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Energy management and economics of a trigeneration system Considering the effect of solar PV, solar collector and fuel price

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ABSTRACT

The effect of solar PVs, solar collectors and fuel price on optimization of a typical micro combined cooling, heating and power (CCHP) system based on a natural-gas generator (NGG) was investigated. The CCHP system was considered to supply the given cooling, heating and electricity demand of a 5 story high residential building; having a total of 1000 m^2 floor area with the peak electricity of 48 kW, heating and cooling needs of 100 and 50 kW, respectively. If Iran removes the fuel subsidy, the cost of fuel would increase and the PV or hybrid PV/Generator systems would become more attractive. In this paper, a techno-economical procedure was conducted by using two definitions of loss of power supply probability (LPSP) and levelized cost of energy (LCOE). The results indicated that the optimal operation strategy changes with boiler and NGG fuel prices while it also changes with increasing the number of solar collectors.

Introduction

The combined heat and power (CHP) system concept refers to the possibility of efficiently and profitably combining heating and power production to satisfy the consumption needs during the energy system operation. Domestic CHP is the energy system applied to the household sector to supply both electric and heat energy to users. The significant benefit of CHP is its total efficiency, which can be as much as 85–90% (Alanne and Sarri, 2004). The CHP systems create less air pollution than the other power generation systems that use fossil-based fuels alone. However, this technology based on fossil fuel generators could be sometimes inefficient because of high fuel consumptions, especially in high energy generation applications. It is believed that micro CHP offers significant benefits to energy suppliers, to households and to the society as a whole (Harrison et al., 2001). With respect to the technical aspect, it is important to underline that for residential end-users, a micro CHP system should be characterized by a low price and easy-to-use operation. A CHP system including the fossil fuel based generators accompanied by renewable energy resources as a part of heat and electricity generations is one of the alternatives to deliver energy savings and emissions reductions.

The main sources of energy in Iran to meet heating, domestic hot water (DHW) and cooking are natural gas (in almost all cities) and kerosene. Cooling of buildings in summer is accomplished predominantly by evaporative coolers and vapor compression refrigeration (Ehyaei and Bahadori, 2007). Contribution of the renewable energy resources in energy generation of the CHP systems is a promising way to increase the advantages of these systems, by decreasing the lower fossil fuel consumptions and consequently by reducing the levels of air pollution. The application of combined heat and power (CHP) production has been studied by several investigators (Ward et al., 1978; Lindsay and Marciniak, 1986; Babus and Probert, 1988; Babus et al., 1990; Azmy, 2003; Tanaka et al., 2000; Massardo et al., 2000; Pearce and Alzahawi, 2001; McDonald and Rodgers, 2001; Mone and Phelan, 2001; Bailey, 2002). Various literatures have been reported on experimental and operational research on micro CHP systems. Dorer and Weber (2009) assessed the energy and CO_2 emission performances of various micro CHP systems for a number of residential building types, while considering different electricity generation mixes. Aussant et al. (2009) examined the feasibility of micro CHP system in Canada by taking into consideration the effect of local conditions on the economic and environmental characteristics. Houwing et al. (2008) discussed the technical, economic and institutional uncertainties in the design and operation of micro CHP systems by using a comprehensive framework for uncertainty analysis.

An experimental analysis on a small scale poly generation system based on a natural gas-fired Micro-CHP and a desiccant HVAC system

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Nomenclature

$A_{Absorber}$	collector total absorbing area
A_i	anisotropy index
A_{pv}	array area (m^2)
BM	boiler annual emission (ton/yr)
$Battery_{costs}$	costs of the batteries ($)
$Battery_{life}$	lifetime of batteries (yr)
$BoilerFuel_{cost}$	*boiler natural gas costs ($)*
C_{bat}	battery nominal capacity (Ah)
$Cooling_{useful}$	useful annual cooling energy (kWh)
$Electrical_{useful}$	annual useful electricity (kWh)
EP	emission penalty (ton/yr)
$Heating_{useful}$	annual useful heating energy (kWh)
I_b	beam solar radiation (W/m^2)
I_{bat}	battery current (A)
I_d	diffuse solar radiation (W/m^2)
$I_{\max}$	battery maximum charge current (A)
$Inverter_{costs}$	costs of the invertors ($)
$Inverter_{life}$	lifetime of inverters (yr)
I_r	hourly solar radiation (W/m^2)
I_{c-bat}	battery current (A)
$I_{c-\max}$	maximum charge current (A)
L	longitude
LCOE	levelized cost of energy ($/kWh)
LPSP	loss of power supply probability (%)
N	day number
NL	number of years (lifetime)
P_{NGG}	NGG power (W)
P_{Bat}	battery power (W)
P_{load}	load power (W)
P_{pv}	PV power (W)
V_b	battery voltage (V)
V_{load}	voltage of the system (V)
Q_E	evaporator cold capacity (W)
Q_G	heat input to generator (W)
δ	declination angle
β	slop surface of panels (radian)
β	incidence angle (deg.)
Δt	hourly time step (hour)
COP	chiller coefficient of performance
f	cloud cover
N_h	number of time intervals
P_f	packing factor
PV	photovoltaic modules
R_b	geometric factor
η_c	collector efficiency
η_{in}	inverter efficiency
η_m	module reference efficiency
η_{pc}	power conditioning efficiency
ρ_g	ground reflectance

was carried out by Angrisania et al. (2010). In that work, the Micro-CHP was considered to provide thermal power, recovered from engine cooling and exhaust gas, for the regeneration of the desiccant wheel and electric power for the chiller, the auxiliaries and the external units (computers, lights, etc.).

Ziher and Poredos (2006) considered a cogeneration system based on a natural-gas turbine with an absorption chiller to support the heating, cooling and electricity demands of Slovenia's biggest hospitals. They also considered the possibility of cold storage and the application of an additional gas boiler in order to fully address the heating needs of that hospital. The results have shown that the payback period was low, net present value was high and profitability index was more than 1.

A structural configuration of the combined cooling, heating and power (CCHP) system with hybrid chillers, consisting of a combined electric and absorption chiller was proposed by Liu et al. (2012). They developed a new operation strategy, based on the variation of electric cooling to cool load ratio, for the CCHP system with unlimited and limited power generation unit (PGU) capacity. In addition, a case study was conducted to verify the feasibility of the proposed CCHP system structure and the corresponding optimal operation strategy.

Ebrahimi and Keshavarz (2013) proposed a multi-criteria sizing function (MCSF) for designing the optimum size and operating strategy of the prime mover of a residential micro-combined cooling heating and power (CCHP) system. The CCHP system was investigated to prepare the electrical, thermal, cooling, and domestic hot water demands of the same building in five different climates in Iran. In that study, different parameters such as fuel energy saving ratio, exergy efficiency, net present value, internal rate of return & payback period, and CO_2, CO and NO_x reduction were considered.

A novel hybrid PV-trigeneration system was introduced by Nosrat and Pearce (2011). In order to reduce waste from excess heat, an absorption chiller was proposed to use the thermal energy generated by that hybrid system. The authors of that study introduced a dispatch strategy for such a system that accounts for electric, domestic hot water, space heating, and space cooling load categories. The dispatch strategy was applied for a typical home in Vancouver. The results of that study have shown an improvement in performance of over 50% for the described PV-trigeneration system.

Klaassen and Patel (2013) investigated a number of different methods to calculate energy savings from CHP-Natural gas fired systems and the conventional domestic gas-fired condensing boiler systems. Real hourly CHP plant performance data was used. The results of that study have shown that supplying dwellings with district heat from a CHP-Natural gas system saves energy, regardless of the calculation method and for a rather wide range of reference efficiencies. CO_2 mitigation costs were also found to be acceptable from a social perspective (at discount rates up to 4%, excluding fuel taxes) and negative from a private perspective (at discount rates up to 10%, including fuel taxes).

Comodi et al. (2014) investigated the application of renewables in micro-cogeneration technology in order to reduce household consumption in a medium Italian. The results of cogeneration and renewables (PV (photovoltaic) and solar thermal panels) are valuable solutions to reduce the energetic and environmental burden of the household sector. Also, it was found that Micro-CHP entails a global reduction of energy consumption but greater local emissions.

Generally, according to the introductions illustrated above, it can be found that as one of the promising instruments to cope with the increased CO_2 emissions and costs in the residential sector, micro CHP systems have been paid much attention among researchers. However, as one of the initiators of micro CHP in the world, littler research has been reported about the application and consequences of micro CHP systems for residential buildings in Iran. Also, no considerable efforts have been made on combination of solar collectors and photovoltaic panels with the CHP systems. In addition, most of the economic assessment illustrated above is based solely on the running cost, a lifecycle cost analysis for various micro CHP alternatives is necessary.

Because of the high fuel subsidization by Iran, for many years the electrical energy has been supplied from the power plants, consuming considerable amounts of fossil fuels. Also, the main sources of energy in Iran to meet heating, domestic hot water (DHW) and cooking are natural gas (in almost all cities). But lately, Iran has decided to eliminate the fuel price subsidies, which causes the increase of electricity and thermal energy costs. The increasing prices of the conventional fuels coupled with environmental degradation have led to the development of renewable energy resources in Iran. In the present study, Kerman (30°15 ′ *N* , 56°58 ′ *E*), Iran, was selected as the district of the study area. According to the Iranian Meteorological Organization (IMO), the annual solar radiation at Kerman, Iran is 7625 $\frac{\text{MJ}}{\text{m}^2}$. Since Kerman has a high irradiation level, a considerable amount of its power and thermal energy requirements may be obtained from solar PVs and solar collectors. Previous studies (Askari and Ameri, 2011) have shown that if Iran does not appropriate any subsidy for fuel, with the present diesel fuel price in Persian Gulf market even with the minimum role of diesel generator in hybrid (PV/diesel) system, the cost of this hybrid system becomes higher than the PV/bat system costs. This study was carried out to consider the effect of removing fuel subsidies and also adopting solar energy sources as the auxiliary source on the economics of residential heating, cooling and power systems in Iran. The main target was to determine the future alternatives for energy management of the combined cooling, heating and power (CCHP) energy systems, in Iran.

Material and methods

Solar radiation data

The solar irradiance data on the horizontal plane were collected in meteorological station of Kerman, Iran. After a comparison between the monthly average daily solar radiation[1] for five years (the period 2000–2004), it was seen that the variation of the solar radiation during that five years is minimal. A minimum difference was also found between the monthly average of that five years and the monthly average of 2004's solar radiation data. Hence, both of these average values could be used in solar energy calculations. However, the real data of cooling, heating and electricity demands of a typical building were available for the year 2004. Hence, 2004's data were used in the calculations of the present study. Fig. 1 presents the monthly average solar radiation in $kWh/m^2/day$ for the year 2004. It can be seen that the insolation level in Kerman is high during the summer months (May (5) to Aug (8)) compared to other months. The yearly average daily value of the solar radiation is 6.37 kWh/m^2 for Kerman, Iran.

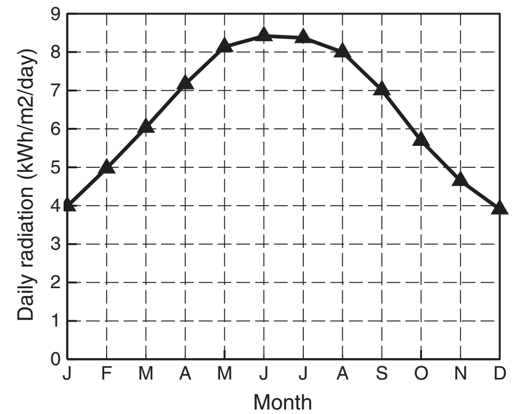


Fig. 1. Monthly average daily radiation (2004).

The conventional energy systems in Iran

The schematic of conventional energy systems that support the thermal and electrical needs of the residential buildings in Iran is shown in Fig. 2. As this figure shows the electricity generated from power plant is used as the main source to meet the dwelling electrical demands such as lighting, refrigerator, TV, microwave as well as the electrical evaporative coolers. Natural gas is passed into the house through the gas pipe lines to be directly used in the stoves and water heaters. One of the disadvantages of this thermal system is the capturing of CO emission through the bad operation of the stove or water heater stacks which leads to people's death during the year.

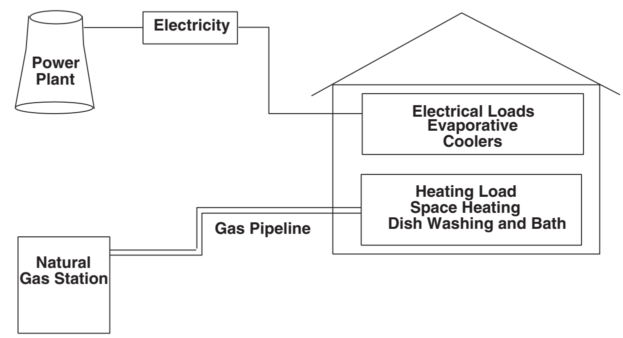


Fig. 2. Conventional electricity, heating and cooling system for residential buildings in Kerman, Iran.

Iran energy market

According to the Iran Petroleum Ministry, the proved natural gas reserves of Iran are about 1046 trillion cubic feet (29.6 trillion cubic meters) or about 15.8% of world's total reserves. Among the world countries, Iran has the world's second-largest reserves of natural gas after Russia. Because fuel price has been highly subsidized in Iran, no considerable attention has been devoted to energy saving and consumption for many years. For instance, in Iran electricity generation, transmission and distribution costs are about 0.224 $/kWh, however, the electricity has been sold to the users at a cost of 0.016 $/kWh for many years. Iran has started to increase electricity and fuel costs from 2012 and according to the Iran economic policy, this trend has to be continued until a universal cost of energy is achieved. Table 1 shows the variations in the average cost of fuel and energy in the residential sector for the years 2012 up to 2014.

The tabulated data were collected from the electricity and natural gas consumption bills of the study building. As Table 1 shows, there is an increase of approximately 45% in the average of energy costs from a fix value of 0.0175 $/kWh in 2012 to an average value of 0.024 $/kWh in 2013. Also, an increase of 30% has been exerted on the average energy costs from 2013 to 2014. According to the electricity and fuel consumptions of the building studied in the present paper, the average energy cost is 0.035 $/kWh for the year 2014, which corresponds to a medium consumption of the energy by users. As it is shown in Table 6, for medium energy consumption in 2014, the natural gas price has been subsidized to be 0.083 $/m3.

Electrical load and demand

In the present work, load demand was the electrical energy needs of a 5 story high residential building; having a total of 1000 m^2 floor area for the year 2004, which were collected from the south region of Kerman province electrical power distribution company. Because the energy consumption of the air-conditioning systems in warm months was considered to be supplied by the absorption chiller, the hourly electricity consumption of the evaporative coolers during the warm months of the year was calculated[2] and subtracted from the total electrical load. The hourly electrical load during a typical year and also the average daily electrical load for month June are shown in Figs. 3 and 4, respectively. The electricity load that is shown in Fig. 3 is the electricity

[1] The average of five years of daily values for each month (approximately, 150 days).

[2] [1]The evaporative coolers number of working hours was available for the year 2004.

Table 1
Subsidized energy costs collected from residential gas and electricity bills.

Year		Subsidized natural gas price ($/m3)	Subsidized electricity ($/kWh)	Subsidized thermal ($/kWh)	Average energy costs ($/kWh)
2012	Fix price	0.045	0.031	0.004	0.0175
	Low consumption	0.020	0.015	0.0017	0.008
	Medium consumption	0.054	0.052	0.0047	0.028
	High consumption	0.096	0.069	0.0085	0.038
2014	Low consumption	0.043	0.018	0.0038	0.011
	Medium consumption	0.083	0.064	0.0073	0.035
	High consumption	0.112	0.085	0.01	0.047

consumption for lighting, refrigeration, TVs, computers, irons, hair dryers and other partial electrical loads of the building with a peak of 48 kW.

Heating and cooling energy needs

The heating and cooling demands were calculated for all 5 units considering the heat demands of internal stairs spaces using commercial software by applying the weather condition data of Kerman for the year of 2004. Hourly heating load was the heat energy needs of the described building during the cold months as well as the energy needs for domestic hot water (DHW) during the year. The annual heat requirement was 226 MWh with the peak of 100 kWh in cold months of Jan, Feb, Nov and Dec. The hot water consumption was assumed to be uniformly distributed between 6 a.m. and 11 p.m., with no hot water consumed in the building between 11 p.m. and 6 a.m.

The cooling load was the energy consumption of the air-conditioning systems in hot months. The refrigeration cooling load was assumed to be supported by using the electricity generation by CCHP system. The annual cooling demand was 74.7 MWh with the peak of 50 kW. Hourly heating and cooling energy needs of the current study are shown in Fig. 5.

CCHP system operation and components

The combined cooling, heating and power (CCHP) system considered in the present work comprised of different combinations of PV modules, flat solar collectors, natural gas generators, battery system, power converter, boiler and absorption chiller (Lithium/Bromide/Water), as shown in Fig. 6.

The interaction between different components of system is as follows:

In normal operation, PV modules and natural-gas generators (NGGs) feed the electrical demand. In the event, that the output electricity from the PVs and NGGs is not sufficient to supply the electricity demand, then the battery discharges to satisfy the load requirement. If the produced power from PVs and NGGs is above the hourly demand, then the excess energy is stored in the battery until full capacity of the battery is reached. If the output power from the PVs and NGGs exceeds the load demand and the battery capacity is full, then the excess energy is used to support the heating and cooling requirements.

The heat generated by NGGs and dumped electricity, which are both the inevitable part of the CHP system, is used to support part of the hourly heating and cooling demands. If these two energy sources are not sufficient to supply the heating and cooling needs, then depending on the fuel costs and availability of solar energy the boiler or solar collectors (during the day time) serve the heating and cooling demands. It is necessary to mention that the boiler is the main source of heating and cooling energy needs and its capacity is specified according to the heating and cooling peak demands regardless of the existence of solar collectors or availability of NGG heat recovery and dumped electricity. In other words, a boiler is designed to support the peak of the heating demands. Hence, solar collectors, NGG heat recovery and dumped electricity are used to reduce the boiler operational hours and consequently its fuel consumptions. In the present study, the boiler and absorption chiller weren't considered in the economics calculations.

In the present work, no tracking system was used in the solar energy calculations. So, the slope of PV modules was assumed to be constant and equal to the latitudinal (30.15°*N*) position of Kerman, Iran. NGG is sized to meet the peak demand of the power. The peak demand of the present case study was 48 kW. Hence, several NGGs with different capacities were considered. For NGG with more than 10 kW power, multiple NGGs were considered to reduce excess energy. Battery storage is sized to meet the load demand during non-availability period of renewable energy resources, commonly referred to hours or days of autonomy.

The characteristics of the batteries, PV modules and a typical NGG which were used in the present study are tabulated in Table 2.

A power inverter is needed to maintain the flow of energy between AC load and DC components (PV modules). Different sizes of inverter

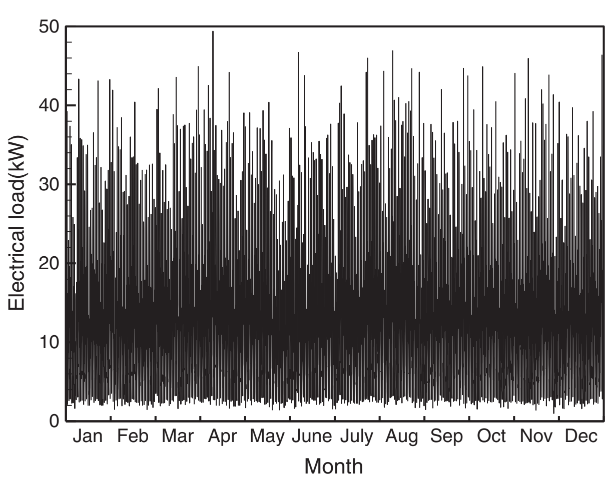


Fig. 3. Hourly electrical load for year 2004 mines the electricity load of the evaporative coolers.

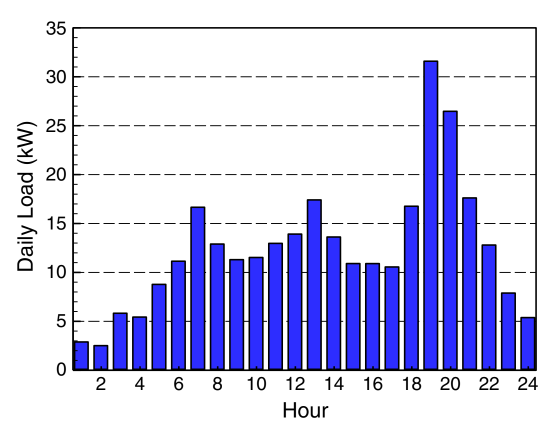
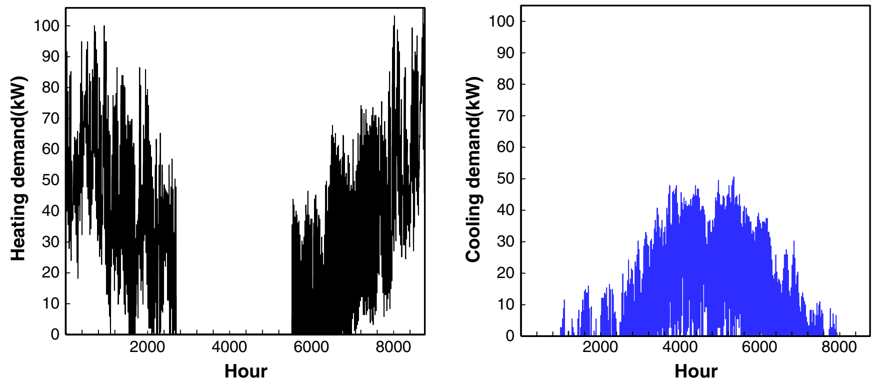


Fig. 4. Average daily electrical load for June.



a. Hourly heating load(2004) **b.** Hourly cooling load(2004)

Fig. 5. Hourly heating and cooling load. a. Hourly heating load (2004). b. Hourly cooling load (2004).

(kW) were taken into account in the present study and the lifetime of a unit was considered to be 15 years with an efficiency of 92%.

Modeling of solar PVs

Solar energy calculations are made by using the hourly solar radiation data. The electricity power generated by photovoltaic (PV) systems is directly related to the solar energy received by PV panels, while the PV panels can be placed at any tilt angle and orientation. Most local solar observatories only provide solar irradiance data on a horizontal plane. Thus, an estimate of the total solar radiation incident on any required sloping surfaces is needed. In the present work, the slope of PV panels was considered to be constant and equal to the latitudinal (30.15°N) position of Kerman, Iran. HDKR model (the Hay, Davies, Klucher, Reindl model) (Duffie and Beckman, 1990) was utilized to estimate the incident diffuse solar radiation. According to this model, the total solar radiation on the tilted surface can be estimated by:

$$I_t = (I_b + I_d A_i) \times R_b + I_d \times (1 - A_i) \times \left(\frac{1+\cos\beta}{2}\right) \times \left[1 + f\sin^3\left(\frac{\beta}{2}\right)\right] + I_r \rho_g \left(\frac{1-\cos\beta}{2}\right) \tag{1}$$

where I_b is direct normal solar radiation, I_d is diffuse solar radiation, I_r is the hourly solar radiation on horizontal surface, A_i is the Anisotropy index and R_b is the Geometric factor which is defined as bellow:

$$R_b = \frac{\cos\theta}{\cos\theta_z} \tag{2}$$

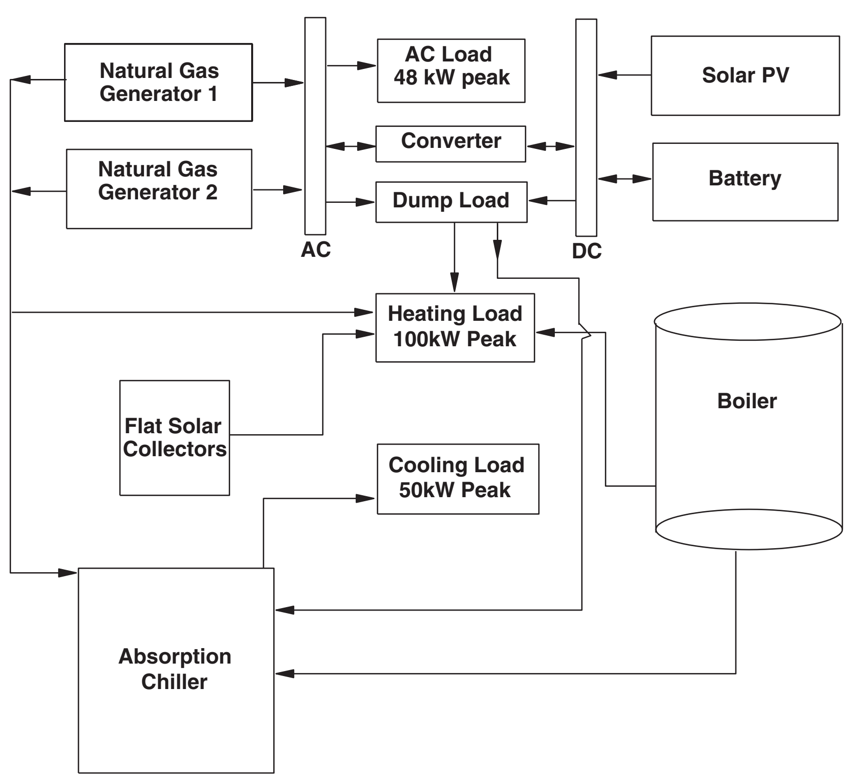


Fig. 6. The schematic of combined cooling, heating and power (CCHP) system considered in the present work.

Table 2
Characteristics of the CCHP system components.

Characteristics of PV modules

Height	Width	PV area	Electrical performance		
(mm)	(mm)	(m^2)	I_{sc}	V_{oc}	P_{max}
1280	528	0.67	2.98(A)	22(V)	80(W)

Specifications of NGG

Rated power (kW)	Minimum allowed power	No load fuel consumption (m^3/h)	Heat recovery ratio (%)	Life time
20	33% of rated power	1.5	40	35,000 h

Battery specifications

Nominal capacity (Ah)	Nominal voltage (v)	Round trip efficiency	Minimum state of charge (%)	Maximum charge rate(A/Ah)	Maximum charge current(A)	Maximum capacity(Ah)
3000	2	0.86	30	1	610	3572

In the above relation, θ and θ_z are incidence and zenith angles, respectively, f is the cloudiness factor and is given by the following equation:

$$f = \sqrt{\frac{I_b}{I_r}} \tag{3}$$

where, "f" is calculated using I_b. The direct solar radiation, I_b is determined using the value of diffuse solar radiation of I_d. The Erbs (Duffie and Beckman, 1990) correlation was applied to determine the fraction of the hourly radiation on a horizontal plane which is diffuse, $\frac{I_d}{I_r}$. The Erbs et al. correlation is as follows:

$$\frac{I_d}{I_r} = \begin{cases} 1.0 - 0.09k_T & \text{for } k_T \le 0.22 \\ 0.9511 - 0.1604k_T + 4.388k_T^2 & \text{for } 0.22 < k_T \le 0.8 \\ \qquad -16.638k_T^3 + 12.336k_T^4 & \\ 0.165 & \text{for } k_T > 0.80 \end{cases} \tag{4}$$

where, k_T is hourly clearness index which is calculated using the following equation:

$$k_T = \frac{I_r}{I_\circ} \tag{5}$$

where, I_r and $I_\circ$ are the total radiation on horizontal surface and the extraterrestrial radiation on a horizontal surface for an hour period, respectively. The hourly extraterrestrial radiation on a horizontal surface was determined using the following equation (Duffie and Beckman, 1990):

$$\begin{aligned} I_\circ = \frac{12 \times 3600\, G_{sc}}{\pi} \times \left[1 + 0.033 \times \cos\left(\frac{360 \times N}{365}\right)\right] \\ \times \left[\cos(L) \times \cos(\delta)\sin(\omega_2 - \omega_1) + \left(\frac{\pi(\omega_2 - \omega_1)}{180}\right)\right. \\ \left. \times \sin(L) \times \sin(\delta)\right] \end{aligned} \tag{6}$$

where, G_{sc} is solar constant that is equal to 1366.1 W/m^2. N is the day number, L and δ are the longitude and the declination angle, respectively. ω_2 and ω_1 are the hour angles between two specific hours that extraterrestrial radiation should be calculated. Substituting I_r and $I_\circ$ into Eq. (5) yields the hourly clearness index which is used to calculate the hourly diffuse solar radiation using Erbs correlation (Eq. (4)). Finally, I_b is determined as follows:

$$I_b = I_r - I_d \tag{7}$$

In Eq. (1), β is the slope of photovoltaic panels and ρ_g, the ground reflectance (also called Albedo), is the fraction of solar radiation incident on the ground that is reflected. A typical value for grass-covered areas is 20%, snow-covered area is 70%, grass-plot area is 30% and for desert dry lands is 45%. In this paper, the value of the ground reflectance was considered to be 45% according to state of the objective region and using the albedo atlas prepared by the TERRA satellite (http://www.eoearth.org/view/article/149954, 2002). The total solar energy generated from the PV system is calculated using the following equation (El-Rafey and El-Sherbiny, 1988):

$$E_{PV} = I_t \eta_m \eta_{pc} P_f A_{pv} \tag{8}$$

where A_{pv} is the total area of the PV modules in m^2, η_m is the module reference efficiency(0.11), P_f is the packing factor (0.91), η_{pc} is the power conditioning efficiency (0.83), and I_t is the hourly total solar radiation (kWh/m^2) which is calculated from Eq. (1).

Modeling of solar collectors

Flat collectors were considered in the solar heat energy calculations of the present work. The solar collectors' efficiency (η_c) is determined by:

$$\eta_c = \frac{Q_{Solar,net}}{I_T \cdot A_{Absorber}} \tag{9}$$

where, $Q_{Solar,net}$ is the net thermal power gained by the water from the collectors' field, I_t is the solar insolation in the collector absorber plane (Eq. (1)) and $A_{Absorber}$ is the total absorbing area of the collectors' field, respectively. The chiller coefficient of performance, COP, is defined as the ratio of the evaporator cold capacity Q_E to the heat input to generator Q_G as follows:

$$COP = \frac{Q_E}{Q_G} \tag{10}$$

Finally, A_s, which defines the collector area per target cold capacity of the absorption chiller, is determined as follows (Henning, 2007; Hamza et al., 2008):

$$A_s = \frac{1}{I_T \cdot \eta_{daily,avg} \cdot COP_{daily,avg}} \quad \left(m^2/kW_{cold}\right) \tag{11}$$

In the present work, considering the losses occurred in solar collectors and absorption chiller, the average values of 65% and 0.55 were used for $\eta_{daily,avg}$ and $COP_{daily,avg}$, respectively. From Eq. (11), in a cooling system comprises of an absorption chiller, the required solar collector area to produce 1 kW of cooling is nearly 2.8 m^2, when the solar insolation is 1 kW.

Modeling of battery system

The selection of a proper size of the battery bank for this type of applications requires a complete analysis of the battery's charge and discharge requirements, including load, output power of the system energy resources and the battery's state of charge at each hour of the year. The charged quality of the battery, charge and discharge calculations, battery current were all calculated from the equations, which have been totally explained in the reference Askari and Ameri (2009).

$$I_{c-bat}(t) = \frac{P_{PV}(t)}{V_{bat}} - \frac{P_{load}(t)/\eta_{in}}{V_{bat}} \quad \text{Charge current} \tag{12}$$

$$I_{c-bat}(t) = \frac{P_{load}(t)/\eta_{in}}{V_{bat}} - \frac{P_{PV}(t)}{V_{bat}} \quad \text{Discharge current} \tag{13}$$

Criteria for the high reliability and low costs

Electrical power reliability

Electrical power reliability of the CCHP systems was considered with the implemented criterion of loss of power supply probability (LPSP), which is defined as a loss of power occurs whenever the electrical demand exceeds the available generating capacity of the system. The objective function, LPSP, from time 0 to T can be described by (Yang et al., 2003):

$$LPSP = \frac{\sum_{t=0}^{T} \text{hours}(I_{c-supply}(t) < I_{c-needed}(t))}{N_h} \tag{14}$$

In the above relation, N_h is the number of time intervals (8760, number of hours in a year) and $I_{c-needed}(t)$ is the current needed by the load and can be expressed as:

$$I_{c-needed}(t) = \frac{P_{load}(t) - P_{PV}(t)}{V_{load}} \times \eta(I_{c-bat}(t)) - \frac{P_{NGG}(t)}{V_{load}} \tag{15}$$

and the current supplied from the photovoltaic panels can be expressed as:

$$I_{c-supply}(t) = \min\left(I_{c-max} = \frac{0.2SOC}{\Delta t}, \frac{SOC(t) \times \sigma(t) - SOC_{min}}{\Delta t}\right) \tag{16}$$

where, $SOC(t)$ and $SOC_{\min}$ are the state of charge and minimum state of charge of the battery (Askari and Ameri, 2009). Using the LPSP technique, the system configuration can be optimized for a certain electrical load according to the desired reliability of the system. The systems with less LPSP are more reliable.

Cost analysis

Levelized cost of energy (LCOE), which consists of initial capital cost, replacing, operation and maintaining cost of the system components, was used to decide economic feasibility of the system. LCOE is defined as the average cost per *kWh* of useful electrical and thermal energy produced by the CCHP system. To calculate the LCOE, the annualized cost of producing electrical power/thermal energy needs is divided by the total useful electrical/thermal energy production. In order to determine the annualized costs, the real interest rate was calculated using the following equation:

$$i = \frac{i' - i_f}{1 + i_f} \tag{17}$$

where, i' and i_f are nominal interest rate and inflation rate, were considered as 25% and 18%, respectively, according to Iran Central Bank statistics reports (http://www.cbi.ir/section/1372.aspx, 2012). A value of 6% was obtained as the real interest rate, and it was used in the economic calculations of the present study. The Capital Recovery Factor (CRF) was also calculated according to the real interest rate and lifetime (Number of years) of each component included in the system:

$$CRF(i, NL) = \frac{i \times (1+i)^{NL}}{(1+i)^{NL} - 1} \tag{18}$$

where, i and NL are real interest rate and lifetime of each component.

The equation for the LCOE is as follows:

$$LCOE = \frac{PV_{costs}/PV_{life} + Battery_{costs}/Battery_{life} + Inverter_{costs}/Inverter_{life}}{Electrical_{useful,PV}} + \frac{NGG_{costs}/NGG_{life} + (NGGFuel_{cost} + NGG \cdot C_{emission})}{Electrical_{useful,NGG} + Heating_{useful} + Cooling_{useful}} + \frac{BoilerFuel_{cost} + Boiler \cdot C_{emission} + SolarCol_{costs}/SolarCol_{life}}{Heating_{useful} + Cooling_{useful}} \quad (/\text{kWh}) \tag{19}$$

where, $NGG \cdot C_{emission}$ and $Boiler \cdot C_{emission}$ are the penalty for emissions generated by natural gas generators and boiler, respectively. Following equation was used to calculate the penalty for emissions:

$$NGG \cdot C_{emission} = \frac{NEP_{Co2}NM_{Co2} + EP_{Co}NM_{Co} + EP_{other}NM_{other}}{1000} \quad (\$/\text{yr}) \tag{20}$$

$$Boiler \cdot C_{emission} = \frac{EP_{Co2}BM_{Co2} + EP_{Co}BM_{Co} + EP_{other}BM_{other}}{1000} \quad (\$/\text{yr}) \tag{21}$$

In above equations, EP_{Co_2}, EP_{Co} and EP_{other} are the penalties for emissions of CO_2, CO and other emissions (No_x, So_x, particular matter and methane) in terms of ($/ton). NM_{Co2} and BM_{Co2} are annual emissions of CO_2 (kg/yr) produced by NGGs and Boiler, respectively. In all calculations, PV_{costs}, $Battery_{costs}$, $Inverter_{costs}$ and NGG_{costs} are the sum of initial capital cost and operation-maintenance cost of the PV modules, battery bank, inverter and NGGs, respectively, in the life-span of these components. PV_{life}, $Battery_{life}$, $Inverter_{life}$ and $diesel_{life}$ are the lifetime year of PV system, battery bank, power inverter and NGGs, respectively. Also, $NGGFuel_{cost}$, $BoilerFuel_{cost}$ are the annual costs of fueling the generator and boiler, respectively, which are calculated by multiplying the natural gas fuel price by the amount of fuel used by the generator and boiler in one year. $Electrical_{useful,PV}$ and $Electrical_{useful,NGG}$ are the annual useful electricity produced by the PVs and NGGs, respectively.

Results and discussion

Technical assessment of the system

Electricity supply

A techno-economic study on sizing of a combined cooling, heating and power (CCHP) system was conducted using a computer program provided by the authors in FORTRAN language. The main target was to find the effect of solar PVs, solar collectors and fuel price on optimization of a typical micro CCHP system based on a natural-gas generator (NGG) under three different fuel prices. The hourly values of solar

Table 3
Optimization search space.

PV (kW)	NGG (kW)	Bat (Nos.)	Con (kW)	Solar Col. area (m2)
0	0	0	5	0
10	2	2	10	20
20	4	4	15	40
25	.	.	.	
	.	.	.	
	.	.	.	
	.	.	.	
65	48	80	70	100

radiation, electricity demand, heating and cooling energy needs were used in the system calculations. In the present work, because of the high costs of electricity generation compared to heating energy generation costs, the prior object was to optimize the systems to support the electrical demands. At first, the described CCHP system was optimized based on the electricity demand using the LPSP definition, and then the capability of the system in supporting the heating and cooling load demands was techno-economically considered.

Several configurations of the CCHP system which comprised of different combinations of PV modules (kW), NGG powers and solar collector areas supplemented with battery bank were examined to find the best configuration. The search space applied for making the optimization process is tabulated in Table 3.

The results show that the CCHP system with a 44 kW NGG and no PV panels and battery storages is capable to support the electrical demands with the LPSP of 1%. The impact of increasing NGG power on the LPSP of the CCHP system is shown in Fig. 7, at two circumstances of no PVs and 10 kW of PV powers. As can be seen from this figure, the required NGG sizes in the CCHP system with LPSP of 1% are 44 kW for no PV configuration and 28 kW when 10 kW of PV powers is used in the CCHP configuration.

Solar collector heating

As it is mentioned in the previous sections, in the present study, the cooling load was considered to be supplied by an absorption chiller during the warm seasons. In order to reduce the calculation times, the absorption chiller cooling energy was converted into the heating energy that is needed in the absorption chiller generator to do the compression process, using Eq. (6) and assuming a COP of 0.55. The total heat demand (the required heating energy in cold months and the heating energy needs in absorption chiller) is shown in Fig. 8.

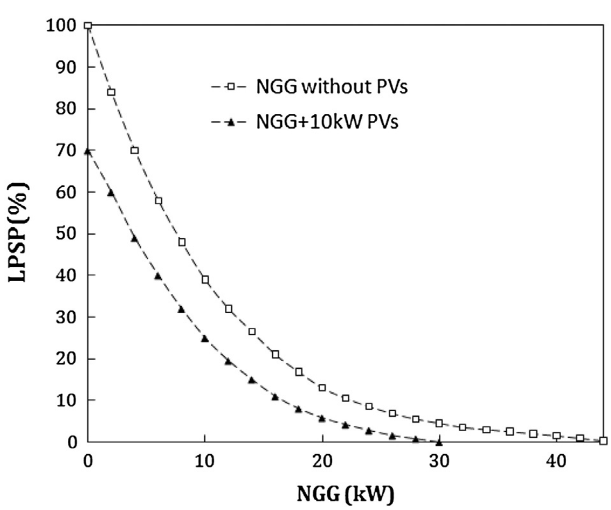


Fig. 7. The impact of addition of 10 kW solar PVs.

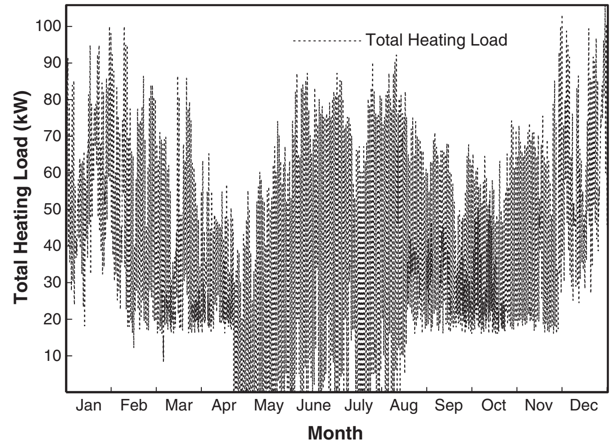


Fig. 8. The required heating energy in cold months and the heating energy needs in absorption chiller.

The capability of solar collectors to support part of the heating load during six months of the year is shown in Fig. 9. As this figure shows, for cold months such as January a considerable amount of heating demand could be meet by increasing of solar collector areas, for the hours between 10 am and 3 pm. Because of the coincidence of the heating demand (absorption chiller evaporator) and high level of solar radiation during the warm months, the application of solar collectors in that months is more effective than in the other months. For instance, the increase of solar collector areas from 20 m^2 to 100 m^2 is found to be suitable to support a considerable part of heating demand for the hours between 8 am and 5 pm in July. According to Fig. 9, no considerable part of heating demand could be supplied by increasing the solar collector areas for more than 80 m^2 during the moderate months such as March, May, Sep and Nov. Because no heat energy storage system was used in the calculations of the present work, the solar heat energy is inefficient between the sunset and sunrise hours.

A boiler is required to meet the thermal energy needs during non-availability period of solar collector heating energy, and recovered heat from NGGs. The size of the boiler in a heating system is determined according to maximum heating energy needs over the hours of the year. According to the peak of heating energy needs in the present work (Fig. 8), a boiler with capacity of 110 kW was used in thermal calculations. Different CCHP configurations with high reliability in supporting the electrical loads were determined from the previous section. For all configurations, the heat recovery ratio of NGGs was considered to be 40%. The boiler is switched on during the times when NGG recovered heat and solar collector heats are inefficient to supply the thermal needs.

Economical assessment

After determining the CCHP systems with high reliability in the previous section, LCOE analysis was utilized to find high reliable systems with the lowest costs under four different fuel price scenarios. All costs were considered over the whole project life which is 20 years. Table 4 shows the initial capital, replacement and maintenance costs of the system components that were used in the present study. As it can be seen in Table 4, the replacement cost of the PV modules and solar collectors are zero. This is because, the system lifetime was assumed to be equal to the lifetime years of PV system (and solar collectors). NGGs and boiler fuel were natural gas, which costs were considered under four different scenarios, as shown in Table 5.

Five different configurations of the CCHP system were found under different fuel price scenarios (Table 6). The solar collector areas were allowed to change from 0 m^2 to 100 m^2 for each configuration. The

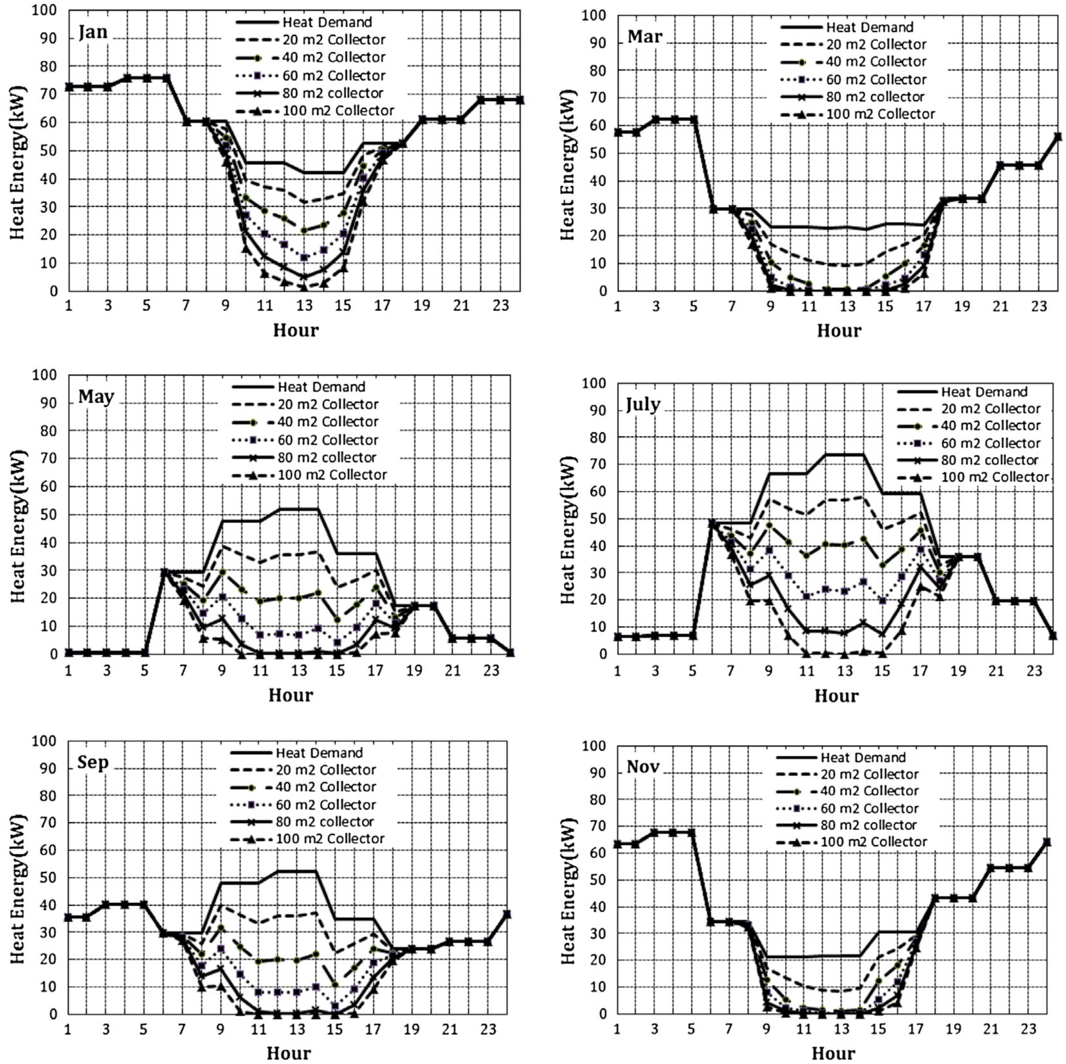


Fig. 9. The effect of solar collector on decreasing the NGGs and boiler required heating energy needs.

curves of the LCOE for five different CCHP configurations meeting the LPSPs of less than 1% are shown in Figs. 10 to13.

Fig. 10 shows that the LCOE of the CCHP configurations increases by decreasing the role of NGGs in energy generation, so that the configuration with 65 kW of solar PVs with no contribution of NGG has the highest LCOE. The effect of increasing solar PVs on LCOE of the CCHP system is clearly evident when the sizes of solar PV power increase from 25 kW to 65 kW. Because of the low cost of fuel (0.1\$/m^3), the configurations with high solar PV powers are not economically compatible with the CCHP configurations including the NGGs. Also, it can be seen that the increase of solar collector areas increases the LCOE of each five CCHP configurations. A comparison was made between the current average energy costs of the studied building (Table 1, year 2014, medium consumption) and the costs obtained from Fig. 10. The results demonstrate that the CCHP configuration including no solar PVs and solar collectors with a fuel price of 0.1 \$/kWh and the conventional energy system with a subsidized fuel price of 0.083 \$/kWh (Table 1) has approximately the same energy price of 0.035 \$/kWh. Fig. 10 and Table 1 also show that if the fuel price of the conventional energy system would be increased to 0.1 \$/kWh, the energy produced by CCHP configuration with 44 kW NGGs, no PVs and 100 m2 of solar collectors would have the same value of 0.045 \$/kWh as the current conventional energy system.

Fig. 11 shows the change in the LCOE of different CCHP configuration under fuel price of 0.3 \$/m^3. As can be seen, the LCOE of the CCHP system is increased by increasing the solar PV powers. A comparison between Figs. 10 and 11 shows that, the difference between the LCOEs of the configurations with 25 kW PVs (22 kW NGG) and 65 kW PVs (without NGG) will be decreased by increasing the fuel cost from 0.1 \$/m^3 to 0.3 \$/m^3. Also, it is clear that the increase of fuel price changes the variation trend of the LCOE of each configuration. Unlike Fig. 10 (fuel price of 0.1 \$/m^3), Fig. 11 shows a minimum LCOE for the configurations with 60 m^2 of solar collector areas. This proves that the application of solar collector in the CCHP systems presented in the current study becomes economically justified by increasing of the fuel prices. This is most evident in Figs. 12 and 13, where the fuel prices are 0.6 \$/m^3 and 0.9 \$/m^3, respectively. As can be seen from these figures, the LCOEs of the configurations with both contribution of PVs and NGGs are considerably decreased by increasing of the solar collector areas from 0 m^2 to 80 m^2. As it is depicted in Fig. 13, under fuel price of 0.9 \$/m^2, the CCHP configuration with the maximum contribution of solar energy (65 kW of PVs and 100 m^2 of

Table 4
Cost figures used for the various components of hybrid systems.

	Initial capital (\$/kW)	Replacement cost (\$/kW)	Operation and maintenance cost
PV modules	4300	0	15 (\$/kW per year)
Battery bank	273	250	7 (\$/kW per year)
NGG	500	450	Table 4
Converter	520	450	10 (\$/kW per year)
Flat solar collectors	37(\$/m^2)	0	4 (\$/m^2 per year)

Table 5
Fuel price, operation and maintenance cost of NGGs.

	Natural gas price($/m^3)	O&M cost ($/h)
Scenario A (subsidized fuel price)	0.1	0.016
Scenario B	0.3	0.18
Scenario C	0.6	0.28
Scenario D	0.9	0.5

Table 6
The results of techno-economic process, five different CCHP configurations.

PV (kW)	NNG (kW)	Battery number/autonomy (h)	Converter (kW)
0	44	0/0	0
10	30	7/2.35	5
20	24	8/3.5	8
25	22	8/3.5	10
65	0	70/24	40

solar collectors) has the minimum LCOE compared to others. Furthermore Fig. 13 shows that among the five CCHP configurations, the CCHP configuration with the maximum solar PV power (and solar collector area of more than 20 m^2) has the minimum LCOE under fuel price scenario of 0.9 $/m^3.

The effect of solar collectors on thermal excess energy is presented in Fig. 14. It is observed that part of the heat generation from NGGs and solar collectors is wasted during the year. It mostly occurred in the CCHP configurations with high contributions of NGGs. For instance, in the configuration with 44 kW of NGGs and no solar collectors, 31 kWh of the heating energy is wasted during the year. This is because of the mismatch between the heating energy recovered from the NGGs and the required thermal load. At these times, the boiler supplies the heating needs. When a configuration with 44 kW NGGs and no solar PVs is used as the main source of electricity demands, a two-fold increase occurred in the amount of wasted heat by increasing the solar collector areas from 0 m^2 to 100 m^2.

The emission produced by the CCHP systems is always of concern to the engineers and decision makers. In the present study, the fuel consumption was calculated during the working hours of NGGs and boiler in order to estimate the amount of CO_2, CO, NO_x, SO_x, particular matters and methane emissions. A value of 17 $/ton was used as the emission penalty in the present work.

For all configurations, the variation in CCHP total annual emissions at different sizes of solar collector areas and PV powers was determined and is depicted in Fig. 15. It can be observed that the increasing of solar PV powers (and decreasing the NGG powers) from 0 kW to 10 kW decreases the amount of total annual emissions by about 18%. This percentage is approximately 13%, if the solar PV

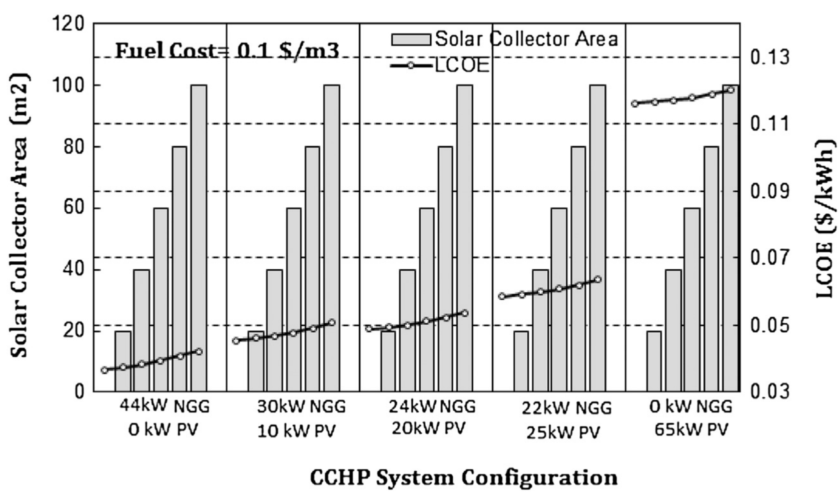


Fig. 10. The effect of solar collector and solar PVs on LCOE of the CCHP systems (fuel cost of 0.1 $/m3).

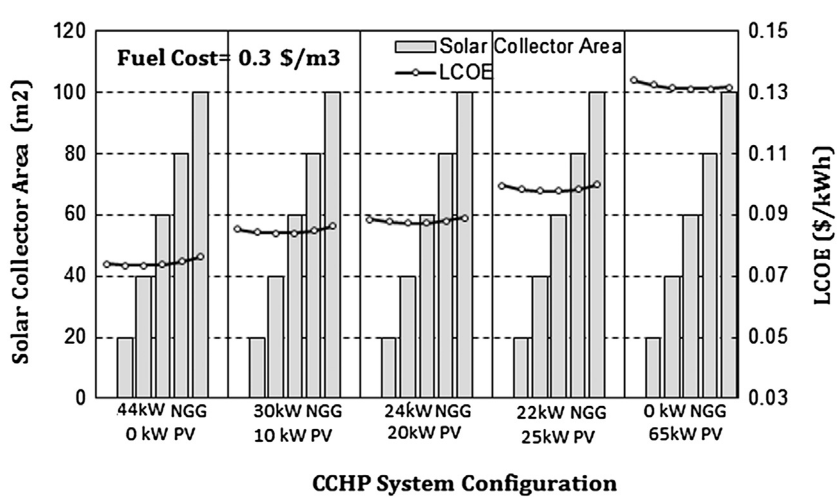


Fig. 11. The effect of solar collector and solar PVs on LCOE of the CCHP systems (fuel cost of 0.3 $/m3).

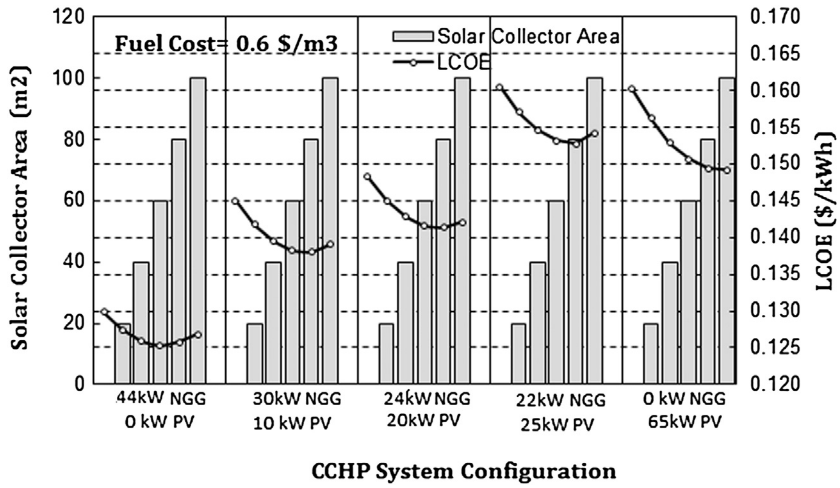


Fig. 12. The effect of solar collector and solar PVs on LCOE of the CCHP systems (fuel cost of 0.6 $/m3).

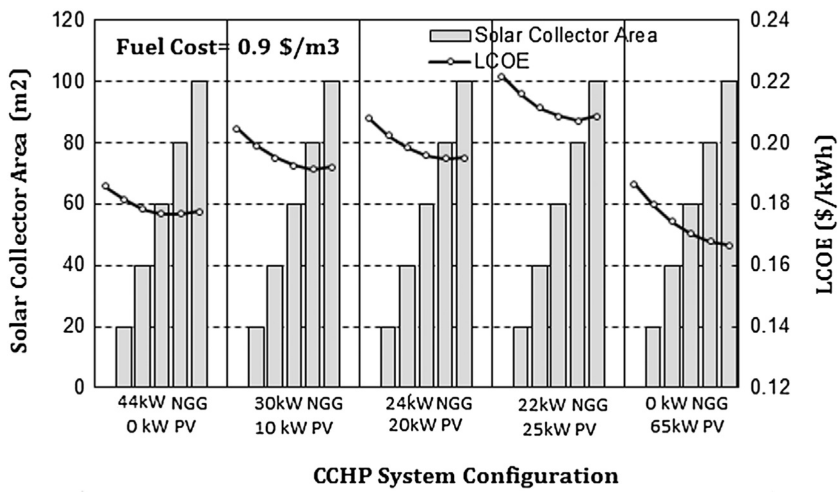


Fig. 13. The effect of solar collector and solar PVs on LCOE of the CCHP systems (fuel cost of 0.9 $/m3).

power increases from 10 kW to 25 kW. Also, a 60% decrease in the total annual emission is obtained by increasing the solar PV powers from 25 kW to 65 kW.

The effect of increasing solar collector areas (from 0 m^2 to 100 m^2) on percentage decrease in the emission produced by each CCHP configurations is listed in Table 7. As it is clear from this table, the effect of

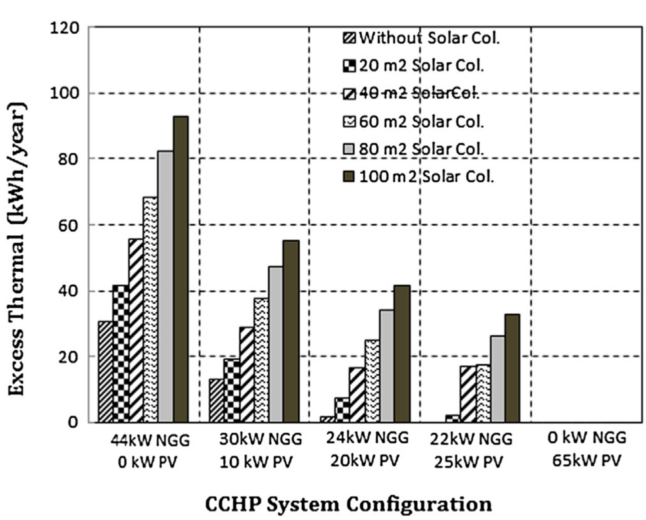


Fig. 14. The effect of solar collectors on thermal excess energy.

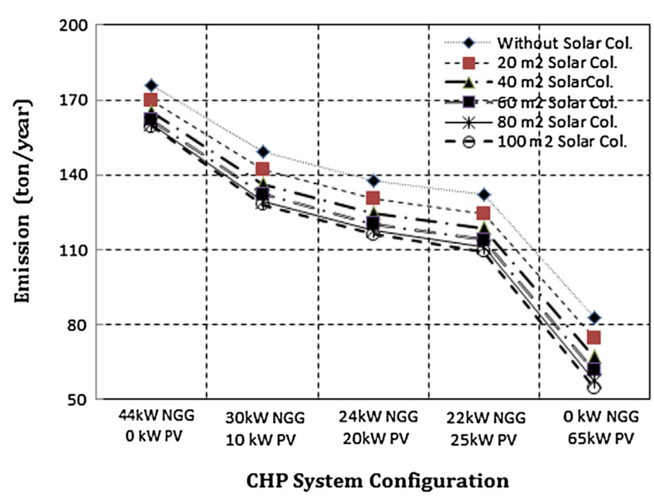


Fig. 15. The effect of solar collectors and solar PVs on total annual emissions of CCHP systems.

Table 7
The percentage decrease in annual emission by increasing the solar collector areas from 0 m^2 to 100 m^2.

CCHP configuration	Percentage decrease in total annual emission (%)
44 kW NGG + 0 kW PV	10.22
30 kW NGG + 10 kW PV	16.49
24 kW NGG + 20 kW PV	18.73
22 kW NGG + 25 kW PV	20.66
0 kW NGG + 65 kW PV	51.12

increasing solar collector areas on decreasing the emissions is most evident as the portion of NGGs in the CCHP configuration is decreased.

The best configurations with minimum costs under four different fuel price scenarios were determined and the variations of their LCOE and total annual emissions are shown in Fig. 16.

By using Fig. 16, it is possible to choose a CCHP system according to our requirements and design constraints. For instance, if the fuel price is between 0.3 $/m^3 and 0.6 $/m^3, and the total annual emission constrains is defined as a value of less than 112 ton/yr, then the selection of CCHP system is limited to the configurations with less than 24 kW NGGs. In this case, the LCOE of the CCHP system can be estimated to be between 0.1 $/kWh and 0.16 $/kWh. It is necessary to mention that the weather condition, the profiles of the electricity and heating load demands may change the results.

Conclusions

A micro CCHP system based on a natural-gas generator (NGG), solar panels (PVs) and solar collectors was investigated to meet the electrical and thermal energy requirements of a 5 story high residential building; having a total of 1000 m^2 floor area with the peak electricity of 48 kW, heating and cooling needs of 100 and 50 kW, respectively. All the calculations were done under four different fuel price scenarios. The excess electrical energy produced by the NGGs, the solar collector heat generations and a natural-gas boiler was considered to be used in a heat exchanger/absorption chiller system to meet a portion of the heating/cooling energy needs of the building. Results show that the fuel price plays a vital role in the optimization of a CCHP system.

- If a low cost of fuel (0.1 $/m^3) is used in the calculations, the configurations with high solar PV powers are not economically compatible with the CCHP configurations with more portions of NGGs in energy generation and vice versa.
- The CCHP system with 44 kW of NGGs and under fuel price of 0.1 $/m^3 has the same unit energy cost as the conventional energy systems.

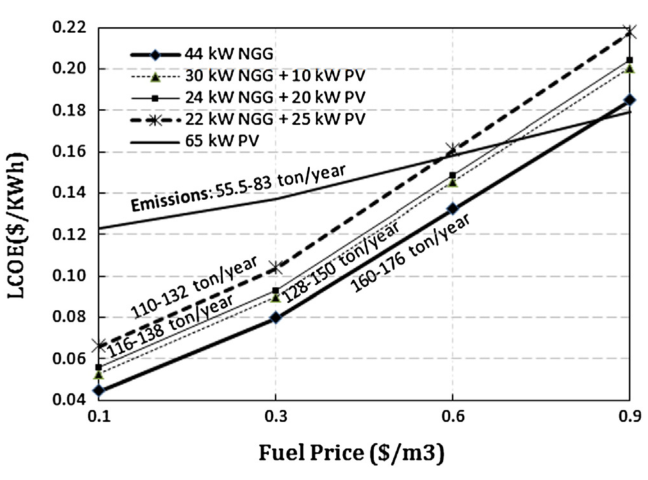


Fig. 16. The LCOE and total annual emissions of the high reliable CCHP systems under different fuel prices.

- If the fuel price of the current conventional energy system is increased to 0.1 $/m^3, the application of solar collectors in the CCHP system would be economically justified.
- The applications of solar collector becomes economically justified by increasing the fuel costs more than and equal to 0.3 $/m^3.
- The selection of a proper CCHP system varies depending on its total annual emissions, fuel price and also the total excess heating and thermal energy generations.

The applications of solar PVs and solar collectors in the CCHP system will be economically justified, only if Iran removes its fuel price subsidies. With increasing the fuel price for more than nearly 0.6 $/m^3 and considering the total annual emission produced by CCHP configurations with high contributions of NGGs, these configurations become insufficient compared to the configurations with high contributions of solar PV and solar collectors.

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