Determining the Optimal Size and Operation Sensitivity Analysis of a CCHP System Implemented in a Residential unit in Tehran

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Received: 10 November 2011, Revised: 5 Mars 2012, Accepted: 2 May 2012

Abstract: Implementing a combined cooling, heating and power system(CCHP) to cool, heat and produce electricity is growing rapidly due to its efficiency and low emissions. In this paper, using economic analysis, the size and operation detail of the required gas engine and the specific electricity, cooling and heating load curves for a one year operating period has been determined. The proposed CCHP system meets thermal demands of the facility and has been evaluated under such strategy. Net Annual Profit (NAP) has been introduced as an objective function to be maximized through a developed nonlinear mixed integer programming software. The operation strategy and the payback period of the chosen system have also been determined. A study with the purpose of including or excluding subsidy prices has been carried out. Furthermore, a sensitivity analysis was elaborated in order to show the dependency of optimal solutions to some key contributing factors such as fuel price, electricity buying price and electricity selling price. Results show that, these parameters have significant effect on the system's performance.

Keywords: Apartment, Combined Cooling, Heating and Power- Optimization, Gas Engine, Mixed Integer Nonlinear, Subside

Reference: Gholami, A., Fathi, A., Ghazizadeh, M. S., and Mirrezai Roudaki, S. J., "Determining the Optimal Size and Operation Sensitivity Analysis of a CCHP System Implemented in a Residential unit in Tehran", Int J of Advanced Design and Manufacturing Technology, Vol. 6/No. 3, 2013, pp. 99-107.

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1 INTRODUCTION

Many flaws have been identified in the current electricity generation mechanism employed in the developed countries. Combined cooling, heating and power (CCHP) means to produce cooling, heating and power simultaneously from a single fuel source, often identified as tri-generation. CCHP systems have the potential for higher thermal efficiency over the separate production of power, cooling and heating. Therefore, less fuel is consumed for the same output, thereby reducing greenhouse gas emissions and lowering operational costs. The heat generated as a byproduct from traditional, centralized power generation is typically lost to the atmosphere through cooling towers, fuel gas or other means. Over two-third of all the fuel used to generate power in Iran is lost as heat.

In Iran, CCHP systems have been developed rapidly during the last 5 years, and are mainly installed in industrial sectors. However, in recent years, residential buildings as a key sector of energy consumption have become an attractive consumer of CCHP systems. It is believed that residential CCHP offers significant benefits to energy suppliers (improved profitability and customer retention), to household (reduced energy bills, increase reliability and availability) and to society (reduced CO2 emissions, reduced primary energy consumption, avoidance of central plant and network construction) as a whole. However, there are many barriers to develop residential CCHP penetration in Iran. Lack of a tool to evaluate the decision on the design and operation of the residential CCHP system is one of the major barriers. Various methods are used for economic study of CCHP systems [1].

Optimal capacity of CCHP system has been determined according to energy, economic and environmental analysis in states that CCHP is performed as FEL energy supplier, FTL energy supplier and hybrid electric-thermal load operation (HETS) energy supplier. References [2], [3] indicate the issue based on the view of an industrialist aiming to reduce the sample pay-back period for a gas engine and sterling engine. Reference [4] resolved the issue in the view of apartment owner aiming to increase NPV using genetic algorithm. Reference [5] resolved the optimization aiming to reduce CCHP system cost by nonlinear mixed integer programming and the results were analyzed for their sensitivity. Reference [6] resolved optimization issue aiming at maximizing the annual profit (AP).

In reference [7], the author initially referred to the energy balance for CCHP and obtained the optimal answer for the system aiming at maximizing the annual total cost saving (ATCS) plus primary energy savings (PES) plus Carbon Dioxide Emission Reduction (CDER). In reference [8], for micro turbine, the author obtained the cost of electricity and the heat produced using economic-energy analysis and then considering the annual profit as its objective function, obtained the maximum capacity in two states, network connected and network disconnected.

Hongbo Ren et al. used mixed-integer nonlinear programming for deciding the optimal size of cogeneration system from the aspect of plant's annual operational strategy [9].

2 CCHP SYSTEM DESCRIPTION

The CCHP system is shown in Figure 1which consists of gas engine, auxiliary boiler, absorption chiller, heat recovery generation and the coil system.

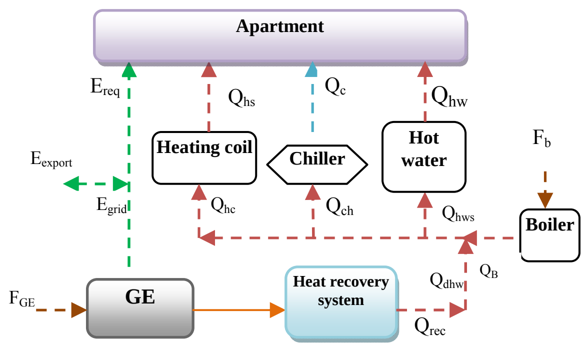

Fig. 1 Schematic of CCHP system

The high-temperature exhaust gas of GE is recovered to accommodate the thermal load for cooling in summer and heating in winter. If the heat recovered from the GE is not enough to fulfill the thermal energy requirement for building space cooling and heating, a boiler is used to provide the remaining required heat. The capacity of CCHP based on gas engine is usually between 50 kW to 10 MW [2].

The overall efficiency of these systems is about 80-95 percent. As energy saving measures is being seriously followed by the government, projects aiming at increasing the efficiency of power plants have gained considerable interest.

In this research, the integrated performance of the CCHP is presented as an objective function, by which GAMS software is employed to optimize its design capacity and operation. Furthermore, a sensitivity analysis was elaborated in order to show how the optimal solutions would vary, following changes on some key parameters.

3 CCHP SYSTEM ECONOMICAL MODEL

In order to utilize the high economical and energy-saving potentials of the residential CCHP systems, the system sizing, especially the capacities and operation of prime movers is very important. This is because if the capacities of prime movers are underestimated, the effect of introducing CCHP plants becomes relatively insignificant, and if they are overestimated, the feasibility of the system decreases. For residential buildings, electricity, cooling and thermal energy demands fluctuate seasonally and hourly, so it is necessary to take account of the plant's annual operational strategies for the variations of load demands.

However, the operation of residential CCHP system is subjected not only to the variation of load demands, but also to the fuel price, electricity price and other energy policies as well. Therefore, it is necessary to develop a rational method of determining system's sizes and operational strategies throughout the year utilizing CCHP to produce electricity, heat and cooling. It should be noted that management strategy of this system is only from investor's point of view [2], [4-6].

The model, in turn, determines the following parameters:

1. Maximize NAP of meeting electrical and heat demand
2. Optimal design capacity of the GE
3. Optimal back-up boiler capacity for the system
4. Optimal operating strategy of GE
5. Optimal operating strategy of back-up boiler
6. Other economic characteristics

Optimizing the objective function through the investor's criterion determines these parameters, where both states of including and excluding energy subsidy prices are investigated. Hence a careful determination of the objective function and its related constraints will lead to solving the problem.

Objective function

The objective function of the model is to maximize NAP for the building's energy system. Hence, the objective function is then formulated as follows [5-10], [12], [13]:

$$NAP = AP + R_S\left(\frac{1}{(1+i)^n}\right) - I_{CCHP}\left(\frac{i(1+i)^n}{(1+i)^{n-1}}\right) \quad (1)$$

AP in Eq. (1) presents the average annual benefit and its calculation is based on the Eq. (2).

$$AP = (R_S + R_{Re} + R_b + R_M) - (C_{Fuel} + C_{O\&M} + C_{grid}) \quad (2)$$

Investment cost of gas engine:

To determine the investment cost of gas engine, Regression's estimation is used. The initial cost of gas engine is presented in Eq. (3).

$$I_{GE} = \alpha + \beta E_{GE} \quad (3)$$

$$J = \sum_d (\alpha + \beta.E_{GE} - I_{GE})^2 \quad (4)$$

$$\frac{\partial J}{\partial \alpha} = \sum_d 2(\alpha + \beta.E_{GE} - I_{0GE}) \quad (5)$$

$$\frac{\partial J}{\partial \beta} = \sum_d 2.E_{GE}(\alpha + \beta.E_{GE} - I_{0GE}) = 0 \quad (6)$$

The cost of gas engine, with 1 MW capacity is 450000$, as it is mentioned in the MWM company catalogue. To estimate the cost of gas engines for other capacities, Eq. (7) is used [13].

$$C_y = C_W\left(\frac{X_Y}{X_W}\right)^{\gamma} \quad (7)$$

Where C_W (C_y) is the cost of W's (Y's) equipment with a capacity of X_W (X_y), and different values of γ is shown in table1.

Table1 The amount of γ for various equipments

power	range	γ	equipment
0.78	0.5-10(MW)	Thermal load	boiler
0.81	0.007-10(MW)	power	Reciprocating engine
0.30	0.07-150(m^3)	volume	Storage tank

Therefore, according to equations (3) to (7) the investment cost of the gas engine is formulated as follows:

$$I_{GE} = 139803.4 + 300.7E_{GE} \quad (8)$$

This cost encompasses the cost of engine and equipments such as heat recovery system and generator, where E_{GE} is the capacity of gas engine (the unit of E_{GE} is kW).

Investment cost of boiler:

Investment cost of boiler is shown in Eq. (9) [8]:

$$I_b = 250 \times 10^4 . H^{0.87} \tag{9}$$

Where 'H' is the capacity of boiler (the unit of H is kW in this paper).

Investment cost of absorption chiller:

Investment cost of absorption chiller is shown in Eq. (10) [12]:

$$I_{AB} = cp_{AB} . \mathrm{C}_{AB} \tag{10}$$

Where cP_{AB} is the capacity of absorption chiller (the unit of C_{AB} is \$/kWh in this paper).

Annual maintenance costs for gas engine and back-up boiler:

These costs are described by Eqs. (11)-(12). The maintenance cost is calculated with cumulative electricity or heat energy, multiplied by a unit maintenance cost coefficient.

$$C_{O\&MGE} = \sum_d \sum_h E_{GE}^{d,h} (\mathrm{C}_{O\&M\_GE}) \tag{11}$$

$$C_{O\&Mb} = \sum_d \sum_h H_b^{d,h} (\mathrm{C}_{O\&M\_b}) \tag{12}$$

(Measurement unit of $C_{O\&M}$ is \$/kWh in this paper).

The Annual fuel cost:

The Annual fuel cost is described in Eq. (13).

$$C_f = \sum_d \sum_h E_{GE}^{d,h} . (\frac{c_f}{HR . \alpha_{d,h}}) \tag{13}$$

The fuel cost is calculated with cumulative fuel consumption for each period of CHP plant multiplied by the fuel price. The $\alpha_{d,h}$ is estimated by Eq. (14)and $X_{d,h}$ is calculated using Eq. (15).

$$\alpha_{d,h} = \begin{cases} \frac{\alpha^{25\%} . X_{d,h}}{0.25} & \text{if} \quad 0 \prec X \le 0.25 \\ \frac{\alpha^{25\%} . (0.5 - X) + \alpha^{50\%} . (X - 0.25)}{0.25} & \text{if} \quad 0.25 \prec X \le 0.5 \\ \frac{\alpha^{50\%} . (0.75 - X) + \alpha^{75\%} . (X - 0.50)}{0.25} & \text{if} \quad 0.5 \prec X \le 0.75 \\ \frac{\alpha^{75\%} . (1 - X) + \alpha^{100\%} . (X - 0.75)}{0.25} & \text{if} \quad 0.75 \prec X \le 1.00 \end{cases} \tag{14}$$

$$X = \frac{E_{GE}^{d,h}}{cp_{GE}} \tag{15}$$

Where Cp_{GE} is the gas engine's nominal capacity.

The personal cost:

The personal cost is constant and for units with a capacity lower than 2 MW, is considered to be zero.

The cost of purchased electricity:

The total cost for purchased electricity is described by Eq. (16), which is calculated with cumulative amount of the electricity purchase deficit multiplied by the utilized electricity rate [4, 5].

$$C_g = \sum_d \sum_h (E_{\mathrm{Req}}^{d,h} - E_{GE}^{d,h}) . c_g \tag{16}$$

If the mount of generating electricity by the CCHP system exceeds users demand, the surplus electricity may be delivered back to the grid. Otherwise, the utilized electricity can support the electricity deficit. The apartment is connected to the local network, and if the gas engine does not produce enough electric energy to satisfy the electric demand, the deficit can be imported from the electric grid.

Revenues:

The revenues of the CCHP system is the summation of all revenues, including the revenue from recovered heat(R_{Re}), the revenue from selling surplus electricity (R_{se}), and the revenue acquired from eliminating purchase of electricity from the grid (R_{ep}) [4], [5], [7].

Revenue acquired from heat recovery:

Revenue from heat recovery is described by Eq. (17). It is calculated with cumulative amount of the difference between heat recovery from gas engine and the heat generated by boiler multiplied by the fuel price.

$$R_{\mathrm{Re}} = \sum_d \sum_h (Q_{req} - Q_b)(\frac{c_f}{HR . \eta_b}) \tag{17}$$

Revenue acquired from selling power to the electrical load:

There is an income due to selling power to electrical load of the facility (avoided cost of purchasing power from the grid). In fact, before installation of the CCHP system, the customer buys electricity from the grid. However, along with installation of the CCHP system, this electricity purchase is eliminated. This income is described by Eq. (18).

$$R_{ep} = \sum_{d}\sum_{h}(E_{D}^{d,h} - E_{g}^{d,h}).c_{g} \quad (18)$$

Revenue acquired from partly Paid back Used Fuel:

In Iran, in order to encourage investors to install CCHP systems, the government pays back a quarter of the cost of natural gas consumption, to customers. This income is described by Eq. (19) [13], [14].

$$R_{f} = 0.25 \times C_{f}.E_{GE}.(\frac{1}{\eta_{GE}.HR}).T_{i} \quad (19)$$

Revenue acquired from selling electricity back to the grid:

The income from selling electricity back to the grid is described for both heat and electric power.

$$R_{se} = \sum_{d}\sum_{h}(E_{GE}^{d,h} - E_{req}).c_{se} \quad (20)$$

If the electricity generated by the CCHP system ($E_{GE}^{d,h}$) is more than the apartment's electric demand (E_{req}), the customer can sell the extra electricity to the grid. C_{se} is the purchased electricity obtained from the CCHP [6], [8], [9], [13]. In Iran, C_{se} is obtained by Eq. (21) [14], [15]:

$$c_{se} = C_{base} + \Delta V.C_{g} \quad (21)$$

Where, ΔV is equal to the actual saved fuel which is calculated from Eq. (22):

$$\Delta V = V_{G_{chp}} - V_{G(\eta_E = 42\%)} \quad (22)$$

Where, V_G is obtained from Eq. (23):

$$V_{G} = \left[\frac{860}{HV_{g}} \times \left(\frac{100}{\eta_{ave}(1-L)} - \frac{100}{\eta_{E}}\right)\right] \quad (23)$$

$$\eta_{E} = \frac{\eta_{e}}{1-(\eta_{t} \times \mu)} \quad (24)$$

According to Eqs. (21)-(25), the cost of purchasing electricity from prime mover with different efficiency is based on table 2.

Table 2 Purchase of electricity based on gas engine's efficiency

Prime mover	Gas engine		
Efficiency (%)	40	39	38
C_{se} (Rial)	420	416	412

Revenue obtained from the salvage value of CCHP system

Salvage value of equipment is a source of revenue as described by Eq. (25). CCHP equipment has a salvage value at the end of its lifetime. This paper calculates the income acquired from this salvage value according to the basic Eq. (4). (The salvage value is 20% the initial capital cost) [10].

$$R_{sa} = 0.2 \times I_{0CCHP} \quad (25)$$

4 CONSTRAINTS

A balance of supply and demand has to be achieved for cooling, heating and electric power. The energy balance is formulated as an inequality in the model in order to avoid problems with infeasibilities. Given that, in real systems, since almost all outputs have positive marginal costs, the inequalities will usually be satisfied as equalities. The electric power balance is shown by Eq. (26). The heat balance is presented by Eq. (27). Eq. (28) limits how much heat can be recovered from the CCHP plant. Eqs. (29)-(30) are constrains which force the CCHP plant to generate no more than its installed capacity. In addition, these equations limit the capacity of the CCHP plant so that it should not be less than the minimal size of the CCHP plant available in the market [4-6], [13].

$$E_{d,h}^{grid} + E_{d,h}^{CHP} + E_{d,h,sal}^{CHP} \geq L_{d,h,ele} \quad (26)$$

$$\gamma.H_{d,h}^{CHP} + H_{d,h}^{Boiler} \geq L_{d,h,thermal} \quad (27)$$

$$H_{d,h}^{CHP} \leq K_{GE}.E_{d,h}^{CHP} \quad (28)$$

$$I \times (H_{CHP}^{\min}) \leq H_{d,h}^{CHP} \leq I \times (H_{CHP}^{\max}) \quad (29)$$

$$I \times (E_{CHP}^{\min}) \leq E_{d,h}^{CHP} \leq I \times (E_{CHP}^{\max}) \quad (30)$$

Where E is the electrical power produced (kW), H is the heat power produced (kW), E^{min} is the minimum limit of generating power (kW)and E^{max} is the maximum limit of generating power (kW). 'I' is the gas engine on-off status, I=1 for running, I=0 for stopping. During the optimal analysis of the CCHP system, some important assumptions are as follows:

- Ramping rate for load adjustment is not included.
- The CCHP system is assumed to be 100% reliable.
- The efficiency drops of CCHP equipment at partially loaded operation are neglected to simplify the analysis and calculation.

5 CASE STUDY

The building considered in this study, is a 5-storey residential building with a total of 15 units, each with a floor area of 100 m^2. The building has a height of 24 m, a length (in east-west direction) of 40 m, and a width of 20 m (in north south direction). The windows area are 30% of the south and north walls area and 20% of the east and west walls area of the building. The external and internal walls are 22 and 12 cm thick, respectively, all made of brick with gypsum plaster on the interior walls.

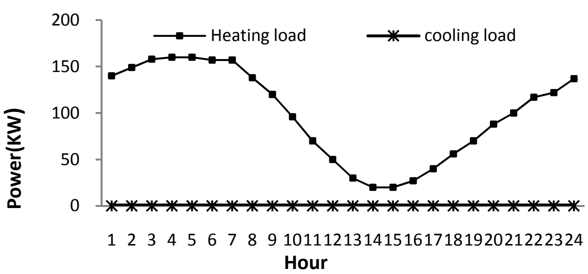

Fig. 2 Heating and cooling energy needs of the building estimated for July

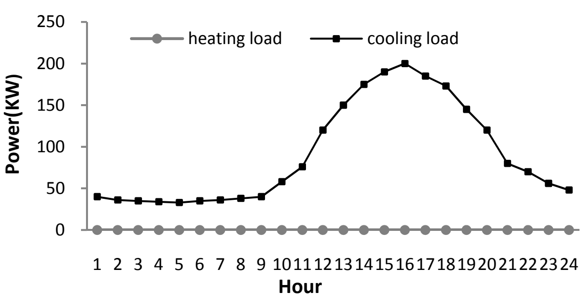

Fig. 3 Heating and cooling energy needs of the building estimated for July

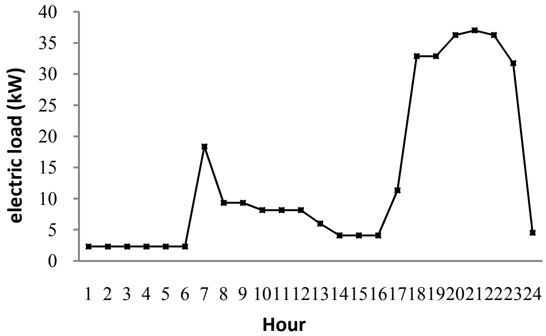

Fig. 4 Electrical energy needs of the building for various hours of the day

The roof is also 22 cm thick, made of brick and roofing materials. No thermal insulation is employed in the walls or the building roof.

Table 3 Technical and economical assumptions of the system [4], [5], [7], [12], [16], [17]

State2	State 1	parameter	State2	State1	parameter
1.2	1.2	K_{GE}	10	10	Q_{GE}^{min}
6	6	i(%)	300	300	Q_{GE}^{max}
0. 7	0.7	COP_{AB}	10	10	E_{GE}^{min}
322	280	Peak-cg	200	200	E_{GE}^{max}
322	112	Middle-cg	10.42	10.42	HR
322	25	Base-cg	700	29.17	C_f
80	80	η_b	150	150	$C_{o\&m}$
43	43	η_{GE}	20	20	n

Measurement of electrical, heating and cooling energy needs of a residential unit

To estimate the total power and the electrical energy requirements of the residential building under consideration, it has been assumed that all 15 residences are similar to the unit whose electrical energy consumption has been measured [7]. Hourly electrical, heating and cooling energy needs of the building have been estimated by employing the Carrier 2005 Hourly Analysis program 4.2. The total heating, cooling and electrical energy needs of the building are shown in Figs. 2-4. These three schemes (Figs. 2-4) and Table 3, demonstrate the data for determination of optimal capacity of the gas engine.

Determination of gas engine optimal capacity:

The results for two states obtained from the MINLP model, are presented in this section. The results of the NAP are presented in Table 4, which indicates that the use of CCHP driven by gas engine in state 1 is not economical. In other words the CCHP system has the negative value because the purchase electricity cost is low, therefore the costumer would prefer to buy electricity from the grid. However, in state 2 the use of CCHP is economical.

Table 4 Optimization results

parameters		State1	State2
E^{CHP}(kW)	peak	115	115
	Medium	69	69
	base	0	152
H^{CHP}(kW)	peak	138	138
	Medium	83	83
	base	0	0
E^{grid}(kW)	peak	79-	79-
	Medium	51-	51-
	base	6	-146
H^{boiler}(kW)	peak	0	0
	Medium	0	0
	base	182	0
NPV(million Rial)		-29.3	137
AP(million Rial)		115	287
SPP(year)		-	7.3

After solving the problem, the optimal GE's capacity and operation strategies are shown in table 4. The electricity and heat generation by the CCHP system in the FTL strategies are also depicted in table 4. The use of CCHP is economical in state 2 because:

- The cost of electricity generated by the CCHP, which is bought by the local network, is higher than the cost of electricity generated by the grid.
- The selling electricity price generated from the grid in state 2 is higher than the selling electricity price generated from the grid in state 1; as a result the revenue acquired from selling power to the electrical load in state 2 is higher.

Table 4 shows the CCHP for the base load in state 1 is off, because the cost of obtaining electricity for the CCHP is very low. As a result to support the electric demands of the building in the base load (6 kW), electricity is bought from the grid and also to completely satisfy the thermal load, an auxiliary boiler is used.

6 SENSITIVITY ANALYSIS

Sensitivity analysis defines the effect of key parameters on the decision to adopt residential CCHP systems. In this study, sensitivity analysis has been performed on natural gas prices, electricity prices, and electricity buy-back prices [5], [9], [13].

Natural gas price sensitivity

The fuel cost which is greatly affected by natural gas price has a significant share in the annual cost of the energy system. In the optimal design, natural gas price mentioned in table 3 is selected as a baseline to determine the optimal economical performance. Then, different baselines are used for subsequent calculations by 10% increments. Sensitivity analysis of natural gas price is shown in Fig. 5. Slight rise in the natural gas cost will reduce the annual profit of the CCHP system. If the heating does not completely satisfy application needs, a back-up boiler may be used.

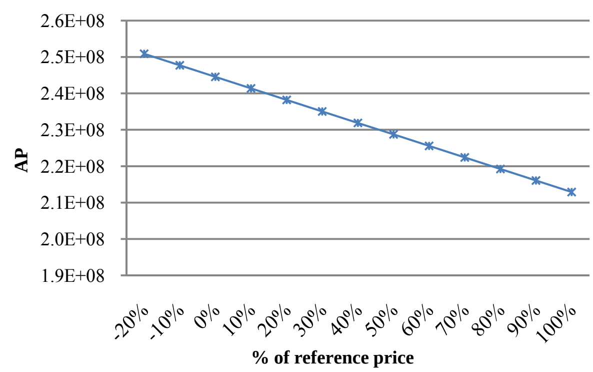

Fig. 5 AP versus gas price

Electricity price sensitivity:

As another main component of the total cost for residential energy system, the electricity purchasing cost is partly decided by the electricity price, which has also a significant effect on the adoption of residential CCHP systems. This is so, because if the electricity price is relatively low, the customer would prefer to purchase electricity from the grid rather than generate it on-site.

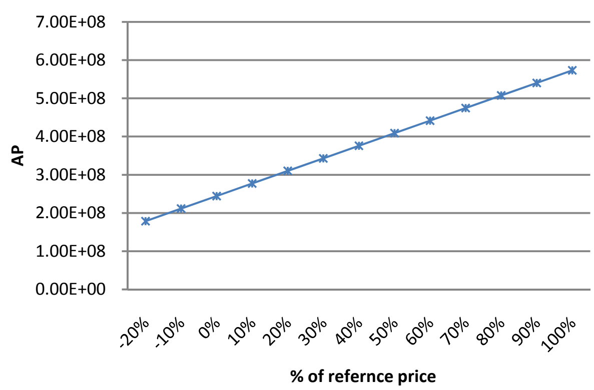

Fig. 6 AP versus electricity price

Fig. 6 shows that economic feasibility of CCHP systems in residential units is quite sensitive to the electricity price. From this figure, it can be deduced that, given a fixed capital cost, the advantage of installing residential CCHP system increases as electricity price increases, where the advantage of installing residential CCHP system decreases as electricity price decreases.

Electricity buy–back price sensitivity:

As an incentive policy for developing residential CCHP systems, electricity buy-back has been available in many countries. Fig. 7 shows the optimal value of AP calculated for different electricity buy-back prices. Furthermore, it can be found that electricity buy-back encourages larger CCHP installations. This is because electricity buy-back allows more on-site generation, and the high overall efficiency can make up the cost of free electricity delivered to the grid. From Fig. 7, it can be deduced that, the advantage of installing residential CCHP system increases as electricity buy-back price increases.

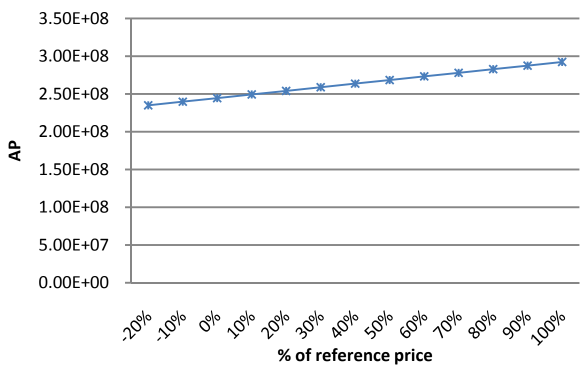

Fig. 7 AP versus electricity buy-back price

Electricity buy–back price, electricity price, fuel price sensitivity:

If the electricity buy–back price, electricity price and natural gas price change simultaneously, AP will change according to Fig. 8. As it can be observed, the advantage of installing residential CCHP system increases as total energy price increases.

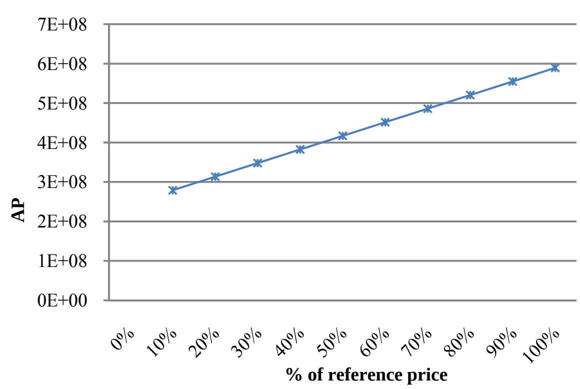

Fig. 8 AP versus total energy price

Electricity buy–back price, electricity price, fuel price sensitivity:

One of the best economic characteristics for evaluating CCHP systems is the simple pay-back period (SPP), hence in this section the effect of total energies' price on the SPP is evaluated.

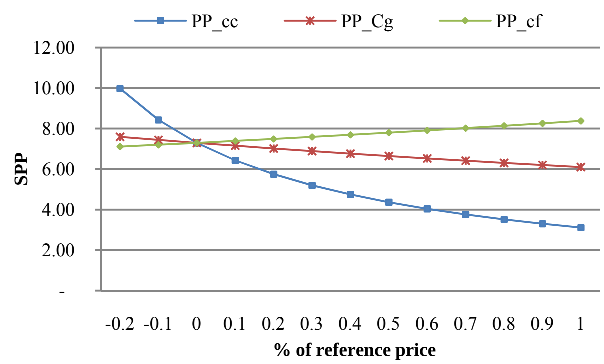

Fig. 9 SPP versus total energies' price

Fig. 9 compares the SPP of the present CCHP system with respect to different energy prices (C_g, C_f, C_c). If the natural gas price increases slightly, the pay-back period of the CCHP system will increase and if the selling electricity price and buying electricity price increase, the payback period of the CCHP system will decrease. In other words if C_f decreases, C_g or C_S would increase, and the CCHP system will be more profitable.

7 CONCLUSION

This paper fully indicates the energy balance for CCHP systems, and presents the performance of a CCHP system for an apartment in two states. Proper mathematical equations with least approximation have been provided to describe the revenues, costs and provisions in the problem. In this paper, using an economic analysis, the size and operational parameters of the Gas engine for the specific electricity, cooling and heating loads of a typical building located in Tehran (Iran) is selected. To carry out this analysis, an objective function, i.e. Net Present Value (NPV), has been introduced and maximized through a nonlinear mixed integer programming method.
The operation strategy and the pay-back period of the chosen system are also determined in this study. In addition, the results of this study, has demonstrated optimal gas engine capacity as well as optimal boiler. For the optimization procedure, GAMS software has been used. Results have shown that application of the CCHP system is economical. Finally, a sensitivity analysis has been carried out in order to show the

sensitivity of optimal solutions to main contributing factors such as fuel cost, electricity buy-back cost and electricity cost. Results show that these parameters have significant effects on the system performance. It has been demonstrated that NPV is more sensitive to the selling price and the grid electricity price than natural gas price.

8 APPENDIX OR NOMENCLATURE

Nomenclature

AP	Annual profit
C	cost
CCHP	combined cooling heat and power
COP	coefficient of performance
CP	capacity
E	electricity
GE	Gas engine
HR	Heat rate
H	heat
K	Ratio of heat to power
NAP	Net Annual Profit

Subscripts

AB	absorption chiller
b	Boiler
c	Cool
d	Day
ep	Eliminating purchase
f	Fuel
h	Hour
hs	Heating space
hw	Hot water
g	electricity grid
min	minimum
max	maximum
O&M	Operation and maintenance
rec	waste heat recovery
req	require
sa	salvage
se	selling

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