Energy and Exergo-Economic Assessments of Gas Turbine Based CHP Systems: A Case Study of SPGC Utility Plant

Bidar, Bahareh; Shahraki, Farhad*+

Center for Process Integration and Control (CPIC), Department of Chemical Engineering, University of Sistan and Baluchestan, Zahedan 98164, I.R. IRAN

ABSTRACT: *Combined heat and power systems are becoming more and more important, regarding their enhanced efficiency, energy saving, and environmental aspects. In the peresent study, three configurations of combined heat and power systems are intended as an alternative to separate production plant by considering environmental aspects. First and second laws of thermodynamics are adapted to the operating data. The energy and exergy indicators, their distribution and exergy loss are evaluated. The economic analysis was done by determining the Rate of Return on Investment, Payback Period and Net Present Worth. The optimal configuration of system equipment has been determined based on economic feasibility and emission saving in view of power and steam demand. The method employed here may be applied to making a decision on the adoption of the combined plant to any separate heat and power systems.*

KEYWORDS: *Combined heat and power systems, Energy and exergy analysis, Performance parameter, Exergy loss, Economic analysis, Emission saving.*

INTRODUCTION

In the recent century, limiting energy sources has caused some problems. Consequently, the price of energy sources has increased and optimum use of energy sources could be an alternative solution to this issue. As consumers and providers seek to reduce energy costs as well as improving service and reliability, there has been growing interests in Combined Heat and Power system (CHP) over the past decade. CHP systems have emerged as an effective method of heat conversion [1].

Since gas turbines have many advantages such as high reliability and flexibility without complexity, short delivery time, low capital cost and fast starting, only gas turbine based combined plants have found wide acceptance up to the present time [2-4].

In conventional plants, a large amount of heat is produced but not used. By designing systems which can use the exhaust heat from the gas turbine, the efficiency of energy production can be increased from the current levels that vary from 35% to 55% in the conventional plant to over 80% in the CHP systems [5].

The most commonly-used method for analysis of an energy-conversion process is the first law of thermodynamics. However, there is an increasing interest in the combined utilization of the first and second laws of thermodynamics [6].

Exergy analysis appears to provide more insights and to be more useful in efficiency improvement efforts than energy analysis in existing systems. Many engineers

***** *To whom correspondence should be addressed.*
+ *E-mail: fshahraki@eng.usb.ac.ir*
1021-9986/2018/5/209-223 15/$/6.05

and scientists suggest that performing an exergy analysis in addition to or in place of conventional energy analysis evaluated the thermodynamic performance of a process in the best way [7, 8].

The economic analysis is a way to justify the installation of a CHP unit and evaluate its profitability. However, it is tightly dependent on user consumption, both electrically and thermally [9].

An engineering and exergy analysis of gas turbine in cogeneration systems performed and designed a gas turbine model [10]. The exergy analysis of simple cogeneration plant through both simple and rational exergy efficiency was studied for as much as exergy loss of each component [11]. The energetic and exergetic comparison of efficiency indicators for cogeneration systems were presented and were concluded that various energy-based efficiency indicators only captured exergetic improvements to a limited degree [12].

Exergy and economic analysis of a cogeneration plant system in Turkey, Esenyurt Thermic Power Plant, were performed based on the measured data during the system operation time. Furthermore, fuel-utilization efficiency, rate of power heat and rate of process heat were determined. Also founded that the second law efficiency is 89.5%, and the payback period of the plant was found 3.5 years, which was accepted as an agreeable value [13]. An economic feasibility study for a natural gas-fired combined heat and power facility in a Chinese industrial area was done. A model was developed, which optimizes the CHP installation capacity under the constraint of the power/heat supply and demand balance, furthermore; energy cost and emissions were taken into account. Their conclusions were mainly focused on the pollutant emission, and they did not use exergy analysis [14].

The optimization of a combined cycle power plant describing and comparing four different gas turbine cycles: simple cycle, intercooled cycle, reheated cycle and intercooled and reheated cycle for a combined power plant working in base load was presented. The results showed that the reheated gas turbine is the most desirable overall, mainly because of its high turbine exhaust gas temperature and resulting high thermal efficiency of the bottoming steam cycle [15].

The thermodynamic analysis of combined cycle gas turbine with an effect different configuration for a gas turbine is presented. The effects of ambient temperature and compression ratio have been proposed to select an optimum configuration for gas turbine and its effect on CHP performance. The results have shown that the simple gas turbine configuration is more suitable with regards to power output, but the regenerative gas turbine configuration has higher efficiency with effect ambient temperature [16].

Energy, exergy and exergo-economic analysis for a combined gas turbine and Organic Rankine Cycle (ORC) was presented. The results have shown that when an ORC is combined with the gas turbine cycle, additional power of 580.3 kW is produced by the ORC using the energy content of exhaust gases. They also reported that the cost rate of exergy destruction is greater than the capital investment of the system so that a reduction in the former should be suggested in optimizing the system performance [17].

Thermodynamic and environmental analysis gas turbine-based combined heat and power plant has been reported. The results of exergy analysis show a higher gas turbine rational efficiency in case of a recuperated gas turbine-combined cycle as compared to the basic gas turbine-combined cycle configuration. Moreover, the power-to-heat ratio and cogeneration energy efficiency of recuperated gas turbine cogeneration configuration are 0.8246 and 56.28% respectively, while cogeneration exergy efficiency for basic gas turbine-based cycle has been found to be 47.67% and the power-to-heat ratio is 0.6749 [18].

Extensive research work including multiple methodologies and numerous simulations have been completed in order to evaluate exergy, economic and environmental impact on gas turbine or cogeneration cycle, separately. To our knowledge, a comprehensive feasibility study on the effectiveness of employing CHP systems in gas turbine based industrial facilities from the viewpoint of energy, exergy, and exergo-economic with online operating data has not been investigated yet while it seems to be promising according to what we explained above. As a result, practical opportunities for CHP at industrial sites are often not realized or even investigated. It follows that there is a need in the CHP related literature for a feasibility analysis that is explicit and yet general enough to determine the economic viability and potential for success of CHP systems at industrial manufacturing facilities.

This work addresses a methodology to compare the economic effectiveness of installation and operation of different proposed configurations of CHP systems at industrial utility plant using Thermoflow; a commercial software for the power and cogeneration industries. The detailed formulations of energy and exergy balance, energy and exergy efficiencies, energy and exergy loss evaluation, performance parameters and economic analysis, emission analysis for the present system and CHP plants are developed. The intent of this work is to aid designers of such systems in optimization activities, and in the selection of the proper configuration of the system to modify the basic design and get more efficiency.

PLANT DESCRIPTION

The present case study is the utility production unit of the first phase of South Pars Gas Complex which is located at Asaluyeh, Iran. The unit consists of four gas turbines (model: GE6561B) for power generation with a capacity of 30 MW and three steam boilers. The nominal capacity of each boiler is equal to 80 tons per hour. Power and heat (or steam) are produced separately in this unit, that makes low fuel utilization. The power plant uses natural gas as fuel which obtained from the nearby gas refinery. Analysis of natural gas fuel is reported as N_2 (2.439), CO_2 (1.802), CH_4 (78.021), C_2H_6 (10.116), C_3H_8 (5.172), n-C_4H_{10} (1.421), C_5H_{12} (0.014), C_6H_6 (0.015), C_7H_8 (0.004), i-C_4H_{10} (0.996) and H_2S (0.0002).

METHODOLOGY

This section presents all steps involved in the analysis of utility production unit such as data extraction, process evaluation by thermodynamic and economic analysis.

Data processing

Since the gas turbine and combined systems should be designed based on the existing conditions, so online data such as Temperature, pressure, flowrates, power and steam conditions are gathered from the energy department for 2 years of plant operating time as they are repored briefly in Table 1. All data are reported as the average value per month, and the steam flow rate is also considered with 10% safety factor to spot all losses.

Table 1: Summary of average operating data of existent plant.

Number of Gas turbines (operating)	2
Power output per unit	16.5 MW
Total power output	32.86 MW
Gas turbine fuel flow rate per unit	5670 NM^3/h
Number of boilers (operating)	2
Steam temperature	243 ^{0}C
Steam pressure	22.5 bar
Steam flow rate per unit	55.5 ton/h.
Total steam flow rate	111 ton/h
Boiler fuel flow rate per unit	3475 NM^3/h

Thermodynamic analysis

The classic evaluation of thermal plants is through energy analysis based on the first law of thermodynamics, used. However, both the first and second laws of thermodynamics are used in exergy analysis. In the present study, both of these analyses are performed as described in details below.

The following assumptions are considered in this study:

- The gas turbine based cogeneration systems operates in a steady-state condition, so the accumulation terms are zero.
- The ideal gas principles are applied to air and exhaust gases.
- The combustion reaction in the combustion chamber of the gas turbine is considered as a complete reaction.
- The kinetic and potential exergy and energy changes are negligible.
- The temperature and pressure of the reference environment are considered as actual ambient conditions (30°C and 1.01 bar).
- The water in the exhaust is generally in vapor state in combustion chambers. As a result, the low heat value (LHV) of the fuel is used.

Equations (1) – (3) show mass, energy and exergy balances with the mentioned assumptions for any control volume, respectively:

$$\sum \dot{m}_i = \sum \dot{m}_e \quad (1)$$

$$\dot{Q} - \dot{W} = \sum \dot{m}_e h_e - \sum \dot{m}_i h_i \quad (2)$$

$$\dot{E}_{heat} - \dot{W} = \sum \dot{m}_e \psi_e - \sum \dot{m}_i \psi_i + \dot{I} \quad (3)$$

Where $\dot{Q}$ and $\dot{W}$ are net heat and work inputs, $\dot{m}$ is the mass flowrate of the fluid stream, his the enthalpy, the subscripts *i* and *e* stand for inlet and exit, $\dot{I}$ is the rate of exergy loss, and $\dot{E}_{heat}$ is the net exergy transfer by heat at temperature T, which is given by:

$$\dot{E}_{heat} = \sum\left(1-\frac{T_0}{T}\right)\dot{Q} \tag{4}$$

Where *T* is the temperature at which heat transfer takes place. The exergy of mechanical shaft work and electrical energy are equal to their energy forms.

The specific exergy on a unit mass basis (ψ) and the total exergy rate $(\dot{E})$, associated with a fluid stream [19]:

$$\psi = (h-h_0) - T_0(s-s_0) \tag{5}$$

$$\dot{E} = \dot{m}\psi \tag{6}$$

Where *h* and *s* are the enthalpy and entropy and the zero subscripts represent reference conditions. Note that specific exergy of fuel ψ_f is calculated as:

$$\psi_f = \gamma_f H_f \tag{5}$$

where γ_f and H_f indicate exergy grade function and lower heating value of the fuel [20]. For a steady state operation, the exergy loss is defined by choosing each component as a control volume as expressed in Table 2 [21].

Performance assessment parameters

It is convenient to define reference plants for separate production. The reference case study configured to supply the heat demand with conventional boilers, while the electrical energy produced by gas turbine power generation system [22].

To judge the feasibility or usefulness of CHP systems, some performance parameters are used. Power to Heat Ratio (PHR), Fuel Utilization Efficiency (FUE) and second law efficiency (exergetic efficiency) are the most useful parameters [23].

The ratio of usable energy to the input energy, usually in the form of LHV of fuel called total energy efficiency [24]. For a CHP system, it is expressed by:

$$\eta_{cogen} = \frac{\dot{W}_{net} + \dot{Q}_{process}}{\dot{Q}_{in}} = \frac{\dot{W}_{net} + \dot{m}_{water}\Delta h}{\dot{m}_{fuel}H_f} \tag{8}$$

Because the efficiencies of power generation and steam production are likely to be considerably different, PHR is expressed as:

$$PHR = \frac{\dot{W}_{net}}{\dot{Q}_{process}} \tag{9}$$

It has an important role in how the total CHP system efficiency might be compared to that of a separate production system. While power generation can be conducted nearly anywhere, heat has to be produced near the user, and it has to be scaled according to the local consumption. Thus, it may be useful to regard a CHP as a heat generator with surplus power generation. FUE is expressed as following:

$$FUE = \frac{\dot{W}_{net}}{\dot{m}_{fuel}H_f - \dot{m}_{water}\Delta h/\eta_{thermal}} \tag{10}$$

$\eta_{thermal}$ is considered as the typical boiler efficiency, usually 80 percent.

Relative Primary Energy Savings (RPES) indicator compares the fuel used by the CHP system to a separate heat and power system [22]. It can be expressed as:

$$PRES = \frac{\dot{m}_{fuel}H_f}{\dot{W}_{net}/\eta_{electrical} + \dot{Q}_{process}/\eta_{thermal}} \tag{11}$$

$\eta_{electrical}$ is the efficiency of power generation in a separate gas turbine plant. Positive values of RPES represent the fuel savings, while negative values indicate that CHP system is using more fuel than the separate production system. This is used as an indicator for the goodness of CHP systems.

When certain amounts of emissions are assigned to the fuel of the CHP plants and reference plants, indicators of emissions savings can be defined. For a natural gas fired CHP system, Relative CO_2 Emissions Savings (RCES) expressed as following [22]:

$$RCES = \frac{RPES}{\dot{W}_{net}/\eta_{electrical}} \times \left(\frac{\dot{W}_{net}}{\eta_{electrical}} + \frac{\dot{Q}_{process}}{\eta_{thermal}}\right) \tag{12}$$

The exergy efficiency (ε) is the ratio of the exergy contained in the useful products to the exergy contained in all input streams which is expressed as following [23]:

$$\varepsilon = \frac{\dot{W} + \dot{E}_{heat}}{\dot{E}_{fuel}} \tag{13}$$

Table 2: The exergy loss and exergy efficiency equations for plant components [25,26].

Plant component	Exergy loss	Exergy efficiency
Air compressor	$\dot{I}_{AC} = \dot{E}_i - \dot{E}_e + \dot{W}_{AC}$	$\varepsilon_{AC} = \frac{\dot{E}_e - \dot{E}_i}{\dot{W}_{AC}}$
Gas turbine	$\dot{I}_{GT} = \dot{E}_i - \dot{E}_e + \dot{W}_{GT}$	$\varepsilon_{GT} = \frac{\dot{W}_{GT}}{\dot{E}_i - \dot{E}_e}$
Condenser	$\dot{I}_C = \sum \dot{E}_i - \sum \dot{E}_e$	$\varepsilon_C = 1 - \frac{\dot{I}_C}{\sum \dot{E}_i}$
HRSG	$\dot{I}_{HRSG} = \sum \dot{E}_i - \sum \dot{E}_e$	$\varepsilon_{HRSG} = 1 - \frac{\dot{I}_{HRSG}}{\sum \dot{E}_i}$
Pump	$\dot{I}_p = \dot{E}_i - \dot{E}_e + \dot{W}_p$	$\varepsilon_p = 1 - \frac{\dot{E}_e - \dot{E}_i}{\dot{W}_p}$
Combustion chamber	$\dot{I}_{CC} = \dot{E}_i - \dot{E}_e + \dot{E}_{fuel}$	$\dot{\varepsilon}_{CC} = \frac{\dot{E}_e}{\dot{E}_i + \dot{E}_{fuel}}$
Steam turbine	$\dot{I}_{GT} = \dot{E}_i - \dot{E}_e - \dot{W}_{GT}$	$\varepsilon_{ST} = \frac{\dot{W}_{ST}}{\dot{E}_i - \dot{E}_e}$
Cycle	$\dot{I}_{Cycle} = \sum_{all\ components} \dot{I}_i$	$\varepsilon_{Cycle} = \frac{\dot{W}_{net}}{\dot{E}_{fuel}}$

For a steady state operation, and choosing each component of the plant as a control volume, the exergy efficiencies are defined [25, 26] as shown in Table 2. The irreversibility or exergy loss is avoided by replacing the reference case (separate production) with a combined system. The term “avoided” presumes that the case is an improvement from the reference case. The exergy loss of a certain case can be expressed as $(1-\varepsilon)\dot{E}_{in}$. The dimensionless form of avoided irreversibility is expressed as RAI as following:

$$RAI = (1-\varepsilon_{ref}) - (1-\varepsilon)\frac{\dot{E}_{in}}{\dot{E}_{in,ref}} \tag{14}$$

This quantity can be regarded as the irreversibility of the specific system subtracted from the irreversibility if the system were not applied.

Economic analysis

Before the capital be invested in a project, it is necessary to know how much profit can be obtained. Thus, the determination and analysis of profits - which is obtainable from the investment of capital - and the choice of the best investment among various alternatives are major goals of economic analysis.

The methodology for the cost estimating of modified utility system investment based on standard chemical engineering costing techniques [27] has been used. All revenues are evaluated based on the difference between production and consumption of new systems with the separate production system. The relations are considered to compute operating costs and unit revenues are expressed as [28]:

Revenue (USD/yr) = (15)
Annual Augmented power sales price +
Annual steam sales price + Boiler fuel saving cost

Operating expenses (USD/yr) = (16)
Fuel increment cost + Imported deminerized water cost +
Operating and maintenance cost

Operating income (USD/yr) = (17)
Revenue – Operating expenses

In this calculation, the electric energy produced by the gas turbine is the main product, and process steam and electric energy produced by steam turbine are considered as the by-products. The most commonly used economical parameters as well as Rate of Return on Investment (ROI), PayBack Period (PBP) and Net Present Worth (NPW)

Table 3: Values of Minimum Acceptable Rate of Return on investment and levels of risk.

Investment description	Level of risk	MARR percent/year
Basis: Safe corporate investment opportunities or cost of capital	Safe	4-8
New capacity with established corporate market position	Low	8-16
New product entering into an established market, or new process technology	Medium	16-24
New product or process in a new application	High	24-32
Everything new, high R&D and marketing effort	Very high	32-48+

of additional investment for CHP system are calculated as follows:

The yearly profit, divided by the total initial investment necessary, represents the fractional return.

$$ROI = \frac{\left(\frac{1}{n}\right)\sum_{j=-b}^{n} N_{pj}}{\sum_{j=-b}^{n} TCI_j} \quad (18)$$

Where *n* is the plant economic life, normally 20 years. N_{pj} is the net profit, which equals to the amount of net income after taxes for each year. The TCI (Total Capital Investment) is sum manufacturing and unit facilities investment FCI (Fixed Capital Investment) and operating expenses WCI (Working Capital Investment). The calculated value from Eq. (18) should be compared with Minimum Acceptable Return on Investment (MARR), which is given in Table 3.

PBP is defined as the minimum length of time theoretically necessary to recover the original capital investment.

$$PBP = \frac{FCI}{\left(\frac{1}{n}\right)\sum_{j=1}^{n} A_j} \quad (19)$$

A_j is the cash flow of each year is defined as follows:

$$A_j = N_{pj} + d_j \quad (20)$$

In Eq. (20), d_j is a depreciation charge. To be acceptable, a project payback period should be less than or equal to the reference value given by:

$$PBP_{ref} = \frac{0.85}{MARR + 0.85/n} \quad (21)$$

The NPW is then the difference between the present value of the annual cash flows and the initial required investment. It is recommended as the most suitable value for assessing profitability because it includes the largest number of factors affecting profitability.

$$NPW = -TCI + \sum_{j=1}^{n} \frac{1}{\left(1 + i_{eff}\right)^n}\left(N_{pj} + d_j\right) \quad (22)$$

In Eq. (22), i_{eff} is the effective annual interest rate. There are several methods for calculating depreciation. In this study, the Modified Accelerated Cost Recovery System (MACRS) has been used. This method used for most income tax purposes and consequently for most economic evaluation [27].

Case studies

In the present study, for evaluating the effect of replacing separate production system with CHP system, three configurations have been considered:

Case 1: Gas turbine power production with process steam production

Case 2: Gas turbine power production with power production by a steam turbine

Case 3: Gas turbine power production with power production by a steam turbine and process steam production

Fig. 1(a-c) illustrates the schematic flow diagram for the mentioned cases. Hot exhaust gases from the turbine are the waste heat sources for process heat production in HRSG system for steam production. The steam that is produced can be used either for process heat or for power generation by a steam turbine or both. HRSG is consist of four major components: the economizer, evaporator, superheater and water preheater. The pinch point and approach point are two variables that directly affect steam production and the gas and steam temperature profiles. The pinch point is the difference between the gas temperature leaving the evaporator and saturation temperature.

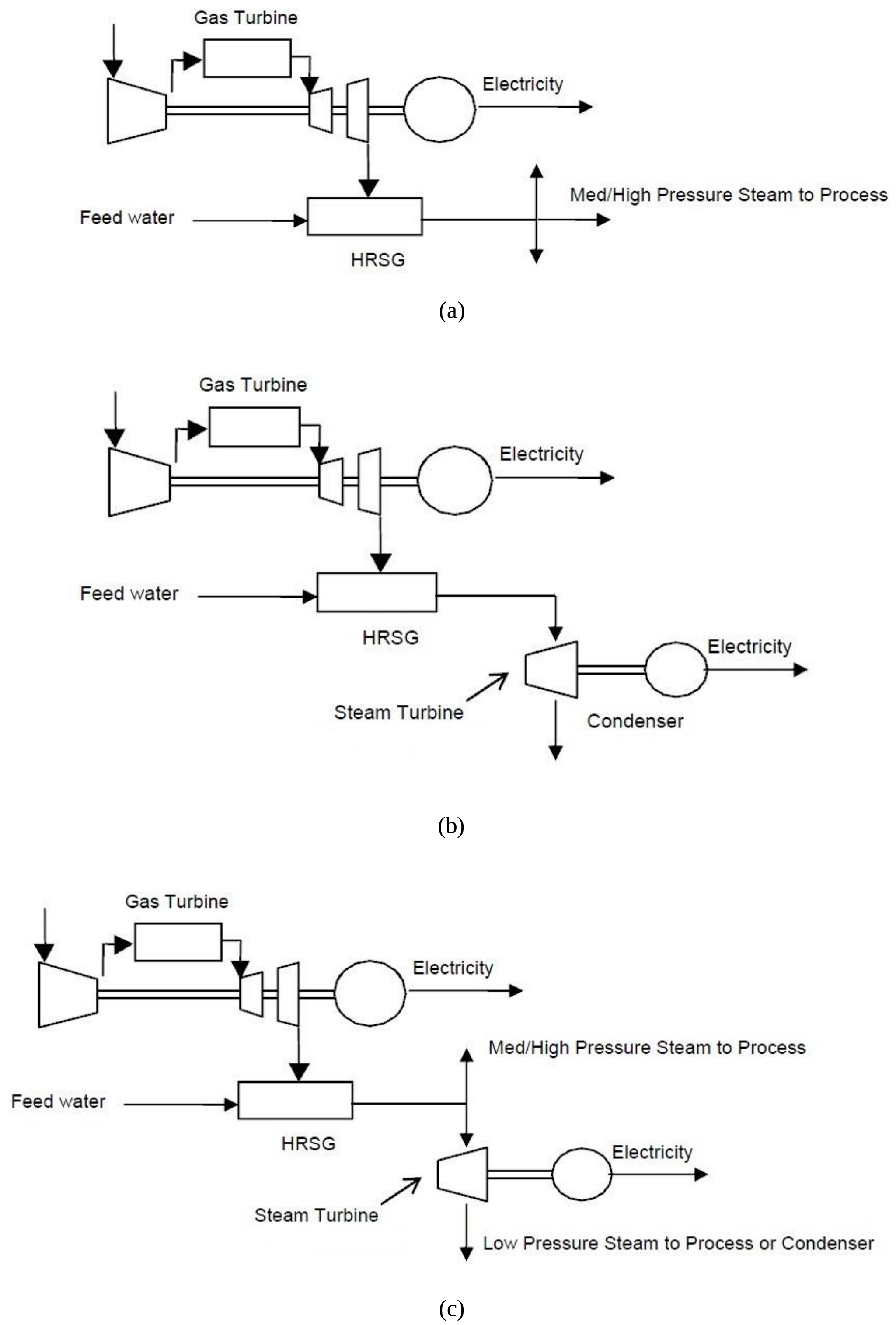

Fig. 1: Schematic diagram for a) Case 1: combined cycle with process steam, b) Case 2: combined cycle with power and without process steam, c) Case 3: combined cycle with power and process steam.

Table 4: Suggested pinch and approach points for HRSG design [30, 31].

Inlet gas temperature (°F)	Pinch Point (°F)		Approach Point (°F)
	Evaporator type		
	Bare	Finned	
1200-1800	130-150	30-60	40-70
700-1200	80-130	10-30	10-40

Table 5: Energy indicators for proposed CHP systems.

Cycle type	PHR	FUE	RPES	RCES
	-	%	%	%
Case 1	0.52	54.03	36	56
Case 2	-	36.75	35	35
Case 3	1.46	42.33	36	56

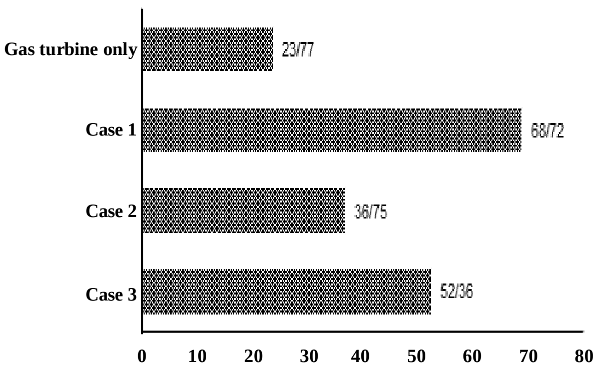

Fig. 2: Comparison of total energy efficiency of gas turbine and CHP systems.

Approach point is the difference between the saturation temperature and the water temperature entering the evaporator. Selection of these two variables also affects the size of the super heater, the evaporator, and the economizer [29]. The suggested values of pinch point and approach point are reported in Table 4 [30, 31].

RESULTS AND DISCUSSION

Based on the governing equations and input parameters, the gas turbine plant and three proposed CHP systems are analysed. Fig. 2 shows the total energy efficiency evaluated for both separate and CHP systems. After using CHP systems, energy efficiency is increased and it is remarkable in case 1 and case 3.

Performance energy indicators are calculated and reported (Table 5). In case 1, the amount of produced power is approximately half of thermal energy. In case 3, the amount of produced power is more than the produced steam due to cycle type and steam conditions. In case 2, in which only electricity is generated, PHR is meaningless and cannot be calculated. Since the aim of applying proposed systems is to provide needful steam by removing conventional boilers, producing more steam is acceptable. Consequently, case 1 can be a better choice.

The FUE indicator expresses CHP efficiency as the ratio of net electrical output to net fuel consumption, where net fuel consumption excludes the portion of the fuel that goes to producing useful heat output. Therefore, it shows that the energy in CHP systems is better used than that in the separate production system. This indicator has the highest value in case 1. The distribution of ingoing and outgoing energy from a separate gas turbine plant is shown in Fig. 3. It can be seen that most of the energy loss of gas turbine was in exhaust gases (Stack).

The energy distribution diagrams of proposed CHP systems are shown in Figs. 4 and 5. It can be found that the maximum energy loss occurs in the condenser. Moreover, compared to Fig. 3, it is clear that that most of exhaust sensible energy of separate gas turbine was recovered about 58%, 60%, and 61% by using case 1, 2 and 3, respectively in HRSG and converted to useful process heat and surplus power. Nevertheless, these energy indicators and diagrams do not provide meaningful and comparable results relative to exergy

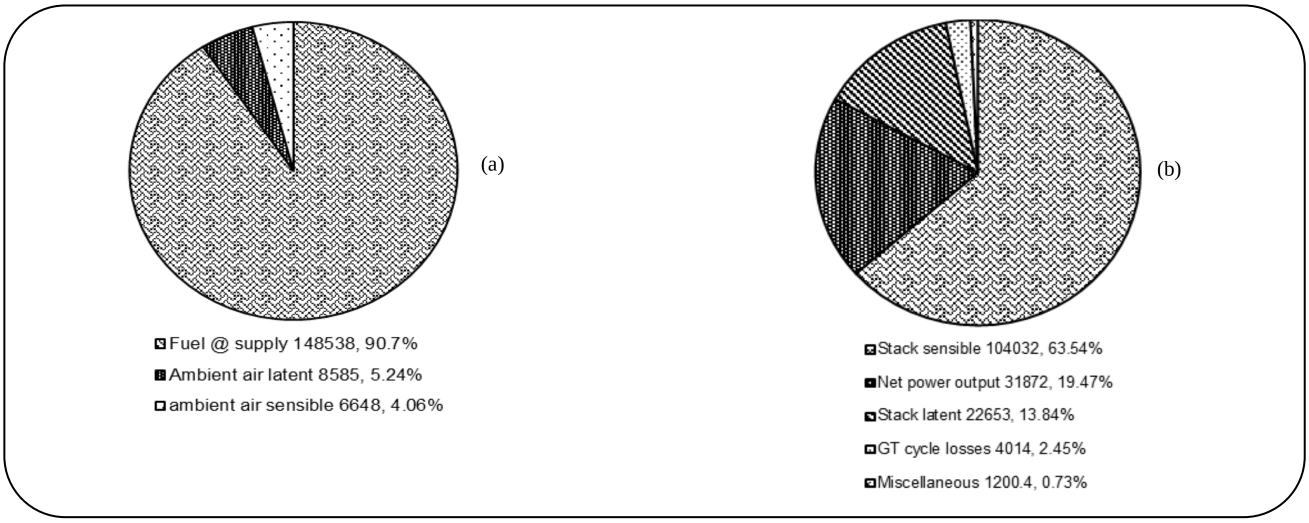

Fig. 3: a) Distribution of ingoing energy to gas turbine plant, b) Distribution of outgoing energy from gas turbine plant.

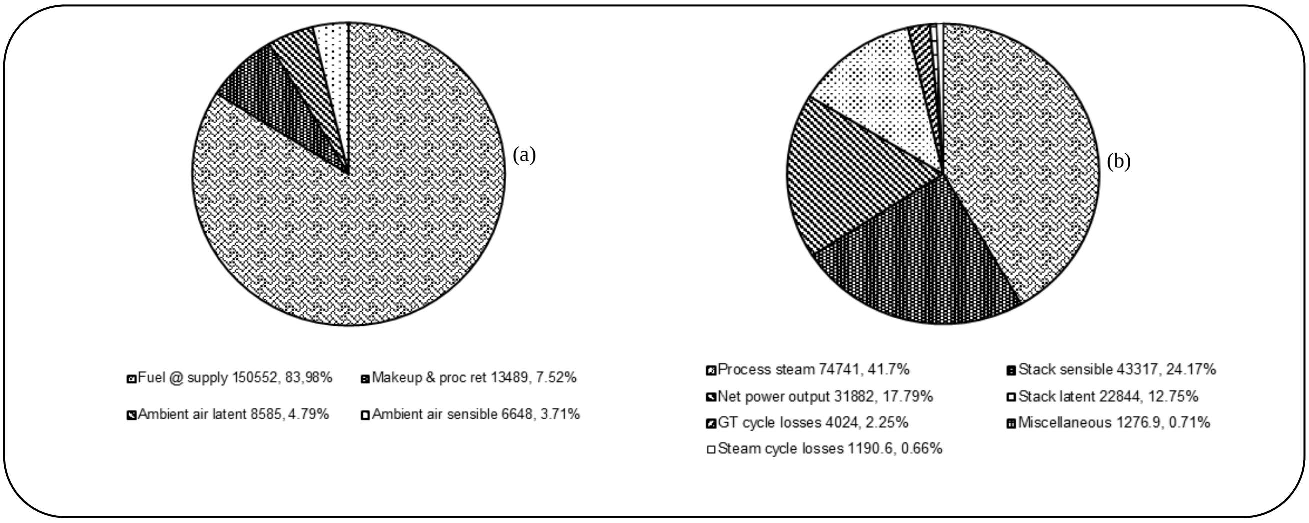

Fig. 4: a) Distribution of ingoing energy to CHP plants, b) Distribution of outgoing energy from Case 1.

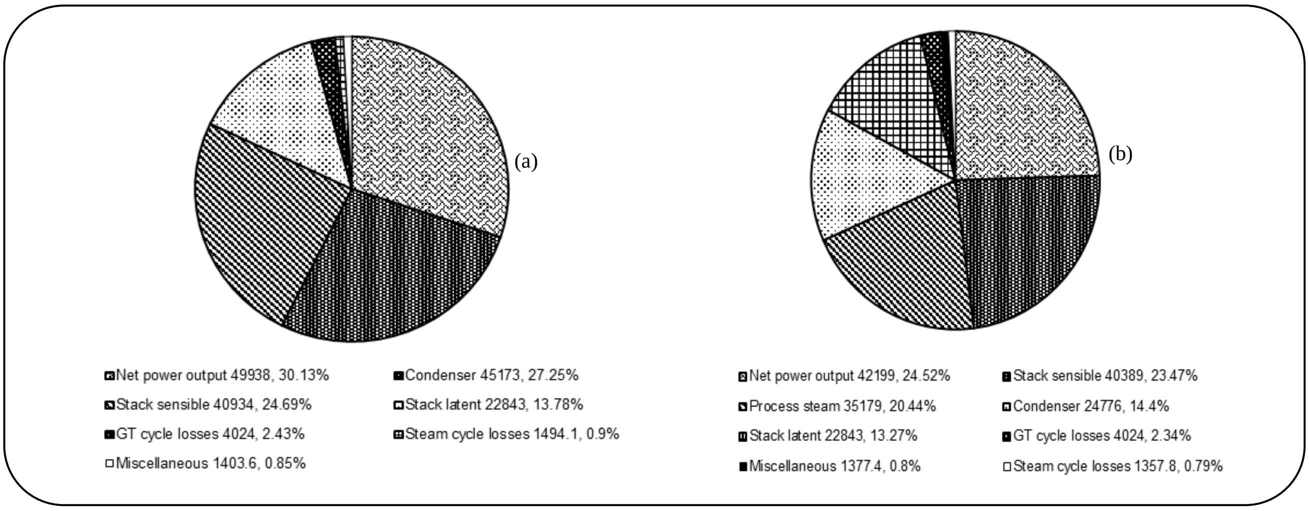

Fig. 5: a) Distribution of outgoing energy from Case 2, b) Distribution of outgoing energy from Case 3.

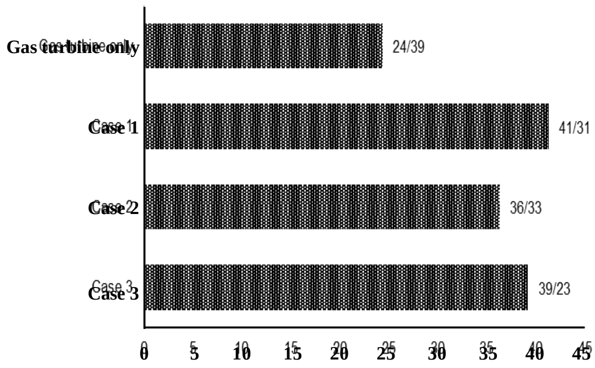

Fig. 6: Comparison of exergy efficiency of gas turbine and CHP systems.

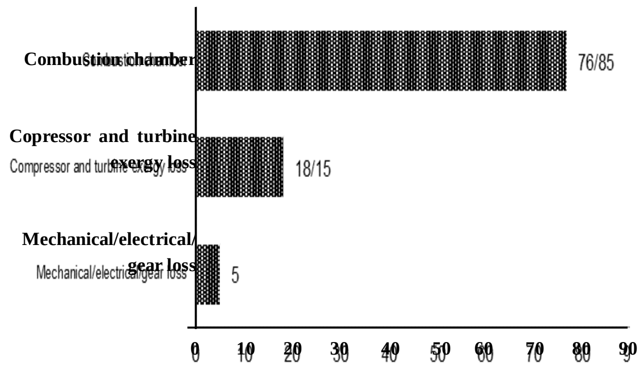

Fig. 7: Exergy Loss of gas turbine components.

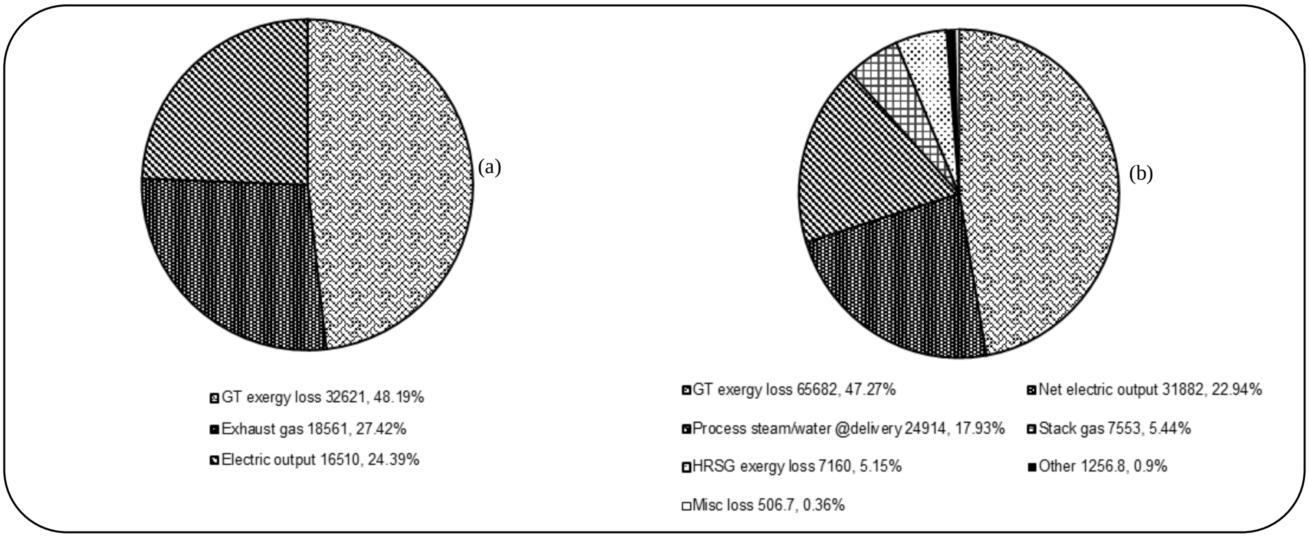

Fig. 8: a) Exergy distribution for a single gas turbine, b) Exergy distribution for Case 1.

efficiencies when the energy of products is in different forms.

Exergy efficiencies of separate and CHP systems are presented in Fig. 6. The results are shown exergy efficiency of separate gas turbine power plant is about 24.4%. Exergy efficiencies of CHP cases reported as 41.3%, 36.3% and 39.2 % for case 1, 2 and 3 respectively. Adding proposed CHP systems caused 69.3%, 48.8%, and 60.6% points exergy efficiency enhancement which, were shown a significant increase compared to the sole gas turbine, especially in Case 1 and Case 3. The magnitudes of RAI are calculated and found as 0.16, 0.11 and 0.14 for case 1, case 2 and case 3, respectively. As the RAI is based on exergy efficiency, it can be seen that a higher RAI usually corresponds to higher exergy efficiency.

Fig. 7 shows the exergy loss of gas turbine components. In comparison with other components, the combustion chamber losses the largest amount of total inlet exergy, due to high irreversibility.

Exergy distribution and exergy loss in gas turbine plant and CHP systems are evaluated and shown in Figs. 8 and 9. Despite low energy loss in a gas turbine, its exergy loss is relatively high. It was found that the amount of exergy loss caused by exhaust gases is reduced from 28% to 5%which is remarkable. The results indicate

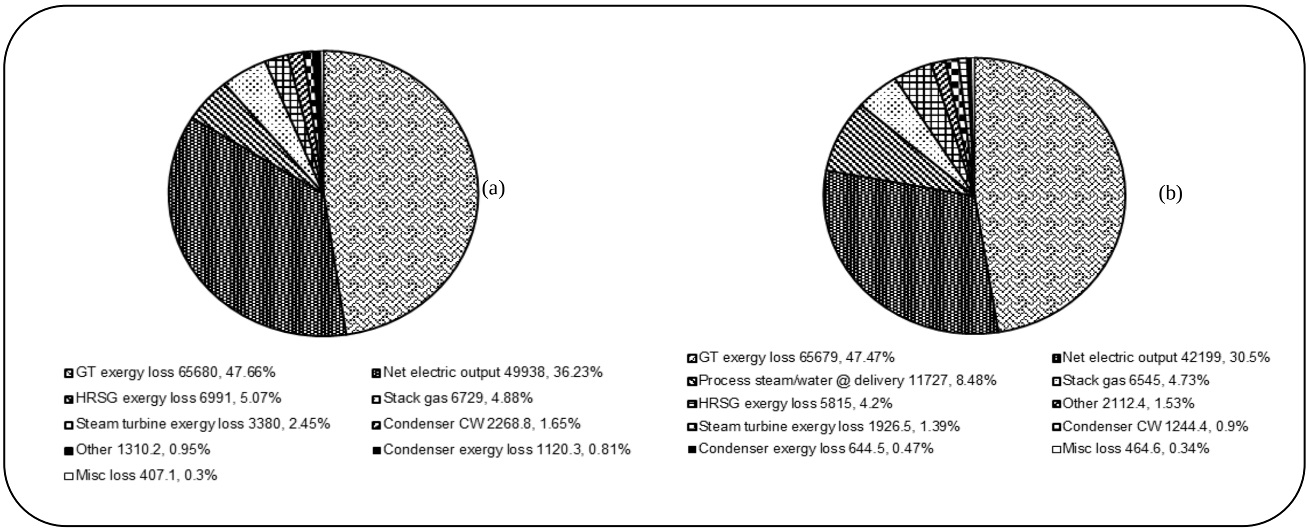

Fig. 9: a) Exergy distribution for Case 2, b) Exergy distribution for Case 3.

that gas turbines and heat recovery boilers have the highest exergy loss. Based on exergy analysis, it is also revealed in case 1 and case 3 is more suitable for the present plant.

As it is seen from Table 6, the most important point that stood out from the others is the production capability of CHP cases. The annual production data of the present system are reported in Table 1. By using case 3, total produced steam by HRSG can be utilized and there is no need to use industrial boilers. By using case 1, one boiler can be removed and one of the industrial boilers remains in the circuit, so the reliability of steam generation is preserved in the unit.So by considering all the above results, both case 1 and case 3 can be used to improve gas turbine plant. In the end, the final decision will be limited to economic constraints. To conclude more accurately, economic analysis is applied to both selected systems.

The price for each product (power and steam) and for each raw material (natural gas and water) is taken from authorities of the South Pars Gas Complex on the local purchasing price and they are reported in Table 7. All prices of purchase, installation, and preparation of unit to erect of CHP systems are calculated based on relationships and the results are shown in Table 8. The TCI of case 1 in less than that one of case 3 because the cost of required steam turbine and electrical and control systems are too much.

The proposed investments must be evaluated for their economic feasibility. The effect of income taxes on the cost of capital is very important. In this study based on existent circumstances and policies, 38% income taxes have been chosen. The inflation rate within the plant entire economic life is 5% in USD. The effective annual interest rate has been estimated at 10% in this study. The cost index (CEPCI) is used to update the costs to the year 2015 [32]. The economic analysis was evaluated by determining the ROI, PBP, and NPW. As can be seen in Table 9, despite the slight difference between the revenues of two cases, the rate of return in case 1 is more than that one in case 3. Moreover, the initial investment of case 1 is lower than that one of case 3. According to Table 3, the MARR is 24-16% for using new technology. Investment on case 1 and case 3 earn 84.12 and 56.55 percent per year, respectively. Therefore, both systems have a greater ROI than MARR, and they make case 1 more acceptable than case 3.

NPW -the present value of additional investment of proposed systems- also indicated that case 1 has higher present value. It shows that this case has greater profitability than other ones in a lifetime of the project. Last but not the least, back payment time of case 1 is found almost a year and the back payment time of case 3 is found one and half year as can be seen in Table 9. The reference PBP corresponding to the MARR of 24% is calculated based on Equation (21), which its value is obtained for 3 years. Both of Payback period of CHP cases are less than the reference value, so investment is acceptable.

Table 6: Power and steam production rate of CHP systems.

Parameter	Unit	Case 1	Case 2	Case 3
The power output of gas turbines	MW	31.88	50.00	42.64
The power output of the steam turbine	MW	–	18.19	10.81
Total power output	MW	31.88	68.19	53.45
Total Steam flow rate	ton/hr	93.7	78.9	119.1

Table 7: Local Cost of product sales and raw materials purchases.

	Unit Cost
0.076 $/kWh	Electricity
2.92 $/m^3	Demineralized water
7.8 $/GJ	Steam
7.75 $/GJ	Fuel (Natural gas)

Table 8: Cost and economics results of case 1 and case 3.

	Case 1	Case 3
Total equipment cost ($)	6,374,135	9,695,429
Equipment installation ($)	2,995,843	4,556,851
Instrumentation and controls ($)	2,294,689	3,490,354
Piping ($)	4,334,412	6,592,892
Electrical systems ($)	701,154	1,066,497
Buildings (includind services) ($)	1,147,344	1,745,177
Yard improvments ($)	637,414	969,543
Service facilities ($)	4,461,895	6,786,800
Total direct plant cost ($)	16,572,751	25,208,115
Engineering and supervision ($)	2,103,465	3,199,492
Construction expenses ($)	2,613,395	3,975,126
Legal Expenses ($)	254,965	387,817
Contractor's fee ($)	1,402,310	2,132,994
Contingency ($)	2,804,619	4,265,989
Total indirect plant cost	9,178,754	13,961,418
Fixed Capital investment ($)	32,125,640	48,864,962
Working Capital investment ($)	5,672,980	8,628,932
Total Capital investment ($)	41,431,720	63,020,049

Table 9: Profitability evaluation results of case 1 and case 3.

	Case 1	Case 3
Initial Equity ($)	41,431,720	63,020,049
Operating Expenses ($)	4,019,522	4,011,132
Revenues ($)	34,068,615	34,552,261
Operating Income ($)	30,049,093	30,541,128
ROI %	84.12	56.55
PBP (year)	1.01	1.5
NPW ($)	174,803,332	159,039,704

Table 10: Values of CO_2 decrement/increment after installing CHP systems.

Specifications	Case 1	Case 3
Annual gas turbine fuel increment (kg/yr)	1.26E6	1.26E6
Annual boilers fuel decrement (kg/yr)	44.47E6	44.47E6
Annual CO_2 increment (kg/yr)	3.34E6	3.34E6
Annual CO_2 decrement (kg/yr)	122.74E6	122.74E6
Net CO_2 decrement (kg/yr)	119.4E6	119.4E6
CO_2 emission before using CHP (kg/yr)	411.46E6	411.46E6
CO_2 emission after using CHP (kg/yr)	292.06E6	292.06E6
Decrement Percent	29%	29%

The results of energy balance calculations were shown, exhaust gas temperature of the gas turbine, case 1 and case 3 were 440.7 °C, 184.3°C, and 186.2°C respectively. In both cases, exhaust gases were released with lower energy content which was highly desirable in terms of reducing thermal pollution.

The other environmental impact of CHP systems are reducing air pollutants such as carbon dioxide. The amount of CO_2 which is produced by the combustion of fuels can be determined based on the analysis of gas turbines and boilers. According to Table 10, the results have been shown that CO_2 increment due to gas turbine fuel augmentation was insignificant versus of CO_2 decrement by eliminating industrial boilers. Moreover based on Table 5, RPES which shows the percent of fuel saving and RCES which shows the precent of emission saving were equal in case 1 and case 3. So based on this indicator, there is no difference between these two systems.

CONCLUSIONS

Energy and exergo-economic analyses along with environmental aspects have been presented as well as the effect of considering CHP systems on the energy and exergy efficiency of an actual gas turbine power plant in this study. In an actual plant, both energy and exergy efficiencies were almost 24% which were very low. So there was a great exergy loss of plant occur in exhaust gas and gas turbine combustion chamber. Thermodynamic evaluation results for three proposed systems showed acceptable improvement in energy and exergy efficiencies. RPES and RCES indicators also illustrated a considerable amount of fuel, and emission saving was considerable case 1 and case 3. Based on PHR indicator and amount of increasing efficiencies, case 1 which only used HRSG to produce steam and case 3 which used both HRSG and a steam turbine to produce steam and power together were better than the other cases. Consequently, the profitability evaluation has also represented that case 1 was found to be more acceptable by all three profitability measure. Decision makers may find the methodology explained in this paper very useful for comparison and selection of CHP systems for gas turbine based utility plants.

Nomenclature

CHP	Combined Heat and Power
FUE	Fuel Utilization Efficiency
FCI	Fixed Capital Investment
HRSG	Heat Recovery Steam Generator
LHV	Low Heat Value
MARR	Minimum Acceptable Rate of Return
MACRS	Modified Accelerated Cost Recovery System
NPW	Net Present Worth
PHR	Power to Heat Ratio
PBP	Payback Period
PWF	Present Worth Factor
RAI	Relative Avoided Irreversibility
RCES	Relative CO_2 Emissions Savings
RPES	Relative Primary Energy Savings
ROI	Rate of Reaturn on Investment
TCI	Total Capital Investment
WCI	Working Capital Investment

Symbols

A_j	Cash flow in a year, $
b	First year of investment
d	Depreciation charge, $
$\dot{E}$	Total exergy rate, kW
H	Specific enthalpy, kJ/kg
H_F	Low heat value of fuel, kJ/kg
Δh	Specific enthalpy change, kJ/kg
i_{eff}	Effective annual interest rate
$\dot{I}$	Exergy loss rate, kW
$\dot{m}$	Mass flow rate, kg/s
n	Plant economic life
N_p	Net profit, $
$\dot{Q}$	Heat transfer rate, kW
s	Specific entropy, kJ/kg.K
T	Temperature, K
$\dot{W}$	Work or power, kW

Greek symbols

η	Energy efficiency, %
ε	Exergy efficiency, %
ψ	Specific exergy, kJ/kg
γ	Exergy factor

Subscripts

e	Exit index
i	Inlet index
j	Year index
f	Fuel index
0	Reference conditions index
ref	Reference condition

Acknowledgement

The authors acknowledge the supports provided by plant management and engineers of the first phase of South Pars Gas Complex throughout this study.

Received : Aug. 10, 2017 ; Accepted : Apr. 23, 2018

REFERENCES

[1] Coelho M., Nash F., Linsell D., Barciela J. P., Cogeneration- the Development and Implementation of a Cogeneration System for a Chemical Plant, Using a Reciprocating Heavy Fuel Oil Engine with a Supplementary Fired Boiler, *J. Power. Energy*, **217**(5): 493–503(2003).

[2] Polyzakis A.L., Koroneos C., Xydis G., Optimum Gas Turbine Cycle for Combined Cycle Power Plant, *Energy Convers. Manage.*, **49**(4): 551–563 (2008).

[3] Khaliq A., Exergy Analysis of Gas Turbine Trigeneration System for Combined Production of Power Heat and Refrigeration, *Int. J. Refrig*, **32**(3): 534–545 (2009).

[4] Suomalainen M.S., Arasto A., Tei S., Siitonen S., Improving a Pre-Combustion CCS Concept in Gas Turbine Combined Cycle for CHP Production, *Energy Procedia*, **37**: 2327–2340 (2013).

[5] Petchers N., "Combined Heating, Cooling and Power Handbook: Technologies and Applications", Fairmont Press, Lilburn, GA (2003).

[6] Najjar Y. S. H., Gas Turbine Cogeneration Systems: A Review of Some Novel Cycles, *Appl. Therm. Eng.*, **20**(2): 179–197 (2000).

[7] Rosen M. A., Dincer I., Exergy as the Confluence of Energy, Environment and Sustainable Development, *Exergy, An Int. Journal*., **1**(1): 3–13 (2001).

[8] Turan O., Aydin H., Exergetic and Exergo-Economic Analyses of an Aero-Derivative Gas Turbine Engine, *Energy*, **74**: 638–650 (2014).

[9] Giaccone L., Canova A., Economical Comparison of CHP Systems for Industrial User with Large Steam Demand, *Applied Energy.*, **86**(6): 904–914 (2009).

[10] Bilgen, E., Exergetic and Engineering Analyses of Gas Turbine Based Cogeneration Systems, *Energy.*, **25**(12): 1215–1229 (2000).

[11] Ferdelji N., Galovic A., Guzovic Z., Exergy Analysis of a Co-generation Plant, *Therm. Sci..*, **12**(4): 75–88 (2008).

[12] Nesheim S.J., Ertesvag I.S., Efficiencies and Indicators Defined to Promote Combined Heat and Power, *Energy Convers. Manage.* **48**(3): 1004–1015 (2007).

[13] Can O.F., Celik N., Dagtekin I., Energetic–Exergetic–Economic Analyses of a Cogeneration Thermic Power Plant in Turkey, *Int. Commun. Heat. Mass.*, **36**(10): 1044–1049 (2009).

[14] Kosugi T., Tokimatsu K., Zhou W., An Economic Analysis of a Clean-Development Mechanism Project: A Case Introducing a Natural Gas-Fired Combined Heat-and Power Facility in a Chinese Industrial Area, *Appl. Energy.*, **80**(2): 197–212 (2005).

[15] Polyzakis A.L., Koroneos C., Xydis G., Optimum Gas Turbine Cycle for Combined Cycle Power Plant, *Energy Convers. Manage.*, **49**(4): 551–563 (2008).

[16] Thamir K. I., Rahman M.M., N Abdalla A., Gas Turbine Configuration for Improving the performance of Combined Cycle Power Plant, *Procedia Eng.*, **15**: 4216–4223, (2011).

[17] Khaljani M., Khoshbakhti Saray R., Bahlouli K., Comprehensive Analysis of Energy, Exergy and Exergo-Economic of Cogeneration of Heat and Power in a Combined Gas Turbine and Organic Rankine Cycle, *Energy Convers. Manage.*, **97**: 154–165 (2015).

[18] Anupam Kumari S., Thermo-environmental Analysis of Recuperated Gas Turbine-Based Cogeneration Power Plant Cycle, *Arab. J. Sci. Eng.*, **41**(2), 691–709, (2016).

[19] Kotas T.J., "The Exergy Method of Thermal Plant Analysis", Exergon Publishing Company, UK, London (2012).

[20] Aljundi I. H, Energy and Exergy Analysis of a Steam Power Plant in Jordan, *Appl. Therm. Eng.* **29**(2–3): 324–328 (2009).

[21] Ahmadi P., Dincer I., Rosen M. A., Exergy, Exergoeconomic and Environmental Analyses and Evolutionary Algorithm Based Multi-Objective Optimization of Combined Cycle Power Plants, *Energy*, **36**(10): 5886–5898 (2011).

[22] Ertesvag I. S., Exergetic Comparison of Efficiency Indicators for Combined Heat and Power (CHP), *Energy*, **32**(11): 2038–2050 (2007).

[23] Kanoglu M., Dincer, I., Performance Assessment of Cogeneration Plants, *Energy Convers. Manage.*: **50**(1): 76–81 (2009).

[24] Bejan A., Tsatsaronis G., Moran M., "Thermal Design and Optimization". 1st ed., John Wiley & Sons, Inc., New York (1996).

[25] Abusoglu A., Kanoglu M. Exergetic and Thermoeconomic Analyses of Diesel Engine Powered Cogeneration: Part 1- Formulations, *Appl. Therm. Eng.* **29**(2−3): 234−241 (2009).

[26] Kanoglu M., Dincer I., Rosen M., Understanding Energy and Exergy Efficiencies for Improved Energy Management in Power Plants, *Energy Policy*, **35**(7): 3967–3978 (2007).

[27] Peters M. S., Timmerhaus K. D., West R. E., "Plant Design and Economics for Chemical Engineers", 5th ed, McGrow-Hill, New York, (2003).

[28] Seider W.D., Seader J. D., Lewin D.R., "Product and Process Design Principles; Synthesis, Analysis, and Evaluation", 2nd ed., John Wiley & Sons, Inc., New York, (2004).

[29] Ganapathy V., "Industrial Boilers and Heat Recovery Steam Generators: Design, Applications and Calculations", Marcel Dekker Inc., Texas, (2003).

[30] Ganapathy V., Heat-Recovery Steam Generators: Understand the Basics, *Chem. Eng. prog.*, **92**(8): 32−45 (1996).

[31] Nessler H., Preiss R., Eisenkolb P., "Developments in HRSG Technology", *The 7th Annual Conference on Industrial and Power Gas Turbine O&M*, Birmingham, UK, 3−5 (2001).

[32] Economic Indicators, *Chem. Eng. Magazine, Essentials for CPI Professional.*, **2016-04**: 96- (2016).