*	0	0
Water in	*62*	0.0596	0.0037	*62*	0.0596	0.0037
Compressor inlet	*-809.2*	-0.0118	0.0095	*-45.35*	-0.3650	0.0166
Fuel in	*64679*	0.0047	0.3040	*72293*	0.0047	0.3398
Turbine exhaust	*14674*	0.0039	0.0572	*17208*	0.0040	0.0683
Net power output	*20873*	0.0156		*21970*	0.0163	

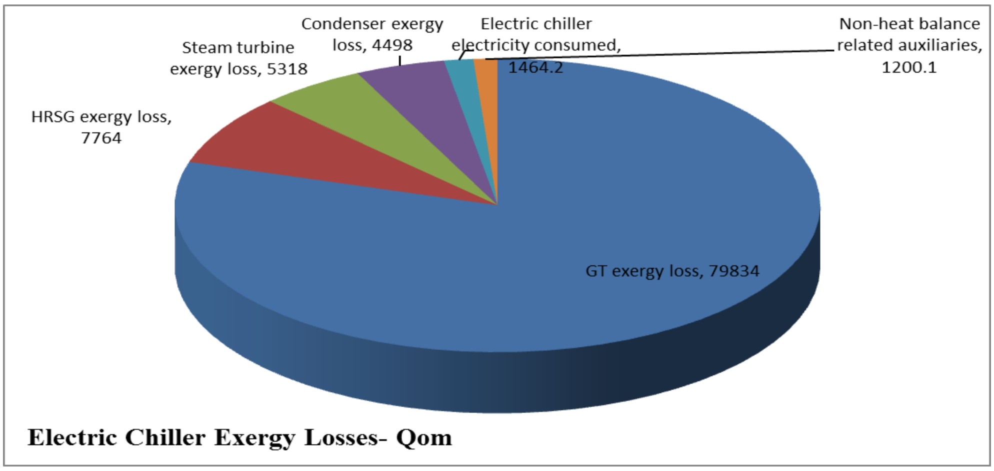

Figure 11. Exergy Destruction of Qom Gas Station with Electric Chiller System (kW)

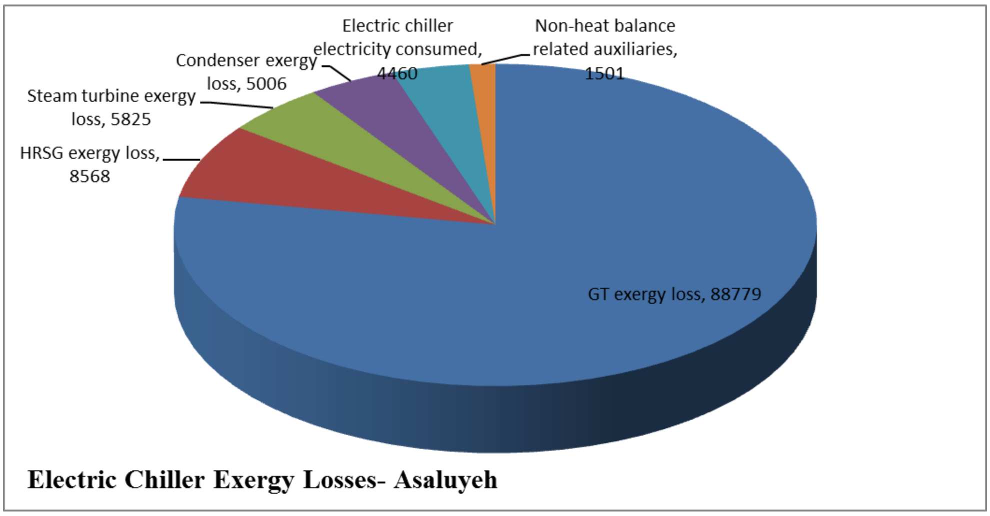

Figure 12. Exergy Destruction of Assaloyeh Gas Station with Electric Chiller System (kW)

The exergy components and cost flow of various streams in Qom and Assaloyeh pipeline gas station with absorption chiller system are tabulated in Table 5.

The exergy destruction of Qom gas station with Absorption chiller system is shown in Fig. (13) and the same for Asaluyeh gas station with is shown in Fig. (14).

Table 5. The Exergy and Cost flow of Various Streams in Qom and Asaluyeh Pipeline Gas Station with Absorption Chiller Intake Air Cooling System

Stream	***Qom***			***Asaluyeh***		
	Exergy(KW)	**c($/MJ)**	**C($/s)**	***Exergy(KW)***	**c($/MJ)**	**C($/s)**
Air in	*0*	0	0	*0*	0	0
Water in	*62*	0.0596	0.0037	*62*	0.0596	0.0037
Compressor inlet	*-809.2*	-0.0201	0.0162	*-45.35*	-0.6815	0.0309
Fuel in	*64679*	0.0047	0.3040	*72293*	0.0047	0.3398
Turbine exhaust	*14674*	0.0020	0.0296	*17208*	0.0005	0.0010
Net power output	*21718*	0.0166		*23781*	0.0185	

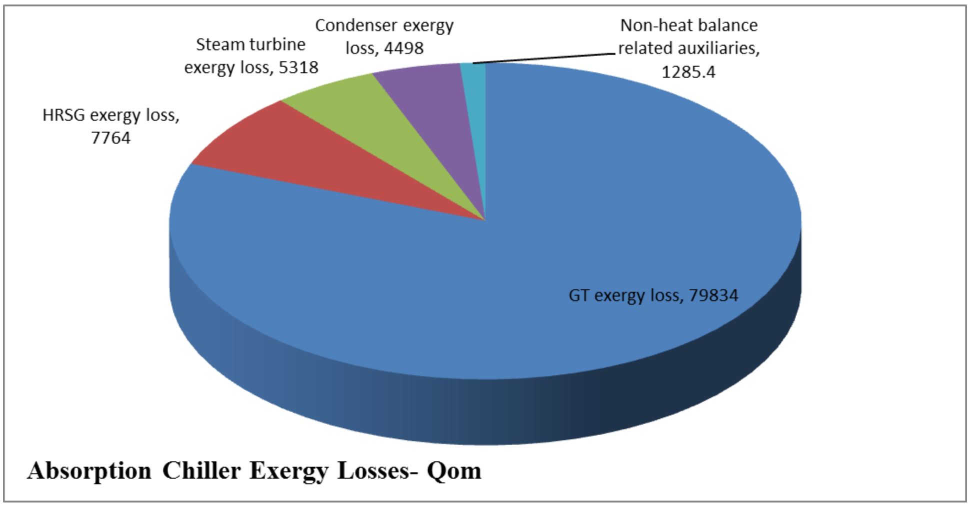

Figure 13. Exergy Destruction of Qom Gas Station with Absorption Chiller System (kW)

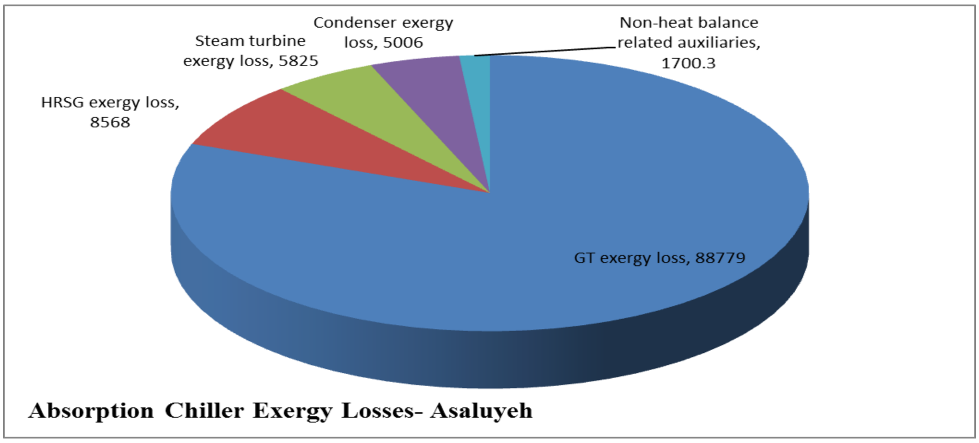

Figure 14. Exergy Destruction of Assaloyeh Gas Station with Absorption Chiller System (kW)

The net power output prices at different intake air cooling systems in Qom and Assaloyeh gas station are tabulated in Table 7. The exergy product cost of net power based on exergoeconomic modeling is expressed in Table 7. As observed in both these Tables as for economic and exergoeconomic parameters, best option for inlet air cooling system for both the stations is the Fog system. According to Fig. (4 and 6), as for performance and thermodynamic parameters the best option is absorption chiller for both the stations.

Table 6. Net Power Output Price of Different Inlet Air Cooling Systems

Intake air cooling system	***Net power output ($/MWh)***	
	Qom	***Asaluyeh***
Evaporative cooler	*55.6*	*55.5*
Fog	*55.2*	*55.4*
Electric chiller	*56.1*	*58.5*
Absorption chiller	*59.6*	*66.4*

Table 7. Exergy Product Cost of Different Inlet Air Cooling Systems

Intake air cooling system	***Net power output price ($/MWh)***	
	Qom	***Assaluyeh***
Evaporative cooler	0.0154	0.0155
Fog	0.0153	0.0154
Electric chiller	0.0156	0.0163
Absorption chiller	0.0166	0.0185

Conclusion

In this article heat recovery from gas exhaust of two gas turbine compressor stations are applied as a proposed combined cycle equipped with and without gas turbine inlet air cooling systems.

Here, four different intake air-cooling methods are applied in two pipeline gas stations in Qom as a warm dry climate and Assaloyeh as a warm humid climate in Iran. Techno-economic and exergoeconomic assessment is applied for different air cooling system.

The obtained results indicate that when the inlet air is cooled to 10oC by Chillers and to the lowest possible temperatures through Evaporative Cooling (85%) and Fogging (98%) approaches, the intake air cooling systems through chiller achieve greater power capacity enhancement than those applying evaporative cooling and fogging in nine months especially the warm months because chillers can reduce the inlet temperature to 10°C, which is much lower than what could possibly be achieved through evaporative cooling and fogging. Absorption chiller produces higher enhancement than the electric chiller because of its low power consumption.

Based on techno-economic and exergoeconomic assessments, the best choice for gas turbine inlet air cooling for both the dry and humid climates is the Fog system.

To better understand the combined system, it can be considered advanced exergoeconomic and Environmental Impact evaluation in the future researches.

Steam injection in combustion chamber of gas turbine for emission reduction should be assessed more.

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