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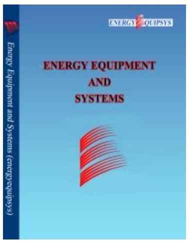

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Equipment capacity optimization of an educational building's CCHP system by genetic algorithm and sensitivity analysis

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ABSTRACT

Combined cooling, heating, and power (CCHP) systems produce electricity, cooling, and heat due to their high efficiency and low emission. These systems have been widely applied in various building types, such as offices, hotels, hospitals and malls. In this paper, an economic and technical analysis to determine the size and operation of the required gas engine for specific electricity, cooling, and heating load curves during a year has been conducted for a building. To perform this task, an objective function net present value (NPV) was introduced and maximized by a genetic algorithm (GA). In addition, the results end up finding optimal capacities. Furthermore, a sensitivity analysis was necessary to show how the optimal solutions vary due to changes in some key parameters such as fuel price, buying electricity price, and selling electricity price. The results show that these parameters have an effect on the system's performance.

Keywords: Combined Cooling Heating and Power, Net Present Value, Internal Rate of Return, Primary Energy Saving, Genetic Algorithm.

1. Introduction

Higher energy demand, reduced resources of fossil fuels, pollution of the environment by large-scale power plants, losses of power conduction lines, and renovation in the electricity industry force countries throughout the world to use distributed generation systems. Among them, using a combined cooling, heating, and power (CCHP) system with a total efficiency of 70 to90% is one of the effective alternatives in optimizing energy consumption. Therefore, CCHP systems emit less environmental pollutants and Iran is one of the countries that can develop such systems. To install these systems, it is necessary to determine accurately the kind of prime mover, operation strategy, and optimal capacity of components (auxiliary boiler, thermal storage system, absorption chiller, or compression chiller). If the needed parameters are not selected accurately, the project efficacy could go down.

There are different points of view for determining the parameters of simultaneous production units. The objective functions have been defined from the viewpoints of the network, owner, and investor, and they were studied by different methods [1] used mixed-integer nonlinear programming to decide the

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optimal size of the combined heat and power system in consideration of the plant's annual operational strategy [2]compared a CCHP model with separate generation and the results showed 35% primary energy saving (PES) by the CCHP systems compared to the conventional separate systems.

Lin et al. [3] investigated the experimental model to compare the trigeneration system with separate generation. The test results showed that the total thermal efficiency of the CCHP reaches 67.3% at engine full load, compared to that of the original single generation, which touches 22.1% only. The other experimental investigation had been done by Kamal Kishore Khatri et al.[4].The test results showed that the total thermal efficiency of the CCHP system reaches 86.2% at the full load whereas it is only 33.7% for the original single generation at the same load. The CO2 emission from the CCHP is less than from single generation at the engine's full load. The research done by Jeremy Cockroft and Kelly [5] described an analysis in which the performance of four different technologies of prime movers was compared to a common energy supply from condensing gas boilers and grid electricity for a number of scenarios. Sun [6] studied a combined heat and power system with a gas engine prime mover by considering its economy.

The results showed that comparative PES of the CHP system was more than 37% compared to the conventional separate system at the required energy flows. The total annual income, total annual saving, and payback period of the CHP system were used to analyze its economy. Fumo et al. [7] showed that CHP systems increase site energy consumption (SEC); therefore, primary energy consumption (PEC) should be used instead of SEC when designing CHP systems. Ehyaei and Bahadori [8] studied the optimization of micro turbine applications to meet electric, heating, and cooling loads of a building through an energy economics and environmental analysis. They evaluated three different scenarios.

Typically, there are two basic operation strategies: Following the thermal load (FTL) and following the electric load (FEL). They can also be referred to as thermal demand management (TDM) and electric demand management (EDM) [9]. When operating in FTL mode, the CCHP system satisfies the building's thermal load first; if the by-product electricity cannot meet the electric demand, additional electricity should be purchased from the local grid. The FEL mode provides sufficient electricity for the building first, and then if the by-product heat cannot meet the thermal demand, an auxiliary boiler will be activated. However, both the FEL and FTL strategies will inherently waste energy. Mago et al [10] proposed and investigated an MCCHP system operation following a hybrid electric-thermal load (FHL). This operation strategy was evaluated and compared with MCCHP systems operating FEL and FTL. This evaluation and comparison was based on the SEC, PEC, operational cost, and carbon dioxide emission reduction (CDER). The results showed that MCCHP systems which operated following the hybrid electric-thermal load had better performance than MCCHP-FEL and MCCHP-FTL. In other studies, [11-14] he CCHP systems were investigated based on economic or energetic analysis. These studies consider energy analysis to be a useful tool in performance assessments of CHP systems and permit meaningful comparisons of different combined heat and power systems based on their merits.

Basrawi et al. [15] nvestigated the suitable size (electricity output capacity) of micro gas turbine CHP systems depending on their scale of sewage treatment plant under various ambient temperature conditions. Their results showed that the ratio of heat demand to energy of biogas produced increases when scale of the sewage treatment plant decreases. Ghaebia et al. [16] used an economic model according to the total revenue requirement (TRR) and the cost of the total system product was an objective function and optimized using a GA technique.

Sayyaadi and Abdollahi [17] performed multi-objective optimization for sizing a small-scale CCHP system. Objective functions including energetic efficiency, total levelized cost rate of the system product and cost rate of the environment were optimized by the GA, simultaneously. The economic analysis was conducted in accordance with the TRR method. Wang et al. [18] analyzed the energy flow of the CCHP system. Three criteria—PES, annual total cost saving (ATCS), and CDER—were selected to evaluate the performance of the CCHP system. Then, the objective function of the integrated performance of the CCHP was constructed and the GA was employed to optimize design capacity and operation.

In this study, the annual profit (AP) for a CCHP system was formulated. Then, the objective function NPV of the integrated performance of the CCHP was constructed and the GA employed to optimize design capacity and operation. The NPV depends on three parameters: capacity of the power generation unit, heat produced by the boiler and the ratio of electric cooling to cool load.

Nomenclature

AP	Annual profit
CCHP	Combined cooling heat and power
CHP	Combined heat and power
COP	Coefficient of performance
CP	Capacity
GA	Genetic algorithm
HR	Heat rate kwh/m3
IRR	Internal rate of return
MCCHP	Micro combined cooling heat and power
NAP	Net annual profit
NPV	Net present value
PES	Primary energy saving
PGU	Power generation unit
SP	Separation production

Subscripts

AB	Absorption chiller
b	Boiler
c	Cool
D	Demand
DH	Domestic heat
d	Day
e	Electricity
EC	Electric chiller
F	Fuel
G	Electricity grid
h	Hour
re	The part of recovery heat for cooling
rec	Waste heat recovery
rh	The part of recovery heat for heating

Symbols

C	Cost
E	Electricity
Q	Heat

2. Analysis

The main difference between the simultaneous production systems and the typical methods of electric generation is the utilization of waste heat rejected by the prime mover in order to satisfy the thermal demand of a facility (cooling, heating, or hot water needs). In the CHP system, the waste heat is used to satisfy the heating load of the facility. But in the CCHP system, often identified as the trigeneration or BCHP[1] system, the waste heat is used to satisfy the heating load in winter and the cooling load in summer.

There is no clear border between the two categories (CHP and CCHP units). CCHP systems can cover a wide range of capacity from 500 MW to 1 kW. Most centralized power plants and industries applying CHP exceed 1 MW. The capacity of the distributed CCHP systems ranges from less than 1 kW in domestic dwellings to more than 10 MW in hospitals or university campuses, and as much as 300 MW to supply energy to a district of a city. One report defines ''everything under 1 MW'' as ''small-scale.'. ''Mini'' usage is under 500 kW and ''micro'' use is under 20 kW' [19]. The schematic of CCHP is shown in Fig. 1.

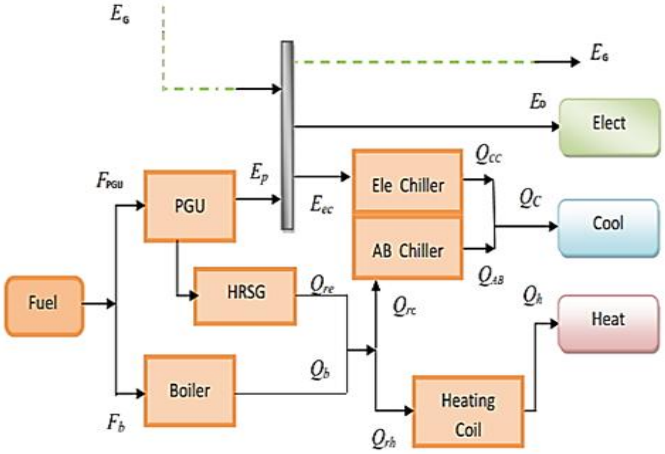

Fig.1. The Schematic diagram of the CCHP system with auxiliary components such as boiler and heating coil

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[1] Building cooling, heating, and power

The balance of the electric energy in a CCHP system is calculated according to Eq. (1) [18-19]:

$$E_{PUG} = \frac{E_{PUG}}{\eta_e} \tag{1}$$

where E_G is the electricity from the grid in the CCHP system (when PGU generates the excess electricity, EG is negative and its value is equal to the excess electricity), E_{PGU} is the generated electricity by PGU, ED is the electric energy use (lights and equipment) of a building, E_P is the parasitic electric energy consumption of the CCHP system, and E_{EC} is the electric energy consumption for the electric chiller providing cooling to the building. The fuel used by the primary driving is obtained from Eq. (2):

$$E_{PGU} + E_G = E_D + E_P + E_{EC} \tag{2}$$

where ηe is the PGU generation efficiency and ηrec the heat recovery system efficiency. The recovered waste heat from the prime mover, Qrec , can be estimated as:

$$Q_{rec} = \frac{E_{PGU}}{\eta_e} \eta_{rec} \left(1 - \eta_e\right) \tag{3}$$

The heat content recycled from the CCHP and produced by the auxiliary boiler is used for providing heat for the thermal coil (Q_{rh}), and absorption chiller (Q_{rc}). Therefore:

$$Q_{rec} + Q_b = Q_{rh} + Q_{rc} \tag{4}$$

The heat required by the thermal coil for supplying the thermal demand of a building is obtained by:

$$Q_{rh} = \frac{Q_{DH}}{\eta_{hc}} \tag{5}$$

where Q_{DH} is the heat demand for space heating and domestic hot water, and η_{hc} is the efficiency of the thermal coil. The heat required by the absorption chiller (Q_{rc}) that can supply the cooling demand is given by Eq. (6):

$$Q_{rc} = \frac{Q_{AB}}{COP_{AB}} \tag{6}$$

where Q_{AB} and COP_{AB} represent the cooling provided by the absorption chiller and the absorption chiller coefficient of performance, respectively. EEC is the electric energy consumption for the electric chiller, which provides cooling to the building. The electricity used by the electric chiller is calculated as:

$$E_{EC} = \frac{Q_{EC}}{COP_{EC}} \tag{7}$$

where Q_{EC} and COP_{EC} represent the cooling provided by the electric chiller and the electric chiller's coefficient of performance, respectively. The balance of the cooling load of the building is expressed as:

$$Q_c = Q_{EC} + Q_{AB} \tag{8}$$

where Q_c is the maximum cooling load of building, which is provided by both the electric and absorption chillers.

The supplementary fuel energy consumption of the boiler, F_b, can be computed as:

$$F_b = \begin{cases} \dfrac{Q_{rc} + Q_{rh} - Q_{rec}}{\eta_b} & Q_{rc} + Q_{rh} > Q_{rec} \\ 0 & Q_{rc} + Q_{rh} \leq Q_{rec} \end{cases} \tag{9}$$

where η_b is the back-up boiler efficiency. Therefore, the total fuel energy consumption for the site is calculated as:

$$F_{CCHP} = F_{PGU} + F_b \tag{10}$$

The total fuel energy consumption is estimated by Eq. (11).

$$F = \left(E_{PGU} \middle/ \eta_e \right) + F_b + \left(\frac{E_G}{\eta_e^{sp} . \eta_G} . V \right) \tag{11}$$

where η_e is the generation efficiency of SP, η_G is the transmission and distribution efficiency of the electricity grid, and

$$V = \begin{cases} 1, & E_G \geq 0 \\ 0, & E_G < 0 \end{cases} \tag{12}$$

The fuel energy consumption by the conventional power plant and boiler to satisfy the heating and cooling demand is estimated by Eq. (13).

$$F^{sp} = \left(E_D + E_P^{sp}\right) \middle/ \left(\eta_e^{sp} . \eta_G\right) + \frac{\left(Q_{EC} \middle/ COP_{EC} \right)}{\eta_e^{sp} . \eta_G} + Q_{DH} \middle/ \left(\eta_b^{sp} . \eta_h^{sp}\right) + \frac{\left(Q_{AB} \middle/ COP_{AB} \right)}{\left(\eta_b^{sp}\right)} \tag{13}$$

where E_p^{sp} is the additional electrical energy use of the distribution equipment such as pumps and fans in the SP system, and η_b^{sp} and η_h^{sp} are the efficiencies of the boiler and heating coil, respectively.

2.1. Primary energy savings (PES)

PES is defined as the ratio of saving energy of the CCHP system in comparison to the energy consumption of the SP system. It can be written as [18]:

$$\mathrm{PES} = \left(\mathrm{F^{SP}} - \mathrm{F_{CCHP}}\right) \Big/ F^{SP} = 1 - \left(\mathrm{F_{CCHP}} \big/ \mathrm{F^{SP}}\right) \tag{14}$$

2.2. Economic modeling of the CCHP system

To achieve optimal sizing and to operate the CCHP system, economic and technical analysis is essential. The objective function of the model is to maximize NPV for the building energy system. The NPV depends on the electrical power generated by the gas engine (E_{PGU}), the heat produced by the boiler (Q_b), and the ratio of electrical cooling to cooling load (R_c). This equation is displayed in Relation (15).

$$\mathrm{NPV} = \mathrm{f}\left(\mathrm{E_{PGU}}, \mathrm{Q_b}, \mathrm{R_c}\right) \tag{15}$$

where R_c is estimated by Eq. (16).

$$\mathrm{R_c} = \mathrm{Q_{EC}} \big/ \mathrm{Q_c} \tag{16}$$

$$\mathrm{Q_{AB}} = \mathrm{Q_c}\left(1 - \mathrm{R_c}\right) \tag{17}$$

NPV is estimated by Eq. (18). NAP is the net annual profit, RS the salvage's revenue that is obtained by Eq. (19) [20], and CCCHP is the investment cost of the CCHP that is obtained by Eq. (20).

$$\begin{aligned}\mathrm{NPV} = {} & \mathrm{NAP}.\left(\left((1+\mathrm{i})^{\mathrm{n}} - 1\right) \big/ \left(\mathrm{i}(1+\mathrm{i})^{\mathrm{n}}\right)\right) + \\ & \mathrm{R_s}\left(1/(1+\mathrm{i})^{\mathrm{n}}\right) - \mathrm{C_{CCHP}}\end{aligned} \tag{18}$$

$$\mathrm{R_s} = 0.2 \times \mathrm{C_{CCHP}} \tag{19}$$

$$\mathrm{C_{CCHP}} = \mathrm{C_{PGU}} + \mathrm{C_b} + \mathrm{C_{AB}} + \mathrm{C_{EC}} \tag{20}$$

The investment cost for the equipment of the CCHP system has been shown in Table 1.

Table 1. The investment cost for the equipment of the CCHP system [18-23]

Investment cost ($)	Formula
Gas engine	$\mathrm{C_{PGU}} = 139803.4 + 300.7\mathrm{E_{PGU}}$
Boiler	$C_b = 250.Q_b^{0.78}$
Absorption chiller	$C_{AB} = c_{AB}.Q_{AB}$
Compression chiller	$C_{EC} = c_{EC}.Q_{EC}$

AP is obtained by the difference between the revenues and costs of the CCHP. The turnover is the revenue from selling electricity, the income from recovery heat, and the income from eliminate selling electricity from the grid. The costs are the entire sum, over all time steps, of the cost of buying electricity from the network, the cost of O&M of the CCHP plant and back-up boiler, and the cost of fuel of the CCHP plant and back-up boiler. The AP in winter is different from the AP in summer because in winter the building needs just heat but in summer the building needs cooling and a little hot water. Therefore, AP for summer and winter is obtained separately. The AP in summer and in winter is estimated by Eq. (21) and Eq. (22) respectively.

$$\begin{aligned}\mathrm{AP_S} = \sum_{d=1}^{122}\sum_{h=1}^{24}\Bigg[& \left(\left(\mathrm{E_{PGU(d,h)}} - \mathrm{E_{D(d,h)}} - \mathrm{E_{EC(d,h)}}\right).\mathrm{Z}.\mathrm{C_s} + \left(\mathrm{Q_{rec(h,d)}}.\mathrm{U_b} \big/ \mathrm{\eta_b}\right) + \left(\mathrm{E_{D(h,d)}}.\mathrm{Z} + \mathrm{E_{PGU(d,h)}}.\left(1-\mathrm{Z}\right)\right).\mathrm{C_G}\right) \\ & -\left(\left(\mathrm{E_{PGU(d,h)}}.\mathrm{U_{PGU}}\right) + \left(\mathrm{Q_{b(d,h)}}.\mathrm{U_b}\right) + (\mathrm{E_{PGU(d,h)}} + \mathrm{Q_{b(d,h)}} + \mathrm{Q_{AB(d,h)}} + \mathrm{Q_{EC(d,h)}}\right).\mathrm{C1_{OM}} \\ & +\left((\mathrm{E_{D(d,h)}} + \mathrm{E_{EC(d,h)}} - \mathrm{E_{PGU(d,h)}}\right).\left(1-\mathrm{Z}\right).\mathrm{C_g})\Bigg]\end{aligned} \tag{21}$$

$$\begin{aligned}\mathrm{AP_w} = \sum_{d=1}^{155}\sum_{h=1}^{24}\Bigg[& \left(\left(\mathrm{E_{PGU(d,h)}} - \mathrm{E_{D(d,h)}}\right).\mathrm{K}.\mathrm{C_s} + \left(\mathrm{Q_{rec(h,d)}}.\mathrm{U_b} \big/ \mathrm{\eta_b}\right) + \left(\mathrm{E_{D(h,d)}}.\mathrm{K} + \mathrm{E_{PGU(d,h)}}.\left(1-\mathrm{Z}\right)\right).\mathrm{C_G}\right) \\ & -\left(\left(\mathrm{E_{PGU(d,h)}}.\mathrm{U_{PGU}}\right) + \left(\mathrm{Q_{b(d,h)}}.\mathrm{U_b}\right) + (\mathrm{E_{PGU(d,h)}} + \mathrm{Q_{b(d,h)}}\right).\mathrm{C1_{OM}} + \left((\mathrm{E_{D(d,h)}} - \mathrm{E_{PGU(d,h)}}\right).\left(1-\mathrm{K}\right).\mathrm{C_g})\Bigg]\end{aligned} \tag{22}$$

The fuel cost is calculated from the cumulative fuel consumption for each period of the CCHP plant or boiler multiplied by the fuel price by Eq. (23), where C_F is fuel cost and HR is heat rate.

$$U = \frac{C_F}{\eta_{(d,h)}.HR} \tag{23}$$

In general, the AP is obtained by Eq. (23).

$$NAP = AP_S + AP_W - \left(E_{PGU(d,h)} + Q_{b(d,h)} + Q_{AB(d,h)} + Q_{EC(d,h)}\right).C2_{OM} \tag{24}$$

$$K = \begin{cases} 1, & E_{PGU} \geq E_D \\ 0, & E_{PGU} < E_D \end{cases} \tag{25}$$

$$Z = \begin{cases} 1, & E_{PGU} \geq E_D + E_{EC} \\ 0, & E_{PGU} < E_D + E_{EC} \end{cases} \tag{26}$$

Payback period (PP) is the ratio of the capital investment to the projected annual cash flows in the financial period, which is expressed by the following Eq. (27):

$$PP = \frac{C_{CCHP}}{NAP} \tag{27}$$

The data assumption for the analysis is shown in Table 2.

2.3. Main constraint

A balance of supply and demand has to be achieved for both heat and electric power at each point of time. The electric power capacity constraint is shown in Eq. (28) and the cooling load balance is shown in Eq. (29). The performance characteristic of the back-up boiler is constrained by Eq. (30) to prevent it from exceeding its related capacity.

$$E_{min} \leq E_{PGU} \leq \left(\left(\frac{Q_{cmax}}{COP_{AB}}\right).\left(\frac{\eta_e}{1-\eta_e}\right).\eta_{rec}\right)\right) \tag{28}$$

$$Q_{cmax} = Q_{EC} + Q_{AB} \tag{29}$$

$$0 \leq Q_b \leq (\left(\frac{Q_{cmax}}{COP_{AB}}\right) - Q_{rec} \tag{30}$$

Table 2. Data assumption for analysis [18-24]

	Item	Symbol	Value
CCHP plant	PGU efficiency	η_e	0.37
	Heat recovery system efficiency	η_{rec}	0.8
	Heating coil efficiency	η_h	0.8
	Boiler efficiency	η_b	0.8
	Vapor compression coefficient of performance	COP_{EC}	3.4
	Absorption chiller coefficient of performance	COP_{AB}	0.7
SP system	PGU of separation efficiency	η_e^{SP}	0.35
	Grid transmission efficiency	η_G	0.88
Others	Electricity price (R/kwh)	C_G	380
	Electricity buy-back (R/kwh)	C_s	410
	Heat rate (kw h/m^3)	HR	11
	Natural gas (R/m^3)	C_F	1000
	O&M cost (MR/kwh)	$C1_{OM}$	0.176
	O&M cost fix (MR/kw)	$C2_{OM}$	79.2
	Absorption chiller set installation cost (MR/kw)	c_{AB}	3.4
	Electrical chiller set installation cost (MR/kw)	c_{EC}	2.04
	Interest rate (%)	i	10
	Life	n	20

2.4. Case study

The mechanical department of KNT University was selected for this investigation. This building is a 10-storeyed building, with a total floor area of 20000 m2. The electricity demand for the building is supported by the electricity network and the thermal energy is supported by the boiler that has natural gas as fuel. No thermal insulation is employed in the walls or the roof of the building. This study aimed to investigate a building in Tehran, considering the thermal, cooling, and electricity load, as well as evaluating the technical and economic analyses. The plan of the building is shown in Fig. 2. To estimate the electrical energy demand of the building under consideration, a general description of the building is presented in Table 3 and it was compared with the annual consumption of the building (electric bills). The maximum consumption of electricity was 495 kW in July.

Hourly heating and cooling energy demands have been estimated by employing the Carrier 2005 hourly analysis program 4.2. The monthly electricity, heating, and cooling load requirements of the building during a year are shown in Fig. 3. The electrical and cooling hourly load are also calculated and shown in Fig.4.

Fig. 2. The plan of the mechanic's department in Vanak Square in Tehran

Table 3. General description of the building

Building type	**General offices**
Total area	20000 m2
Occupancy schedule	Until (fraction): 6 (0.1), 7 (0.6), 8 (0.8), 12 (1), 16 (0.9), 17 (0.7), 18 (0.4), 24 (0.1)
Electric equipment (such as computers and pumps and etc.)	94800 W
Equipment schedule	Same as for occupancy
Lights	20 w/m^2
Lights schedule	Same as for occupancy

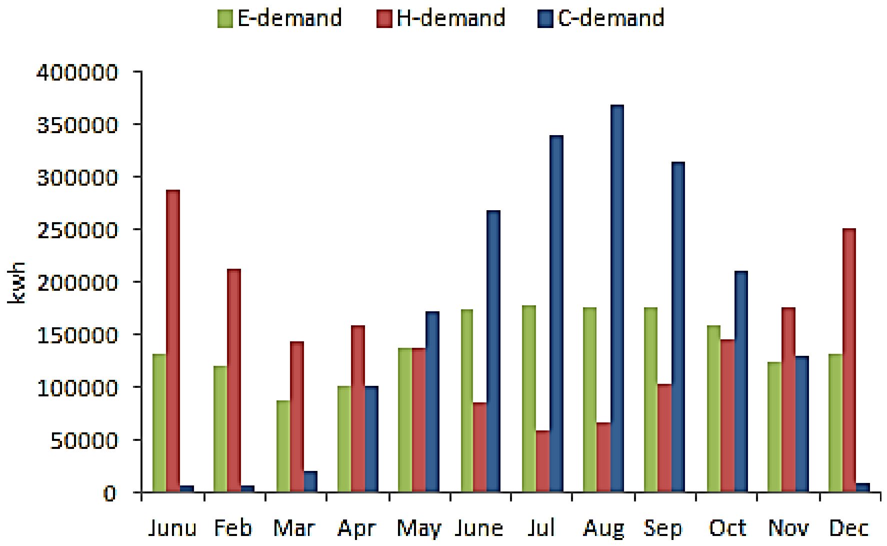

Fig. 3. The required electricity, heating, and cooling loads for the studied building

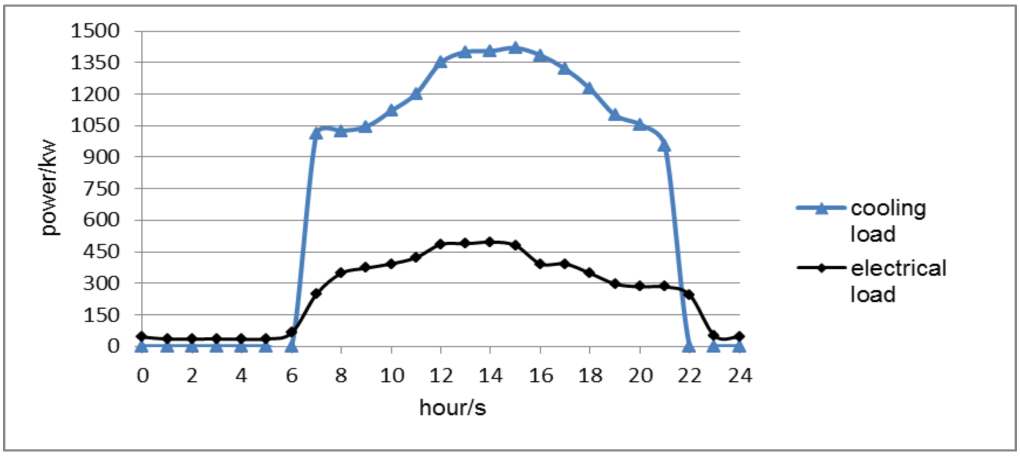

Fig. 4. Hourly load profiles

3. Results

3.1. Optimization calculation

Compared to other methods, the GA is a valid search method that needs no initial information and searches in the global optimization solution. The GA operates in parallel from multi-points, and searches heuristically in the solution area. Consequently, the GA overcomes the search blindness and the search speed of the GA is faster than the simplex method. The major advantages of GAs are: The constraints of any type can easily be implemented and GAs usually find more than one near-optimal point in the optimization space, thus permitting the use of the most applicable solution for the optimization problem at hand.

The optimal values of the capacity of the PGU, the capacity of the boiler, and the ratio of the electric cooling to cool load are searched by GA. Figure 5 shows variables of the objective function NPV and optimum variables are shown in Table 4.

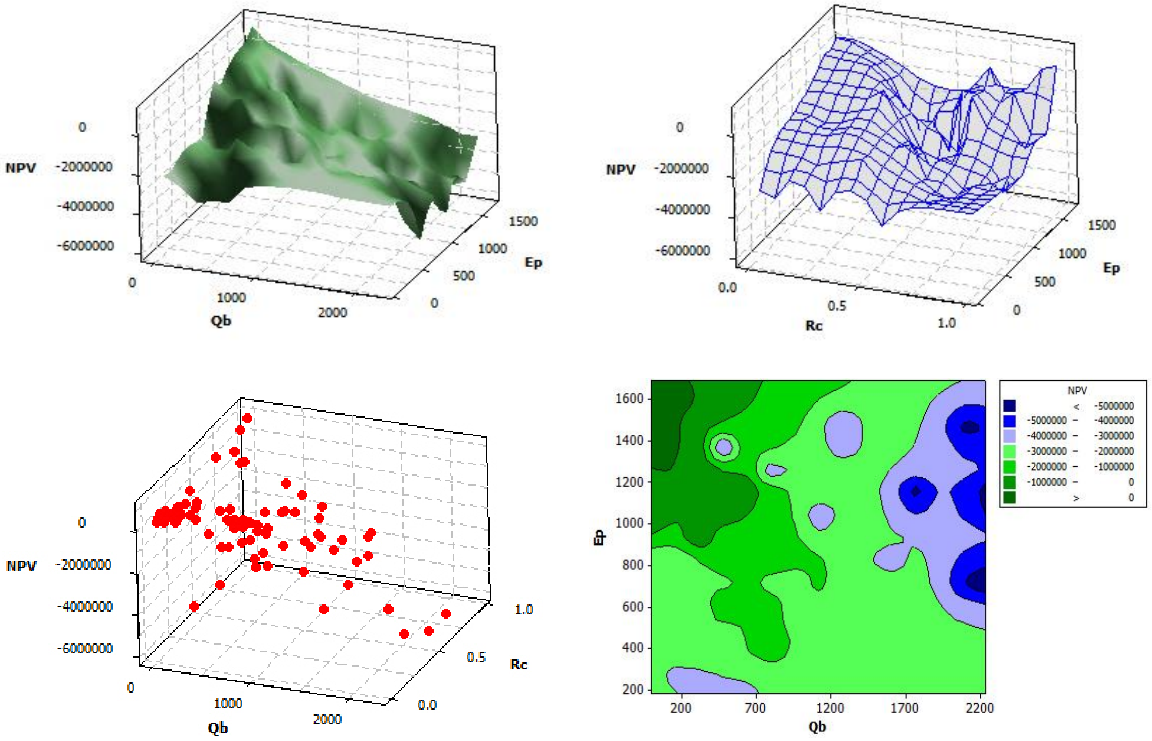

Fig. 5. Optimization process of the objective function by GA

Table 4. The variables are optimized by GA programming

Variable		value
Optimal capacity of PGU (KW)	E_{pgu}	1690
Optimal capacity of boiler (KW)	Q_b	10
Optimal ratio	R_c	0.95
Crossover probability		0.7
Mutation probability		0.02
NPV (MR[1])		8496
Payback period (year)		4.9

3.2. PES analysis

The PES and IRR are calculated when the CCHP system provides the thermal and electrical load of the building. The ‘‘sell’’ mode indicates that selling the excess electricity generated to the grid is allowed. In the ‘‘no sell’’ mode, selling the excess electricity generation to the grid is not allowed. These parameters are shown in Figure 6.

The PES-no-sell is related to the state that the CCHP cannot sell electricity to the grid, but in the sell mode the CCHP can sell extra electricity to the grid.

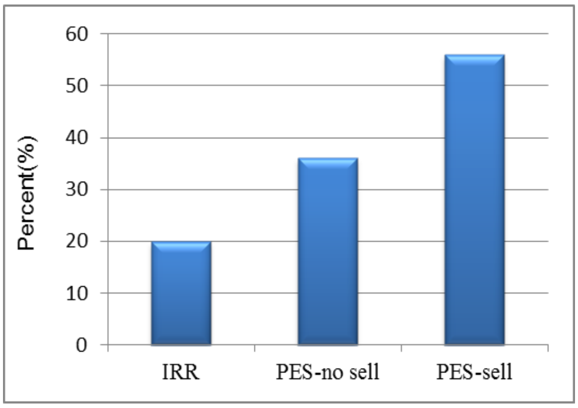

Fig. 6. The calculated values of IRR and PES

3.3. Model CCHP system in the thermoflex software

The optimal CCHP system is modeled by the thermoflex software in order to investigate the system in view of the thermodynamics. The schematic of the CCHP that is modeled in this software is shown in Fig. 7. The results are shown in Table 5.

3.4. Sensitivity analysis

Sensitivity analysis improves understanding of the influence of key parameters on the decision to adopt the CCHP systems. In this study, sensitivity analysis has been performed on natural gas prices, electricity prices, as well as electricity buy-back prices. Another main component of the NPV for residential energy system, cost for electricity buy- back (C_s) is partly decided by the electricity price (C_g), which also has an important effect on the adoption of CCHP systems. This is because if the electricity price is relatively low, the customer will prefer to purchase electricity from the grid rather than generate it on-site. Fig. 8 shows that the intuitive result of the CCHP economic feasibility is quite sensitive to the electricity prices. When C_g and C_s increase, the NPV increases, but the NPV decreases when the C_f increases.

Also, considering changes in PES based on the PGU's electric efficiency, the conventional power plant electric efficiency and grid electric efficiency had been investigated. The results show that when η_{PGU} increases, the PES increases, but the PES decreases with increase in η_{sp} and η_G. These changes are shown in Fig. 9.

The changes of various ratios of electricity cooling are displayed in Fig. 10. When the ratio of electricity cooling to cool load (R_C) increases, the NPV increases.

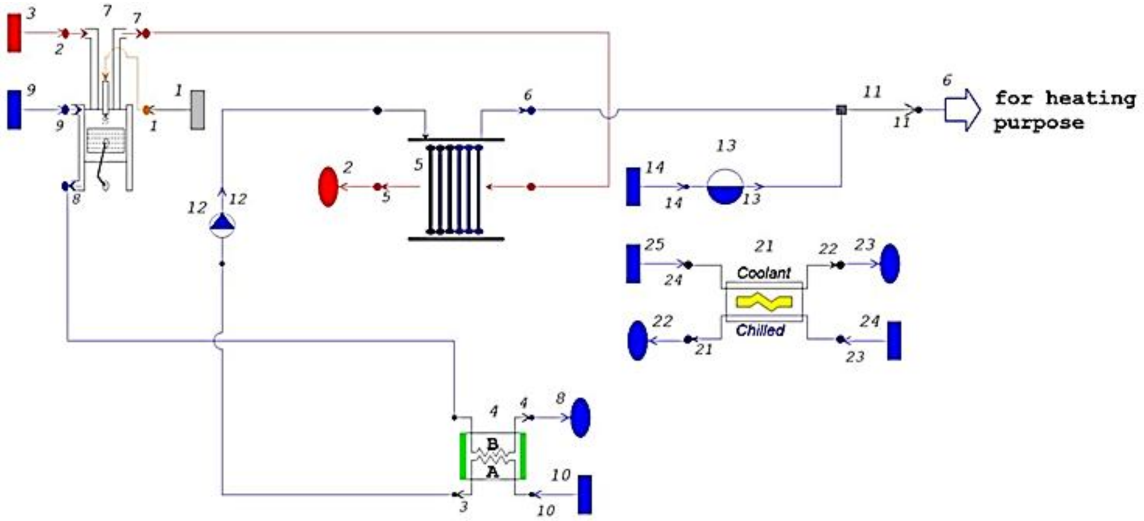

Fig. 7. The CCHP model

Table 5. Plant Summary

Ambient pressure [bar]	1.013	Net fuel input (HHV) [kW]	5190
Ambient RH [%]	60	Plant auxiliary [kW]	456.7
Ambient temperature [°C]	25	Net power [kW]	1293.3
Net process output [kW]	2516.1	CHP efficiency [%]	81.26
Gross electric efficiency (LHV) [%]	37.33	PURPA efficiency [%]	54.42
Gross power [kW]	1750	Total owner's cost [Million R]	7237

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1. Million Rial

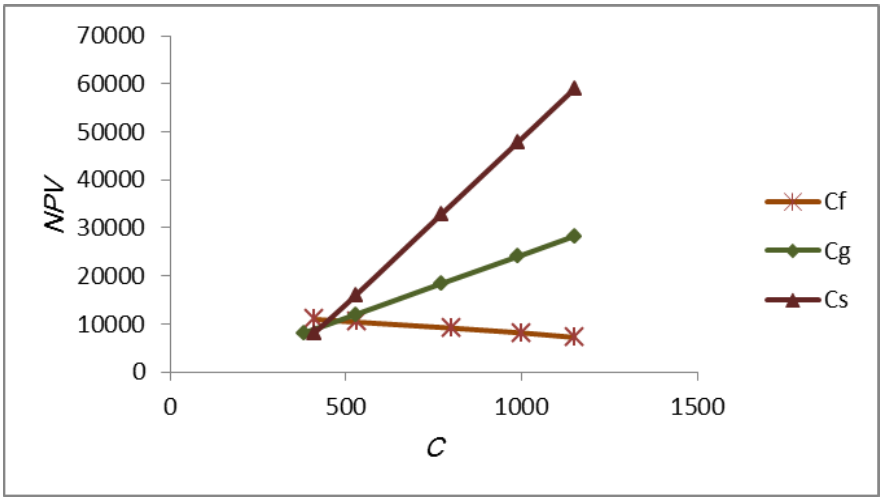

Fig. 8. The effect of natural gas price (Cf), electricity price (Cg), and electricity buy-back price (Cs) on NPV

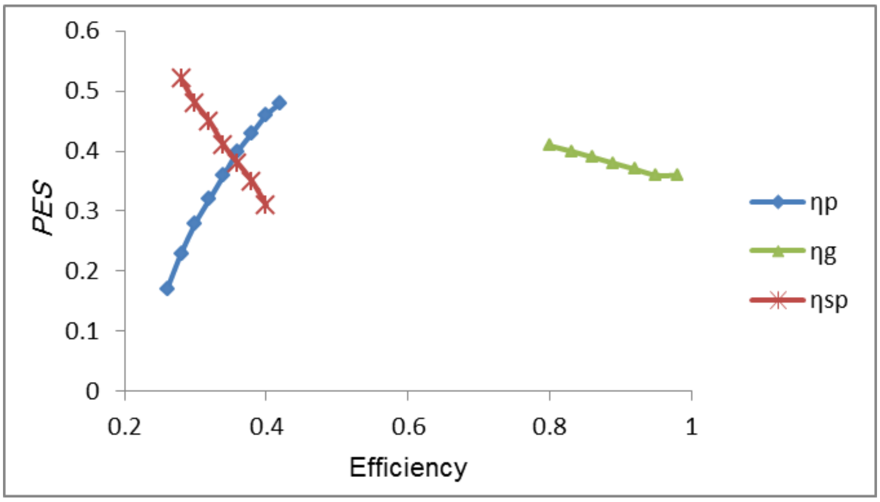

Fig. 9. The effect of η_{PGU}, η_{sp} , η_G on PES

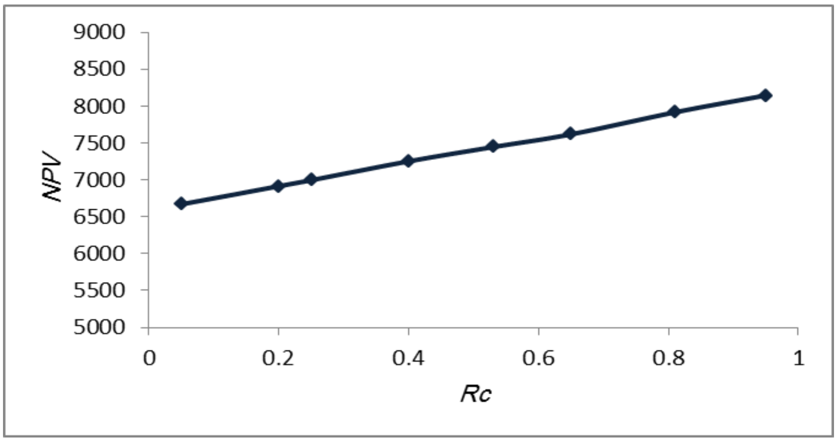

Fig. 10. Rc and NPV sensitivity

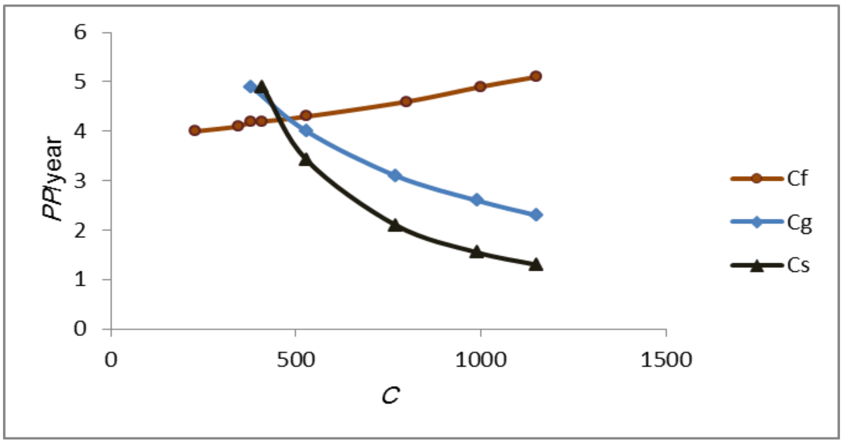

Fig. 11. The effect of natural gas price (Cf),electricity price (Cg), and electricity buy-back price (Cs) on payback period

Figure 11 compares the PP of the present CCHP system with different energy prices (C_G, C_F, C_{se}). If the natural gas cost increases slightly, the payback period of the CCHP system will increase and if the selling electricity cost and buying electricity cost increase slightly, the payback period of the CCHP system will decrease. In other words, if C_F decreases and C_G or C_{se} increases, the CCHP system will be more profitable.

This analysis (Fig. 11) shows that increasing C_G and C_{se} is an effective way to stimulate adoption of the CCHP system because of the increased revenue from not selling electricity and selling electricity to the grid. But increasing the **CF** has a negative effect on the adoption of the CCHP system because of the increased cost of PGU fuel and boiler fuel.

4. Conclusion

In this paper, by using an economical and technical analysis, the size and operational parameters of the gas engine for specific electricity, cooling, and heating loads of a typical building located in Tehran (Iran) were selected. The optimization has been done based on current regulations in Iran. To carry out this analysis, an objective function—i.e. NPV—has been introduced and maximized. The payback period and PES of the chosen system have also been determined in this study. The results of this study have demonstrated optimal gas engine capacity as well as optimal boiler and chiller capacities.

For the optimization, GA has been used. In addition, the CCHP system was modeled by the thermoflex software and analysis was done in view of the reduction in the energy consumed. The results had shown that application of the CCHP based on the gas engine is economical because for the CCHP system selected, the payback period is 4.9 years and IRR is 19.9 percent. Finally, a sensitivity analysis had been done in order to show how the optimal solutions will vary due to changes in some key parameters such as fuel cost and electricity cost. The results showed that these parameters had significant effects on the system's performance.

In future studies, renewable energy can be introduced in the CCHP system. With the help of solar energy or other renewable energy sources, the whole CCHP system can be more efficient and economical.

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