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Present a multi-criteria modeling and optimization (energy, economic and environmental) approach of industrial combined cooling heating and power (CCHP) generation systems using the genetic algorithm, case study: A tile factory

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ABSTRACT

In this study, an industrial combined cooling, heat and power (CCHP) generation system in a tile factory was simulated and optimized by the genetic algorithm approach taking into account electricity, heating and cooling loads. Modeling and optimization were performed based on thermodynamic, environmental and economic analyzes. A multi-criteria function (energy, economic, and environmental) called relative annual benefit (RAB) with a gas engine (with partial load operation) as the prime mover was used in the optimization process. The analysis was performed for three different scenarios of the possibility of selling (selling scenario or SS) and impossibility of selling electricity (no-selling scenario or NS) to the grid and the possibility of selling electricity with similar capacities. The designing variables including the number of prime movers, nominal capacity of movers, backup boiler capacity and the capacity of compression and absorption chillers were optimized. The CCHP system for the tile factory showed the better performance of selling scenario using a gas engine with a capacity of 5000 and 700. However, the nominal capacity of the prime movers in the selling scenario was higher than that in the no-selling strategy. The results showed that the relative annual benefit decreased by choosing a similar capacities.

1. Introduction

Cogeneration is in fact successive production of two or three beneficial forms of energy, i.e. heating, cooling and power, from a fuel energy source. In most applications, the chemical energy of fuel is converted into mechanical and thermal energies. The mechanical energy is usually used for generating electricity while the thermal energy is used to produce steam, hot water or hot air. These systems sometimes are referred to as cooling, heating and power for buildings (CHPB), building cooling, heating and power (BCHIP) or combined cooling, heating and power (CCHP) systems according to applications. These systems are also referred to as dispersed energy resources (DERs) or integrated energy systems (IES) in the literature. The energy shortage crisis is one of the most fundamental issues in human societies. In the meantime, optimal use of single energy resources and cogeneration may preserve fossil fuel resources leading to the sustainable development of human societies. Low efficiency and high heat loss are one of the most important drawbacks in the industrial sector of Iran. For example, a power plant with a combined cycle losses more than 50% of thermal energy in different ways in the best condition. The overall efficiency of these units increases to 70–90% by combined cooling, heating and power (CCHP) systems.

There are many studies on the cogeneration systems. Most studies are devoted to modeling and optimization as well as economic evaluation of these systems. For example, Kong et al. [1], Haghifam et al. [2] and Cardona et al. [3] studied general aspects of these systems. They studied cogeneration systems with gas engine, gas turbine and diesel engine prime movers and compared them with conventional energy production systems to find factors leading to superiority of cogeneration systems. Their results showed the higher economic efficiency of a power generation unit due to supplying electricity and part of heat requirement along with electricity sales.

Some studies have modeled and evaluated these systems for home use. Sanaye et al. [4], Carvalho et al. [5] and Ghafouryan et al.

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[6] studied thermodynamic and economic simulation of heat and power cogeneration systems. They showed that these systems would be cheaper than conventional systems at small (home) scales, because they are associated with lower fuel consumption and higher energy efficiency. This advantage is more visible with reduction of electricity purchasing from the grid.

Along with these studies, a group of researchers evaluated the economics of combined heating, cooling and power (CCHP) generation systems using payback period [7] and annual profit [8]. They introduced a new definition of the payback period. They then compared the results of this parameter with two traditional and classical definitions for a cogeneration system in a residential complex. They showed that if the economic technique is not correctly applied in the payback period, then the results will be completely different.

Some studies are devoted to optimization of cogeneration systems. For example, Sanaye et al. optimized the cogeneration systems in a commercial complex [9] and a power plant [10] only by energy and economic analyses and ignored environmental issues. They provided a two-criteria approach (energy and economic) to optimize the nominal capacity of the power generation, boiler and cooling units. According to their results, optimal operation is obtained when two power generation units supply equal electric loads.

In addition to energy and economic analyzes, some authors studied cogeneration systems from an environmental point of view. Wu et al. [11] and Wang et al. [12] analyzed cogeneration systems with CO_2 pollutant in terms of energy, economic, and environmental issues. They showed if the environmental criterion is considered in the design parameters, the designed cogeneration system will produce less pollutants than the conventional system. More works can be referred about the numerical approaches to simulate the fluid flow concerned industrial applications [13-25].

According to literature [26-40], the use of combined cooling, heating and power (CCHP) generation systems has received much attention in recent years. However, there are few studies on optimization of these systems by energy and environmental and economic analyzes for industrial applications. In fact, the literature lacks studies on the design of cogeneration systems and combination of these systems with industrial units as well as thermodynamic, economic, and environmental analyzes and optimization.

In this study, an objective function is defined by taking into account thermodynamic, economic, and environmental analyzes. The design variables including the nominal capacity and the number of prime movers, heating capacity of boilers, cooling capacity of chillers and the partial load of the prime movers throughout the year will be optimized using the genetic algorithm.

2. Combined cooling, heating and power (CCHP) generation system from the perspective of the first law of thermodynamics and economic and environmental analyses

One of the major goals in the design of energy systems is to achieve a high energy level. On the other hand, economic analysis based on favorable conditions is of fundamental importance, because in addition to approaching the profit or loss resulting from the quality of the selected solution, it depends on the proper use of this technique. Below, energy and economic analyses of the CCHP system are discussed.

2.1. Combined cooling, heating and power (CCHP) generation system from the perspective of the first law of thermodynamics

Due to the variability of electrical, heating and cooling loads and water requirements with time at the place of use, CCHP equipment must have a different output with time. For this reason, the equipment should operate some hours at a load less than their nominal load or so-called “partial load”. By changing the point of operation of the equipment to the partial load, technical parameters of the equipment such as efficiency, fuel consumption and heat loss will vary. In this study, all equipment specifications are considered with respect to the partial load. Heat received from the gas engine includes heat from exhaust, heat generated from lubrication and the heat from the cooling water. The sum of these three thermal energies equals the total heat generation capacity of the power generation unit (H_G).

Nominal efficiency and fuel consumption should be known to calculate technical indicators of gas engines as a function of the partial load and the nominal value of each parameter. These parameters are represented by equations (1) and (2) as a function of the nominal capacity of the gas engine [41-43].

$$m_{f,\text{nom}} = \frac{E_{\text{nom}}}{\eta_{\text{nom}} \times LHV} \tag{1}$$

$$\eta_{\text{nom}} = 1.22 \times \frac{0.0007973 \times E_{\text{nom}} + 30.75}{100} \tag{2}$$

Technical specifications for the boiler, and compression and absorption chillers are obtained by Equations (3), (4) And (5).

$$\frac{\boldsymbol{\eta_{th,PL}}}{\boldsymbol{\eta_{\text{nom},B}}} = 0.0951 + 1.525(PL) - 0.6249(PL)^2 \tag{3}$$

$$\frac{\boldsymbol{COP_{PL,c}}}{\boldsymbol{COP_{\text{nom},c}}} = 1.1819(PL) - 0.819(PL)^2 \tag{4}$$

$$\frac{\boldsymbol{COP_{PL,ab}}}{\boldsymbol{COP_{\text{nom},ab}}} = \frac{PL}{0.75(PL)^2 + 0.0195(PL)} \tag{5}$$

In the present work, $\boldsymbol{COP_{PL,ab}}$ for the absorption chiller equals 0.7, $\boldsymbol{COP_{PL,\ c}}$ for the compression chiller is 3, and the nominal efficiency of the boiler $\eta_{\text{nom,B}}$ equals 90%.

2.2. Economic analysis of combined cooling, heating and power (CCHP) generation systems

Economic analysis of CCHP systems includes initial investment costs of equipment, operating costs, salvage costs and maintenance and fuel costs. The equivalent uniform annual cost was used to compare these costs. In this technique, all costs and revenues are assessed on an annual basis.

The initial cost is annualized by equation (6):

$$\boldsymbol{R} = \beta \times \boldsymbol{C} \tag{6}$$

β is the annuity coefficient which is evaluated by equation (7):

$$\beta = \frac{i(1+i)^k}{(1+i)^k - 1} \tag{7}$$

where i and j respectively represent the interest rate and the number of years of operation of the system.

The equivalent uniform annual cost can be defined as follows by taking into account the initial and salvage costs:

$$EUAC = R - A \tag{8}$$

The annual salvage cost, A, is evaluated by equation (9):

$$\boldsymbol{A} = \boldsymbol{SV} \times \left[\frac{\boldsymbol{i}}{(1+\boldsymbol{i})^{\boldsymbol{k}} - 1}\right] \tag{9}$$

where SV is salvage value in the present year which is usually considered as a percentage of the initial cost of the system.

The cost information in Table 1 is used to take into account the initial costs, maintenance costs and salvage value of equipment in this study.

2.3. Environmental analysis of combined cooling, heating and power generation systems

The environmental criterion considered in this article is CO_2, CO and NO_x emissions calculated by equations (10) to (13) based on the type of energy (power, heating and cooling) [44,45]:

$$m_{k,\mathrm{E}} = \sum_{j=1}^{T} (\xi_{k,\mathrm{E}} \times E_j) \times \tau_j \tag{10}$$

$$m_{k,\mathrm{H}} = \sum_{j=1}^{T} (\xi_{k,\mathrm{H}} \times H_j) \times \tau_j \tag{11}$$

$$m_{k,C_{ab}} = \sum_{j=1}^{T} \left(\xi_{k,\mathrm{H}} \times C_{\mathrm{ab},j}\right) \times \tau_j \tag{12}$$

$$m_{k,C_c} = \sum_{j=1}^{T} \left(\frac{\xi_{k,\mathrm{E}} \times C_{c,j}}{COP_c}\right) \times \tau_j \tag{13}$$

where k represents the pollutant type (CO, NO_x and CO_2), j the month, m the mass of pollutant in kilograms and ξ is the emission factor for each type of energy. Table 1 shows the emission factor for the CCHP and the traditional (trad) systems.

3. Objective function

The relative annual benefit (RAB) was used to optimize the system by energy, economic, and environmental analyses. This function determines the optimal capacity of the equipment by introducing an indicator for annual benefit of CCHP system with respect to the conventional systems. Considering the loads required over a year and taking into account factors such as environmental conditions, system operation at partial load, purchase and maintenance of the prime mover, backup boiler, chillers as well as the price of electricity sales to/from the grid, fuel purchase, annual interest rate and useful life of the equipment in this function, the nominal capacity and number of equipment and partial load are determined to achieve the maximum annual benefit [46-48]. Equation (14) illustrates the details of this objective function.

$$\mathrm{RAB} = TAC_{\mathrm{trad}} - TAC_{\mathrm{system}} \tag{14}$$

where TAC_{trad} represents the costs and revenues of the conventional system. TAC is estimated from equation (15) for the combined cooling, heating and power (CCHP) generation system. Two cost cases are investigated to select the chiller capacity in this system: (1) cooling only with a compression chiller and (2) cooling only with an absorption chiller. The case with a lower cost will be selected.

$$TAC_{\mathrm{trad}} = \sum_{j=1}^{T} \left[E_{\mathrm{b}} \times \rho_{\mathrm{e,b}} + m_f \times \rho_f + \sum_{k=1}^{3} \left(m_{\mathrm{trad}}^{k} \times \varepsilon_k\right)\right] \times \tau \sum_{r=1}^{P} M + EUAC_r \times Nc_r \times n_r \tag{15}$$

Table 1
Fines for CO, CO_2 and NO_x emissions.

Parameter	Symbol	Value
NO_x ($/kg) emission factor	ε_{NOx}	6.853
CO ($/kg) emission factor	ε_{CO}	0.02086
CO_2 ($/kg) emission factor	ε_{CO2}	0.024

These costs include all maintenance costs (M), salvage value (SV), initial investment (R), fuel consumption (ρ_f) and electricity purchase ($\rho_{e,\ b}$) where r represents the type of equipment, n number of equipment and ε the fines for emissions given in Table 1 in terms of pollutant type.

The annual cost of the CCHP system, TAC_{system} (as defined in equation (16)) is similar to that of conventional systems, with a difference in the sale of electricity and equipment of the system.

$$TAC_{\mathrm{system}} = \sum_{j=1}^{T} \left[E_{\mathrm{b}} \times \rho_{\mathrm{e,b}} - E_{\mathrm{s}} \times \rho_{\mathrm{e,s}} + m_f \times \rho_f + \sum_{k=1}^{3} \left(m_{\mathrm{CCHP}}^{k} \times \varepsilon_k\right)\right] \times \tau \sum_{r=1}^{P} M + EUAC_r \times Nc_r \times n_r \tag{16}$$

where ρ_e and $\rho_{e,\ b}$ respectively represent the cost of selling and purchasing electricity and ρ_f is the price of gas given in as a table in terms of type of use and amount of consumption.

4. The industrial complex

In this study, heating, cooling and power loads were studied in a tile factory in Yazd as shown in Figs. 1 and 2. The combined cooling, heating and power (CCHP) generation system in this factory was optimized to improve its performance. The electricity required in this industrial complex (**E_{dem}**) at the place of consumption including the electricity required for lighting and that required for cooling (if using a compression chiller) is purchased from the grid (**E_b**). Heating (**H_{dem}**) is supplied by fuel consumption in the heat generation unit (boiler).

5. Performance strategy

5.1. Traditional system (trad)

In the conventional system in this industrial complex, the maximum cooling and heating determine the nominal capacity of the electric chiller and boiler. The performance strategy of this system is evaluated by equation (17).

$$\begin{cases} H_{\mathrm{b}} = H_{\mathrm{dem}} \quad if \;\; C_{ab} = 0 \\ E_{\mathrm{b}} = E_{\mathrm{dem}} + C_{\mathrm{dem}} \times COP_{\,C} \\ C_{\mathrm{C}} = C_{\mathrm{dem}} \end{cases} \tag{17}$$

When an absorption chiller (not a compression chiller) is used, the heating unit will also supply the heat required for cooling (C_{dem}). In this case, the maximum cooling determines the nominal capacity of the absorption chiller and the total heating required for the building while the heat required for the absorption chiller will determine the nominal capacity of the boiler according to the equation (18):

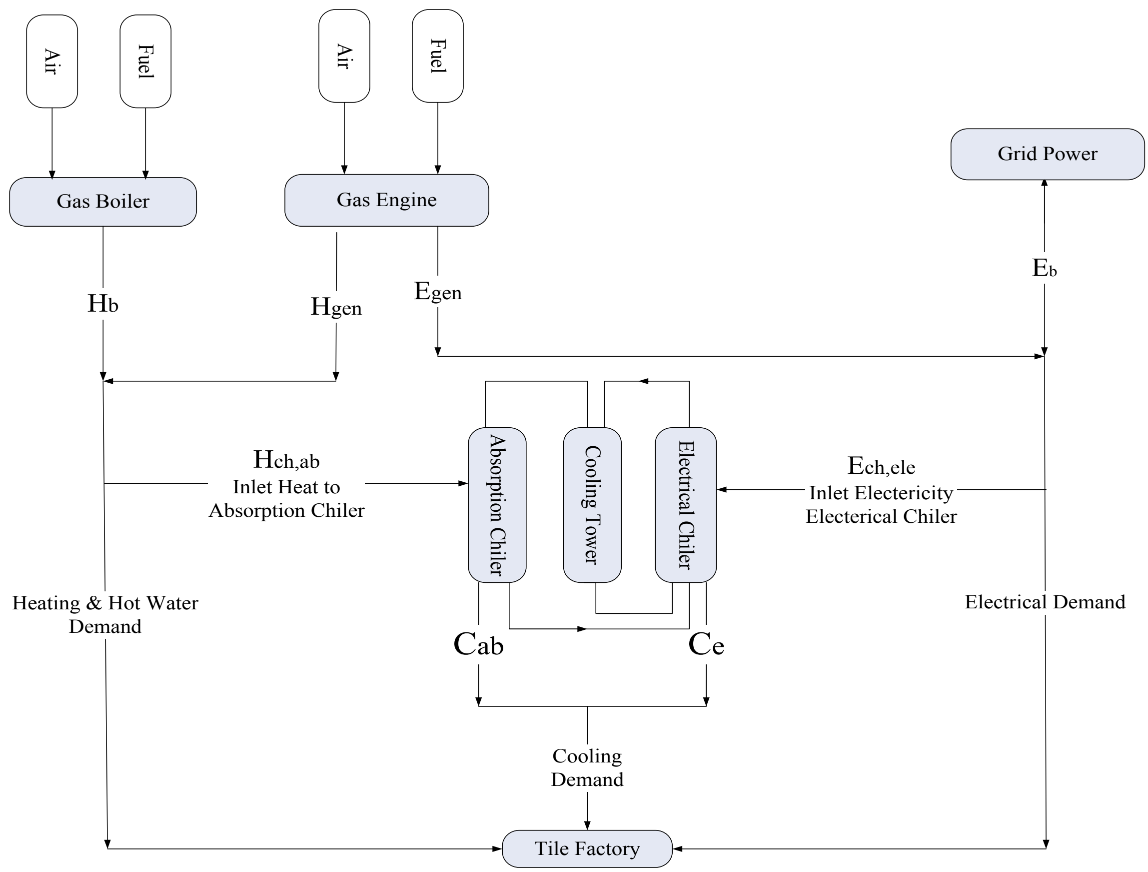

Figure 1. Combined cooling, heating and power generation with the conventional system of the industrial complex.

$$\begin{cases} H_b = H_{dem} + C_{dem} \times COP_{ab} \\ E_b = E_{dem} \\ C_{ab} = C_{dem} \quad if\ E_C = 0 \end{cases} \tag{18}$$

5.2. *Combined cooling, heating and power (CCHP) generation system*

In this system, a gas engine as a power generation unit (prime mover) supplies the electricity required for the building including lighting (E_{dem}) and the electricity required for the compression chiller (E_C).

If the electricity generated by the prime mover (E_G) is less than that required for the building, electricity shortages will be supplied by purchasing electricity from the grid. In this case, the electricity sold (E_s) to the grid will be zero according to the equation (19):

$$\begin{cases} E_s = 0 \quad if\ E_G < (E_{dem} + E_C) \\ E_b = E_{dem} + E_C - E_G \end{cases} \tag{19}$$

If the electricity generated is greater than the required electricity, the system will be able to sell surplus electricity to the grid according to the equation (20):

$$\begin{cases} E_s = E_G - E_{dem} - E_C \quad if\ E_G > (E_{dem} + E_C) \\ E_b = 0 \end{cases} \tag{20}$$

Building heating demand (H_{dem}) will be supplied by the heat losses from the power generation unit (H_G). If the generated heat is higher than the heating demand, the excess heat is used for cooling by the absorption chiller (C_{ab}). If the absorption chiller alone cannot provide the required cooling demand (C_{dem}), the compression chiller (C_c) will supply cooling shortage. This strategy is formulated by the equation (21):

$$\begin{cases} H_b = 0 \quad if\ H_G > H_{dem} \\ C_{ab} = (H_G - H_{dem})/COP_{ab} \\ C_c = C_{dem} - C_{ab} \end{cases} \tag{21}$$

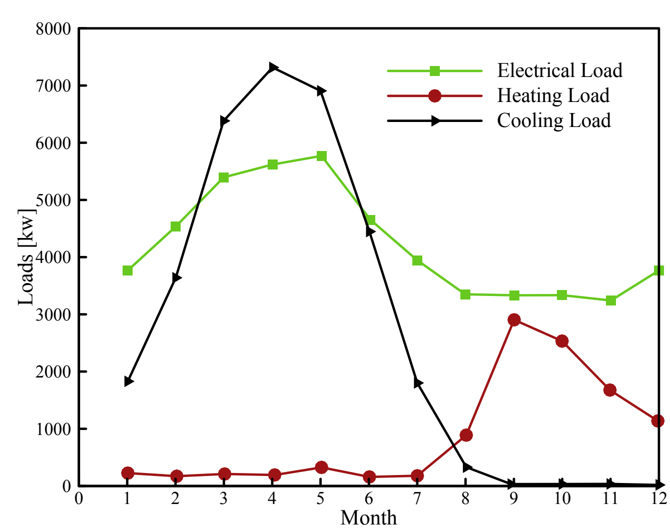

Figure 2. Distribution of annual cooling, heating and electrical loads in the industrial complex.

Table 2
Design parameters in the genetic algorithm.

Parameters	Values
The changes in the nominal capacity of prime movers (kW)	50 to 6000
The changes in the partial load of prime movers (%)	20 to 100
The changes in the heating capacity of the boiler (kW)	0 to 6000
The changes in the cooling capacity of the compression chiller (kW)	0 to 8000
The changes in the cooling capacity of the absorption chiller (kW)	0 to 8000

If the heat generated by the prime mover is less than the heat demand of the industrial complex, additional heating is provided by the boiler while the required cooling is supplied by the compression chiller (C_c) as indicated by the equation (22):

$$\begin{cases} H_{\text{b}} = H_{\text{dem}} - H_{\text{G}} \quad if \;\; H_{\text{G}} < H_{\text{dem}} \\ C_{\text{ab}} = 0 \\ C_{\text{c}} = C_{\text{dem}} \end{cases} \tag{22}$$

6. Multi-criteria optimization (energy, economic and environmental analysis) by the genetic algorithm

In this section, the multi-criteria optimization (energy, economic and environmental) of the combined cooling, heating and power generation system in a tile factory by the genetic algorithm is discussed. The design parameters include the number and capacity of the prime movers, boiler heating capacity, cooling capacity of chillers and the partial load of the prime movers throughout the year in three scenarios of possibility of selling electricity (selling scenario or SS), possibility of selling electricity with similar capacities of the gas engine and impossibility of selling electricity to the grid (no-selling scenario or NS). The design parameters are optimized by using the relative annual benefit (RAB) with the help of the genetic algorithm.

Table 2 shows the range of design parameters and Table 3 lists the optimization constraints. Evolutionary algorithms are the most important applied methods in optimization with a difference in determination of the Pareto front. Since the genetic algorithm often gives best solution with a rapid convergence than other similar evolutionary algorithms, a multi-objective genetic algorithm is used in this study. The optimal value of the design parameters is obtained based on the maximum value of the objective function in the equation (23) [49,50]:

$$Max\{RAB\} = \left(n_{\text{j}} \;\times E_{\text{nom}}\right)^{\text{optimum}} \tag{23}$$

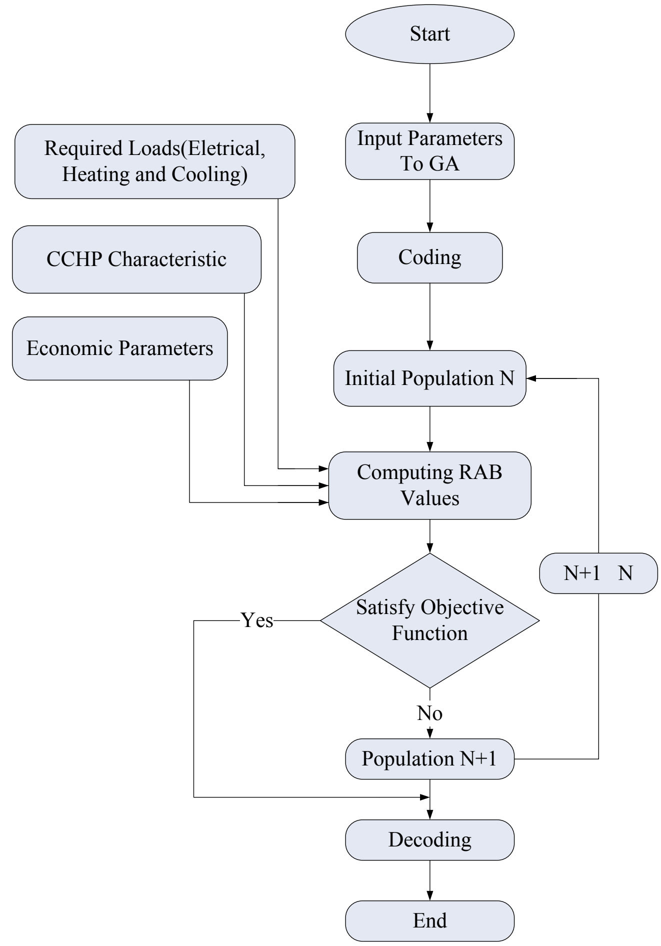

Figure 3. The genetic algorithm flowchart.

7. Algorithm implementation

In this section, the genetic algorithm steps for determination of the optimal parameters of the CCHP system in the tile factory are briefly discussed. The relative annual benefit is a discrete, non-linear, and non-differentiable function. Due to the specific features of the genetic algorithm, this algorithm is used for optimizing the design parameters. Fig. 3 shows the genetic algorithm flowchart to understand the problem solving algorithm.

7.1. Encoding

The first step in the genetic algorithm is to encode the virtual

Table 3
Constraints and optimization conditions in the genetic algorithm.

Parameters	Value	The reasons for constraint
The outlet temperature of the prime mover exhaust	$T < 148.8$	Environmental limitation
The outlet temperature of the boiler exhaust	$T < 121.2$	Environmental limitation
Partial load	$PL > 20$	Efficiency limitation
Gas engine capacity	$E_{\text{nom}} < 6000$	Efficiency and cost limitations
Population	94	Convergence
Selection	*Uniform*	Convergence
Scaling	*Random*	Convergence
The probability of gene combination	0.85	Convergence
Mutation type	–	Limitation-dependent
Minimum mutation rate	0.0005	Mutation type limitation
Initial mutation rate	0.005	Mutation type limitation
Termination criterion	10^{-6}	-

search space. The operating range of each equipment of the CCHP system forms the search space so that each chromosome contains the capacity of each equipment in the CCHP system.

7.2. Fitness function calculation

The selected chromosomes in the genetic algorithm should have high fitness. Hence, the fitness is considered as an inverse of the objective function. Since the objective function can be positive or negative, it is deducted from M to achieve a positive result.

7.3. Objective function calculation

After decoding the chromosomes, the objective function in each generation is determined and then the fitness value for each chromosome is calculated. The new generation will be produced after applying genetic operators to the current generation.

8. Research validity

To evaluate the research validity, the results of optimization with the RAB objective function considering the gas engine prime movers were compared with those obtained by Sanaye *et al.* [8]. Sanaye *et al.* optimized the actual annual benefit (AAB) objective function through economic and energy analyses. In their study, they used a hypothetical system consisting of three prime movers: a gas engine, a diesel engine and a gas turbine with a backup boiler. Fig. 4 compares the results of this study with those obtained by Sanaye *et al.* [8] and shows a good agreement between the results in the high capacity of the gas engine.

9. Optimization of the CCHP system

In this section, the results of optimization of the CCHP system in the industrial complex (the tile factory) are discussed for three different strategies including selling, no-selling and selling with similar capacities. In addition, the design parameters including the number of prime movers, nominal capacity of the prime movers, the capacity of backup boiler and the capacity of absorption and compression chillers are interpreted and discussed.

Table 4
Optimal profitability of the three strategies.

Strategy	Optimal profitability ($/year)
Selling electricity to the grid	1.2981×10^6
Selling electricity to the grid with similar capacities	1.2773×10^6
No-selling	1.1605×10^6

Clearly, the tile factory is profitable in all three strategies. Comparing the above three strategies, it can be found that the selling scenario is more profitable. Table 4 shows the optimal profitability for the above strategies.

Comparing the relative annual benefit from the three strategies in Table 4, it can be seen that selling without similar capacities, selling electricity with similar capacities and no-selling scenarios are profitable, respectively. In other words, the selling scenario with similar capacities shows a moderate performance in terms of relative annual benefit.

Table 5 shows the result of optimizing the design parameters for selling and no-selling scenarios. According to the results:

- The number of initial gas engine prime movers is equal in both strategies.
- The capacity of the prime movers is equal in high capacities but is unequal in low capacities. The capacity of prime movers is higher in selling scenario.
- The required cooling load is provided by absorption and electric chillers in the no-selling strategy. In this case, approximately 30% of the cooling load is provided by an electric chiller.
- The capacity of the backup boiler is zero in the no-selling strategy while it equals 5200 kW in the selling strategy.

To better understand these two strategies, the electrical and

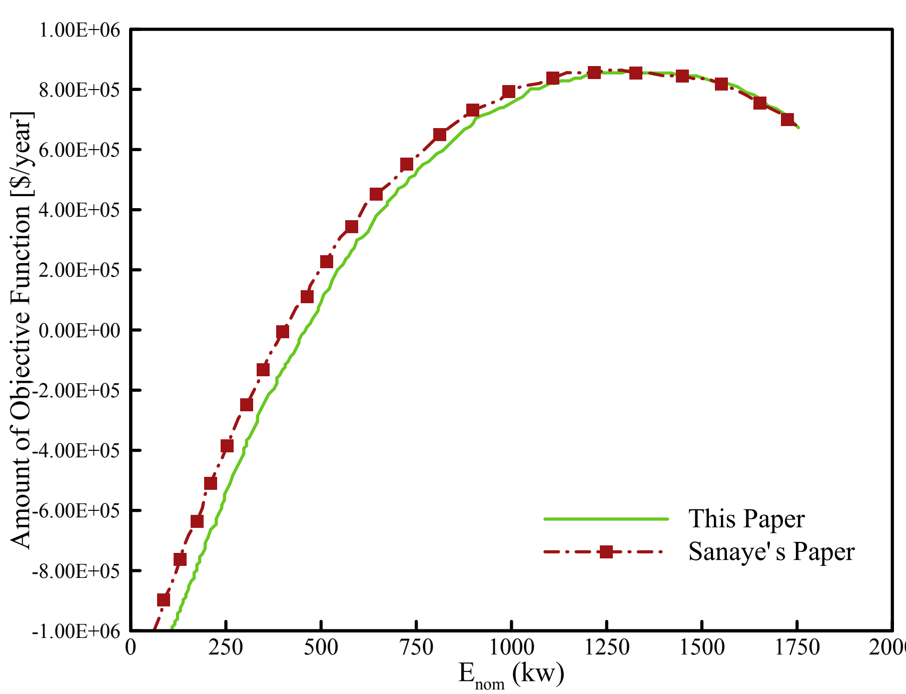

Figure 4. Comparison of the results of this study with those obtained by Sanaye *et al.* [8].

Table 5
The optimal values of design parameters in the selling and no-selling strategies.

Strategy	Selling	No-selling
Design variable	Optimal value	Optimal value
Number of prime movers	2	2
Nominal capacity of prime movers (kW)	5000–700	5000–500
Backup boiler capacity (kW)	4500	0
Electric chiller capacity (kW)	0	2500
Absorption chiller capacity (kW)	7400	4900

thermal performance curves of are shown in Figs. 5 to 8. The following results are obtained by analyzing these curves:

- Comparing the three strategies in terms of electricity purchasing from the grid, the selling strategy without similar capacities needs electricity purchasing with a maximum of one fifth than two other strategies only in five months. This strategy requires this maximum purchase in only one month, while the other two strategies need this five-fold maximum in three months.
- In the no-selling strategy, the heat generated by the prime movers throughout the year is more than that required by the industrial complex. Therefore, the backup boiler will not be used in the system. In other words, the backup boiler will be used to compensate for heat shortage.
- In warm seasons, the absorption chiller makes use of heat loss which is the difference between the heat generation and heat required in the industrial complex to provide the required cooling load. In fact, the maximum heat loss determines the maximum capacity of the absorption chiller. Therefore, the heat generated by the prime movers in warm seasons is more than the heat required in the industrial complex in the selling strategy without similar capacities. Excess heat in this strategy is used to produce cooling by the absorption chiller.
- In the no-selling strategy, approximately 30% of the required cooling load is provided by electric chillers, because the heat loss from the prime movers is low and the absorption chillers are not able to withstand the entire cooling load.

The selling strategy with and without similar capacities was analyzed after comparing the profitability of the selling and no-selling strategies. Table 4 shows the optimal profitability for the two above-mentioned conditions. According to the results, the selling strategy without similar capacities is more profitable. It should be noted that the selling scenario with similar capacities is more profitable than the no-selling strategy. Table 6 compares the design parameters for the above-mentioned conditions. The results are summarized as follows,

- The number of gas engine prime movers in the selling strategy with and without similar capacities is 1 and 2, respectively. This indicates the higher investment costs and consequently higher operating and maintenance costs. It is noteworthy that the selling scenario without the similar capacities with two prime movers is more profitable.
- The heat loss in the selling scenario with similar capacities is lower indicating the higher capacity of the boiler.

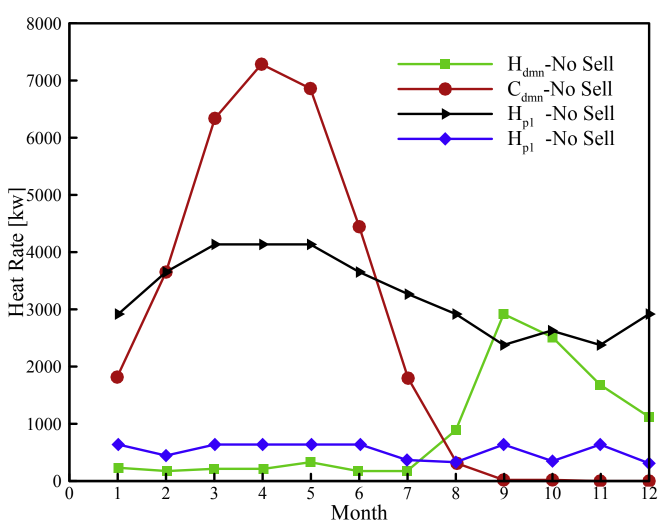

Figure 5. Thermal performance curves of the system in optimal mode (required heat, heat production and required cooling) in the no-selling strategy.

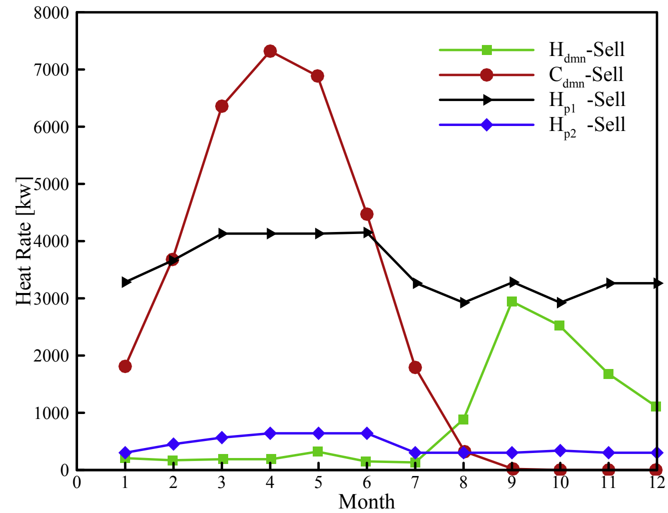

Figure 6. Thermal performance curves of the system in optimal mode (required heat, heat production and required cooling) in the selling strategy.

Figs. 9 and 10 shows the electrical and thermal performance curves for the selling scenario with and without similar capacities. As seen, it is necessary to purchase electricity from the grid with a maximum of about 1000 kW during 3–5 months in the optimal mode. On the other hand, it is possible to sell electricity to the grid in other months with a maximum of about 1000 kW.

10. Conclusion

In this study, modeling and multi-criteria optimization (energy, economic and environmental) of combined cooling, heating and power (CCHP) generation system in a tile factory was performed with the help of the genetic algorithm. In this regard, the difference between the total costs of the traditional and CCHP systems called relative annual benefit (RAB) was used to uniform all initial investment costs, maintenance and salvage costs and fines for polluting emissions, fuel consumption and electricity purchase from the grid by taking into account heating, cooling and electric loads in this industrial complex. In fact, RAB determines the optimal capacity of the CCHP system from the perspective of the first law of thermodynamics and economic and environmental analyses. By introducing a component based on the annual profit of the CCHP system relative to the traditional system, the optimal capacity of the system was obtained. The monthly sale and purchase of electricity and fuel cost, annual interest rate and useful life of equipment, as parameters dependent on the time value of

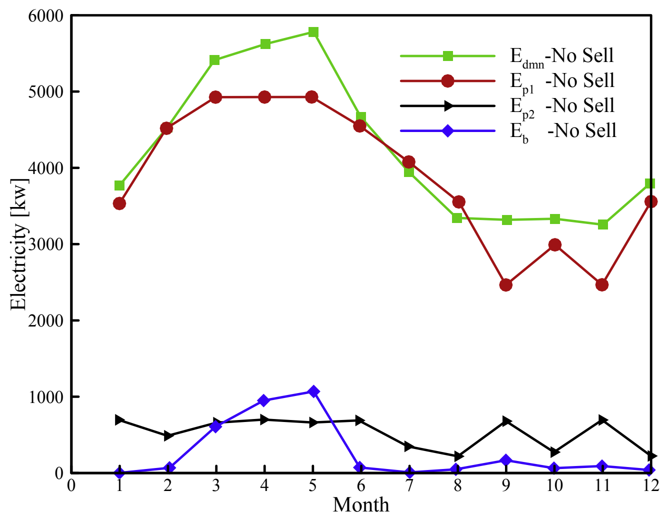

Figure 7. Electrical performance curves of the system in the optimal mode (required, produced and purchased electricity) in the no-selling strategy.

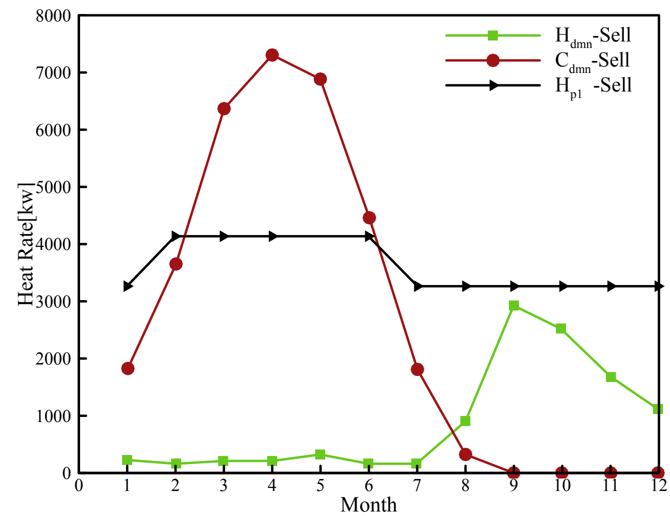

Figure 9. The thermal performance curves of the system in the optimal mode (required heat, heat production and required cooling) in the selling strategy with similar capacities constraint.

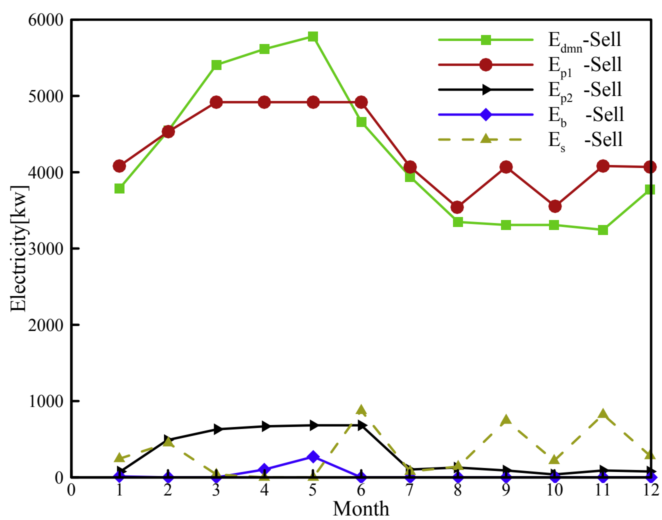

Figure 8. Electrical performance curves of the system in the optimal mode (required, produced and purchased electricity) in the selling strategy.

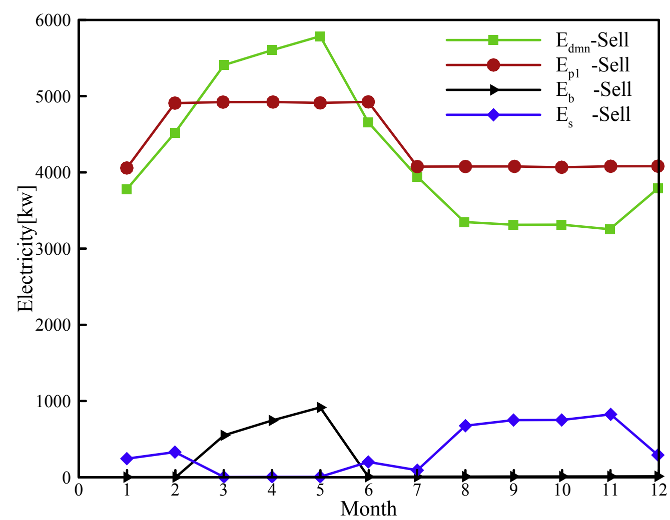

Figure 10. The electrical performance curves of the system in optimal mode (required, produced, purchased and sold electricity) in the selling strategy with similar capacities.

money, are effective in RAB calculations. The design parameters include the number and capacity of the prime movers, boiler heating capacity, cooling capacity of chillers and the partial load of the prime movers throughout the year. These design parameters were optimized using RAB and the genetic algorithm in three strategies of selling, no-selling and selling with similar capacities of the gas engine. The results obtained from this study are briefly represented below:

- ❖ Comparing the relative annual benefit from the three strategies, it can be seen that selling strategy without the similar capacities, selling electricity with similar capacities and no-selling scenarios are profitable, respectively. In other words, the selling scenario with similar capacities showed a moderate performance in terms of relative annual benefit.
- ❖ The tile factory was profitable in all three strategies.

Table 6
The optimal values of the design parameters in the selling scenario with and without similar capacities.

Strategy	With similar capacities	Without similar capacities
Design variable	Optimal value	Optimal value
Number of prime movers	1	2
Nominal capacity of prime movers (kW)	5000	5000–700
Backup boiler capacity (kW)	5200	4500
Electric chiller capacity (kW)	0	0
Absorption chiller capacity (kW)	7400	7400

- Comparing the strategies in terms of electricity purchasing from the grid, the selling strategy without similar capacities needs electricity purchasing with a maximum of one fifth than two other strategies only in five months. This strategy requires this maximum purchase in only one month, while the other two strategies need this five-fold maximum in three months.
- The heat generated by the prime movers in warm seasons is more than the heat required in the industrial complex in the selling strategy with and without similar capacities. Excess heat in this strategy is used for cooling by the absorption chiller.
- Heat generated by the prime movers in the no-selling strategy amounts to the extent that approximately 30% of the required cooling is provided by a compression chiller in the optimization of the CCHP system.
- The CCHP system in this industrial complex shows a better performance in the selling strategy with a capacity of 5000 and 700 for the gas engine. However, the nominal capacity of the prime movers in the selling scenario was higher than that in the no-selling strategy due to the higher flexibility of the selling scenario than the no-selling scenario in generating surplus electricity to sell to the grid.
- The relative annual benefit decreases by selecting a similar capacity.

Nomenclature

A	Annual Salvage Cost $/year
C	Capital investment (cost) ($/kW)
CCHP	Combined cooling, heating and power
COP	Coefficient of performance (%)
E	Electricity (kW)
EUAC	Equivalent Uniform Annual Cost ($/year)
H	Heat (kW)
i	Interest rate (%/year)
j	Counter of month
k	Equipment's life (year)
LHV	Fuel lower heating value (kJ/kg)
m	Mass Flow rate (kg/s)
M	Maintenance cost ($/kWh)
n	Number of Prime Movers
NC	Nominal capacity of equipment's (kW)
PL	Partial load (%)
RAB	Ratio Annual Benefits
R	Pollutant emission reduction (%)
SV	Salvage Value of equipment's ($/kWh)
trad	Traditional System
TAC	Total Annual Cost ($/year)

Greek symbols

β	Capital recovery factor
ε	Pollutant emission surcharge ($/kg)
ξ	Factor emission pollutant (kg/MWh)
η	Efficiency (%)
ρ	Fuel cost ($/kWh)
τ	Time period or hours of a month (hr)

Subscript

ab	Absorption chiller
b	Boiler/buy
C	Chiller(absorption or compression)
CCHP	Combined cooling, heating and power
dem	demand
E	Electricity (kW)
e	Electricity (kW)
c	Compression
f	fuel
G	Generated
H	Heat
j	Number of Equipment's
k	Counter of pollutant type
nom	nominal
PL	Partial Load
PM	Prime Mover
S	Sell

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