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Examination of energy price policies in Iran for optimal configuration of CHP and CCHP systems based on particle swarm optimization algorithm

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ABSTRACT

The current subsidized energy prices in Iran are proposed to be gradually eliminated over the next few years. The objective of this study is to examine the effects of current and future energy price policies on optimal configuration of combined heat and power (CHP) and combined cooling, heating, and power (CCHP) systems in Iran, under the conditions of selling and not-selling electricity to utility. The particle swarm optimization algorithm is used for minimizing the cost function for owning and operating various CHP and CCHP systems in an industrial dairy unit. The results show that with the estimated future unsubsidized utility prices, CHP and CCHP systems operating with reciprocating engine prime mover have total costs of 5.6 and 2.9×10^6 over useful life of 20 years, respectively, while both systems have the same capital recovery periods of 1.3 years. However, for the same prime mover and with current subsidized prices, CHP and CCHP systems require 4.9 and 5.2 years for capital recovery, respectively. It is concluded that the current energy price policies hinder the promotion of installing CHP and CCHP systems and, the policy of selling electricity to utility as well as eliminating subsidies are prerequisites to successful widespread utilization of such systems.

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1. Introduction

Combined cooling, heating, and power (CCHP) systems use energy stored in output thermal energy (TE) of power generation prime movers to meet electricity, heating, and cooling loads. As opposed to electricity driven chillers that may be used in conjunction with combined heating and power (CHP) systems, it is common to utilize thermally activated equipment such as absorption chillers in CCHP systems for meeting required cooling load. While the capital costs of CHP and CCHP systems are comparatively higher than the conventional separate heat and power (SHP) systems, their proper selection and optimal sizing could result in shorter capital recovery period and lower cost of energy supply (Kong, 2008). Aside from the economical advantages due to the reasonable use of input energy, CCHP systems are also highly effective in the preservation of primary energy resources (Chicco and Mancarella, 2007).

Over the years, different countries have introduced various measures and policies for enhancing interest in the installation of CCHP systems. In the United States, the Department of Energy and the Combined Heat and Power Association have attempted to boost the installed capacity of CCHP systems from 46 GW in 1998 to 92 GW in 2010 (Wu and Wang, 2006). The authorities have recommended alleviating the hurdles that hinder CCHP systems from being connected to utility networks. Also by 2010, a substantial portion of the energy demand of the new constructed and existing commercial, institutional, and residential buildings must be met by CCHP systems. Shortening depreciation life and providing an investment tax are the two encouragement policies that are expected to increase the utilization of CCHP systems (Wu and Wang, 2006). In the European Union, the development of CCHP has a large diversity both in the scale and nature of the development and governments' different energy policies have the greatest effects on this diversity (COGEN Europe, 2001). In Austria, CCHP systems have been greatly encouraged because of environmental benefits (COGEN Europe, 2001). In Denmark, availability of district heating and environmental issues are the key factors that inspire the use of CCHP systems and, subsidies and grants are the two encouragement policies for further development of CCHP installations (COGEN Europe, 2001). In the Netherlands, tax exemption for fuels that are used for generating power and TE supplied via CCHP systems encourages people for utilizing them (COGEN Europe, 2001). In Germany, low electricity costs impeded progress of CCHP utilization, however, recently the government has taken several measures for inspiring the development of CCHP systems. With an effective efficiency of more than 70%, CHP systems are exempted from electricity and gas taxes in Germany and, it is obligatory to buy electricity from cogeneration with an

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Nomenclature

C	Cost ($)
Cc	Capital cost ($/kW)
CM	Maintenance coefficient ($/kW h)
Cp	Capacity (kW)
COP	Coefficient of performance
c_1, c_2	Learning factor
E	Electricity production (kW h)
f	Inflation rate
F	Recovery factor
Gas	Gas consumption (m^3)
H	Heat production (kW h)
HPR	Heat to power ratio
HV	Heat value (kW h/m^3)
I	Income ($)
ir	Interest rate
k	Number of iterations
L	Load (kW h)
n	System lifetime (year)
num	Number of paralleled microturbines
p	Particle best position
P	Energy price ($/kW h)
$Pdem$	Demand price ($/kW)
r_1, r_2	Random numbers between 0 and 1
V	Velocity vector
X	Position vector

Greek symbols

η	efficiency
ω	Inertia weight

Subscripts

c	Cooling
d	Day
dem	Demand
ec	Electric cooling
$elec$	Electricity
g	Global
gas	Natural gas
h	Hour
hc	Heat cooling
$heat$	Heating
HX	Heat exchanger
i	Number of particles
$invest$	Investment
max	Maximum
min	Minimum
nom	Nominal
$purch$	Purchase
$sale$	Sale
$self$	Self-use
th	Thermal

Superscripts

abs-chill	Absorption chiller
boiler	Supplementary boiler
comp-chill	Compression chiller
GT	Gas turbine prime mover
loss	Excess heat loss
MT	Microturbine prime mover
PM	Prime mover
RE	Reciprocating engine prime mover
tank	Heat storage tank

Acronyms

APEC	Annual primary energy consumption
CCHP	Combined cool, heat, and power
CHP	Combined heat and power
COP	Coefficient of performance
CRP	Capital recovery period
GT	Gas turbine
MT	Microturbine
Ns	Not selling
PSO	Particle swarm optimization
RE	Reciprocating engine
S	Selling
SHP	Separate heat and power
TC	Total cost
TE	Thermal energy

extra subsidy (Wu and Wang, 2006). Also a quota of sold electricity by utility companies must be met by CCHP systems. In Italy, tax reduction on the use of natural gas for industrial CCHP systems and the carbon tax exemptions for CCHP systems are used as encouragement policies (Wu and Wang, 2006). In UK, the government has recently introduced several measures such as tax credit and grant support to help the development of CCHP systems (Wu and Wang, 2006). The UK CHP installed electricity capacity has doubled in the past 10 years (60,000 MW) (Hinnells, 2008). In Portugal, the government effort to restrain the growth in green house gas emission promoted CHP quota of power production to 12.2% of total (Moreira et al., 2007). In Asia, China introduced several encouragement policies during 1990 to develop CCHP systems, where tax exemption, investment tax credit, and direct subsidy for energy savings are some of the incentives (Wu and Wang, 2006). In Japan, special taxation, low interest loan and investment subsidies are used as effective strategies to promote CCHP systems (Wu and Wang, 2006). In addition to the cited encouragement policies, allowing the private power producer to sell electricity to utility or third parties and obligation for decreasing environmental pollutants play an important role for further development of CCHP system (Wu and Wang, 2006).

In Iran, the heavily subsidized fuel prices allow for energy consumption rate to equal to world's average and several times higher than majority of developing countries. The low cost electricity and gas make it impossible to have a reasonable payback period for implementing an energy efficiency measure such as building wall insulation (Ardehali, 2006) (Ardehali et al., 2007). The annual increase in electricity consumption is about 8.3% (Ghorashi, 2007) in Iran and, the need for the construction of new power generation facilities has led to the development of policies that encourage parallel connection to utility national network for selling electricity by local CHP and CCHP installations, as noted by Iran Ministry of Energy (MOE). (2009). Further, the availability of natural gas through the nation-wide piping network system encourages the utilization of natural gas for CHP and CCHP systems in Iran, especially during spring, summer,

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and fall seasons, as creating higher demand for the available excess capacity favors the utility.

While energy price policies can make CHP and CCHP installations favorable, the success of utilizing such systems is also influenced by their optimal sizing and operation. As the power and TE generation by CHP and CCHP systems are correlated and heating, cooling, and electricity load profiles are site dependent, it is necessary to examine various prime mover technologies for optimal operation during their useful life. Numerous models have been presented for optimal configuration and operation of CHP and CCHP systems in the literature. Kong (2005, 2008) introduced nonlinear programming model for minimizing the energy supply cost of a micro-CCHP system that consists of a gas turbine and an absorption chiller. Simulation by Kong (2008) studied the dependency of recovered TE utilization on the ratio of electricity to gas prices. In that study it is determined that fulfilling cooling loads for higher (close to 4) and heating loads for lower (near 0.39) ratios are most economical. Cho et al. (2008) developed a linear programming model for the optimal operation of a prime mover and its component, where the model minimizes cost of heating, cooling, and power supply minute by minute. Arcur et al. (2007) proposed a linear programming based model for optimal operation and configuration of a CCHP system in a hospital. The cost function in that study includes cost of demand supply and environmental pollutants. Mago and Chamra (2008) introduced a model to determine the optimal operation of a CCHP system where the considered criteria include energy cost, primary energy consumption, and amount of pollutants, where heat following, electricity following, and mixed heat and electricity following operation strategies are used to determine the optimal operation for each criterion. As a result of that study, mixed heat and electricity following operation strategy is found as the most suitable strategy for each criterion. Frangopoulos et al. (1996) presented a linear programming model for the optimization of energy system in a refinery. Oh et al. (2007) and Seo et al. (2008) used mixed integer linear programming models for optimal configuration and operation of CHP systems in commercial and residential sectors, where selling electricity to utility is not available. Ren et al. (2008) presented a nonlinear programming model for optimal sizing of a residential CHP system, where the objective function consists of energy, carbon emission, and equipment capital costs. In that study, heat storage tank is used to store excess TE and cooling load is met by compression chiller. Genetic algorithm is used by Wang et al. (2009) to investigate optimal capacity and operation of a CCHP system. Primary energy consumption, carbon dioxide emission, and sum of annual operation and investment costs are three criteria included in the objective function of that study.

The objective of this study is to examine the effects of current and future energy price policies on optimal configuration of CHP and CCHP systems in Iran, under the conditions of selling and not-selling electricity to utility. In this study, the particle swarm optimization algorithm is used for minimizing the cost function for owning and operating various CHP and CCHP systems in an industrial dairy unit.

2. System description

As shown in Fig. 1, the proposed CCHP system in this study consists of prime mover, heat exchanger, supplementary boiler, absorption chiller, and compression chiller.

For CCHP systems, the prime mover utilizes natural gas to provide electricity and TE for heating and absorption chiller cooling. Priority order of using prime mover output TE is given to cooling rather than heating so that the peak demand for the electricity may be lowered. Whenever output TE is more than required heat for absorption cooling and heating, excess heat is sent to the heat storage tank for later use, otherwise, it is dissipated to outdoor air. Whenever output TE is less than that required by cooling load, the electricity driven compression chiller is used to meet unsatisfied cooling load. If the prime mover output TE is less than that required by heating load, supplementary boiler is used to meet the remaining heating load.

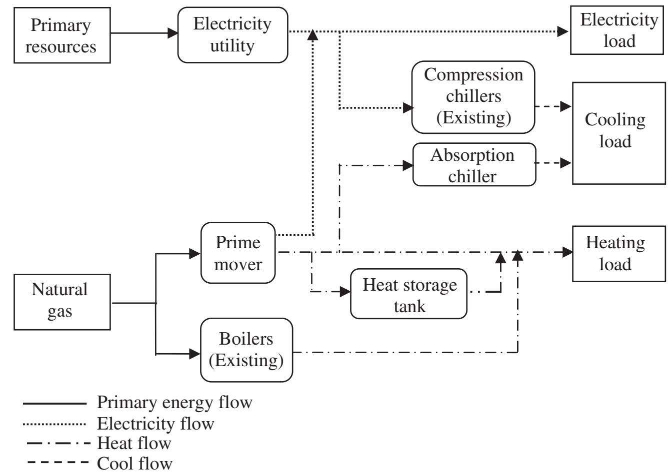

Fig. 1. CCHP system configuration in this study. For CHP system, the absorption chiller is not considered.

For electricity, whenever the power produced is more than the sum of electricity load and unsatisfied cooling load (that must be met by compression chiller), excess electricity is sold to utility. Under the condition of not-selling electricity, prime mover never produces power more than the sum of electricity load and unsatisfied cooling load and the required additional electricity is purchased from utility.

While all aforementioned principles for CCHP systems also hold for CHP systems, the only difference is in the way of meeting cooling load. For CHP systems, there is no absorption chiller and all the recovered TE is used for heating and, cooling load is met by means of compression chillers.

At present, the industrial dairy unit utilizes an SHP system and electricity is purchased from utility to meet the load including that required by the existing compression chillers. The local utility current and future electricity selling and purchasing transaction prices as well as natural gas prices are given in Table 1. Natural gas is purchased to meet all TE requirements by means of existing boilers at the industrial dairy unit.

For systems operation at the industrial dairy unit, the days in a week are divided into 4 types: Saturday as the first working day (type 1), Sunday to Wednesday as regular working days (type 2), Thursday as the last working day (type 3), and Friday as the weekend (type 4). For every week in a year, the data for day type 2 is used for all four regular working days. The data for electricity for cooling load (electricity – cooling), electricity load that does not include electrical energy for compression chillers (electricity – other use), and heat load are collected on hourly basis for everyday type as shown in Fig. 2. The separate metering for electricity—cooling provides for studying the effects of absorption cooling on both TE and electricity generation of CHP and CCHP prime movers. Heat load is estimated based on metered natural gas consumption and it includes necessary conversion factors including that of boiler efficiency. In this study, system life time, effective interest rate, and electricity demand price are 20 years, 7%, and 1.25 ($/kW), respectively.

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Table 1
Current and future utility prices used in this study.

Policy	Utility and transaction	Day	Off-peak (23–25)	Mid-peak (6–17)	Peak (18–22)
Current	Electricity purchasing (subsidized) (\$/kW h)[a]	Friday	0.046	0.046	0.046
		Non-Friday	0.005	0.019	0.061
	Electricity selling (\$/kW h)[b]	Everyday	0	0.035	0.035
	Gas purchasing (\$/m^3) [c]		0.017		
Future	Electricity purchasing (unsubsidized) (\$/kW h)[b]		0.081		
	Electricity selling (\$/kW h)[b]		0.081		
	Gas purchasing (\$/m^3)[b]		0.073		

[a] Source: Electricity Tariff and Their General Condition for Iran, 2008.
[b] Source: Iran MOE, 2009.
[c] Source: Iran Natural Gas Tariff, 2008.

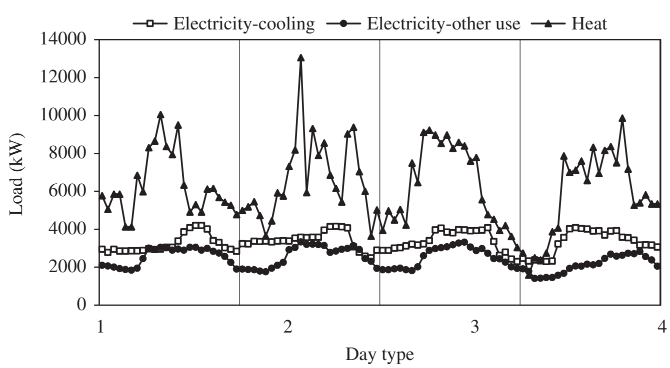

Fig. 2. Electricity – cooling, electricity – other use, and heat load data recorded hourly for a typical week with 4 day types for the industrial dairy unit.

3. Analysis

In this section, the formulation of objective function and constraints along with modeling details for system components for CHP and CCHP systems are presented.

3.1. Objective function

For the CCHP system, the operational costs and capital investments for the new prime mover and absorption chiller are included in the objective function. For the economic analysis, all costs in the objective function are converted to the net present value. The industrial dairy unit benefits from existing boilers and compression chillers and their capital costs are neglected. The capital cost of heat storage tank is assumed negligible, as compared with those of prime mover and absorption chiller. To examine the effects of energy price policies and parallel connection to the national electrical network, two cases of selling and not-selling electricity to utility are considered throughout for the examined CHP and CCHP systems.

The objective function in this study is examined for useful life of the CCHP system (Ren et al., 2008), given by

$$MinC_{total}^{CCHP} = C_{invest}^{PM} + C_{invest}^{abs-chill} + C_{run}^{PM} + C_{run}^{boiler} + C_{purch}^{utility} + C_{dem}^{utility} - I_{sale}^{utility} \quad (1)$$

All variables and symbols are defined in the nomenclature section. In Eq. (1), costs include capital costs for both prime mover and absorption chiller, operation cost of prime mover, operation cost of supplementary boiler, cost of purchasing electricity from utility, demand cost, and income is the revenue from selling electricity to utility.

The capital costs associated with CCHP systems are described by

$$C_{invest}^{PM} = Cc^{PM} Cp^{PM} \quad (2)$$

$$C_{invest}^{abs-chill} = Cc^{abs-chill} Cp^{abs-chill} \quad (3)$$

The fuel cost for each hour can be obtained from multiplying fuel of prime mover or boiler by the fuel price. The hourly maintenance cost of prime mover is calculated with the multiplication of generated power for each hour by maintenance cost coefficient (Ren et al., 2008). Maintenance cost of boiler is assumed negligible in this study (Wang et al., 2009). The operation costs of prime mover and supplementary boiler are defined by

$$C_{run}^{PM} = \sum_{d=1}^{7} \sum_{h=1}^{24} \left[E_{d,h}^{PM} \left(\frac{P_{gas}}{\eta_{d,h}^{PM} HV} + CM \right) \right] \frac{365}{7} F \quad (4)$$

where the electrical efficiency varies as a function of load, and

$$C_{run}^{boiler} = \sum_{d=1}^{7} \sum_{h=1}^{24} \left[H_{d,h}^{boiler} \left(\frac{P_{gas}}{\eta^{boiler} HV} \right) \right] \frac{365}{7} F \quad (5)$$

where the boiler efficiency (η) is usually considered constant under different part load conditions. F is a factor for conversion of costs to the present value given by

$$F = \frac{(1+ir)^n - 1)}{ir(1+ir)^n} \quad (6)$$

where

$$ir = \frac{(ir_{nom} - f)}{(1+f)} \quad (7)$$

When heat to power ratio (HPR) is constant, thermal efficiency of prime mover is given by (Ren et al., 2008)

$$\eta_{d,h,th} = \eta_{d,h}^{PM} HPR \quad (8)$$

and, when HPR is regarded as recoverable heat to power ratio, it is multiplied by heat exchanger efficiency to obtain net recovered heat to power ratio.

Prime mover output heat is (Firestone, 2004)

$$H_{d,h}^{PM} = HPRE_{d,h}^{PM} \quad (9)$$

However, in general, HPR is not constant and heat output is a function of produced power (Brujic et al., 2007)

$$H_{d,h}^{PM} = f(E_{d,h}^{PM}) \quad (10)$$

The total cost of purchased electricity from utility is the product of hourly purchased electricity and utility electricity price for each hour (Ren et al., 2008)

$$C_{purch}^{utility} = \sum_{d=1}^{7} \sum_{h=1}^{24} [E_{d,h}^{utility} P_{purch,d,h}] \frac{365}{7} F \quad (11)$$

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The demand cost is the product of maximum purchased power from utility for each month and demand price

$$C_{dem}^{utility} = \sum_{d=1}^{7}\sum_{h=1}^{24} max(E_{d,h}^{utility})Pdem(12)F \quad (12)$$

The income from selling electricity to utility is the product of hourly sold electricity and regulated price for each hour that depends on encouragement policy (Ren et al., 2008)

$$I_{sale}^{utility} = \sum_{d=1}^{7}\sum_{h=1}^{24}\left[E_{d,h,sale}^{PM}P_{sale,d,h}\right]\frac{365}{7}F \quad (13)$$

3.2. Constraints

In this section, the constraints applied for both selling and not selling the excess electricity to utility are given.

3.2.1. Selling electricity

Balance between supply and demand must be fulfilled for both TE and electricity at each hourly time step. The balances for heat and electricity are

$$E_{d,h}^{utility}+E_{d,h,self}^{PM}+E_{d,h,sale}^{PM}=L_{d,h,elec}+\frac{L_{d,h,ec}}{COP^{comp-chill}} \quad d=1,\ldots,7 \quad h=1,\ldots,24 \quad (14)$$

$$H_{d,h}^{PM}+H_{d,h}^{boiler}+H_{d,h}^{tank}+H_{d,h}^{loss}=L_{d,h,heat}+\frac{L_{d,h,hc}}{COP^{abs-chill}} \quad d=1,\ldots,7 \quad h=1,\ldots,24 \quad (15)$$

where

$$L_{d,h,ec}=L_{d,h,c}-L_{d,h,hc} \quad d=1,\ldots,7 \quad h=1,\ldots,24 \quad (16)$$

As it is not possible to sell and buy electricity at the same time,

$$E_{d,h}^{utility}E_{d,h,sale}^{PM}=0 \quad d=1,\ldots,7 \quad h=1,\ldots,24 \quad (17)$$

Performance constraint for prime mover prevents the unit from producing electric power in excess of its installed capacity (Ren et al., 2008)

$$E_{d,h,self}^{PM}+E_{d,h,sale}^{PM}\le Cp^{PM} \quad d=1,\ldots,7 \quad h=1,\ldots,24 \quad (18)$$

The prime mover installed capacity is limited to capacities available for purchase in the market (Ren et al., 2008).

$$Cp_{min}^{PM}\le Cp^{PM}\le Cp_{max}^{PM} \quad (19)$$

The cooling load met by absorption chiller should not exceed the installed capacity

$$L_{d,h,hc}\le Cp^{abs-chill} \quad d=1,\ldots,7 \quad h=1,\ldots,24 \quad (20)$$

The absorption chiller installed capacity may not exceed ranges available for purchase in the market

$$Cp_{min}^{abs-chill}\le Cp^{abs-chill}\le Cp_{max}^{abs-chill} \quad (21)$$

The minimum and maximum TE that can be stored in the storage tank is limited by

$$E_{\min}^{tank}\le E_{d,h}^{tank}\le E_{\max}^{tank} \quad d=1,\ldots,7 \quad h=1,\ldots,24 \quad (22)$$

For every week in a year, the initial and final conditions of heat stored in the heat storage tank are equal

$$E_{1,0}^{tank}=E_{7,24}^{tank} \quad (23)$$

The prime mover operates at different partial loads, but it is not reasonable to operate it below a minimum value. In this study, it is assumed that the prime mover cannot work below 30% (Wang et al., 2009) of its rated power

$$E_{d,h,self}^{PM}+E_{d,h,sale}^{PM}>0.3Cp^{PM} \quad d=1,\ldots,7 \quad h=1,\ldots,24 \quad (24)$$

Otherwise

$$E_{d,h,self}^{PM}+E_{d,h,sale}^{PM}=0 \quad d=1,\ldots,7 \quad h=1,\ldots,24$$

For CHP system, the modeling relations are given by Eqs. (1–13) and the constraints are described by Eqs. (14–24). Further, the absorption chiller is unavailable

$$Cp^{abs-chill}=0\Rightarrow L_{d,h,hc}=0 \quad d=1,\ldots,7 \quad h=1,\ldots,24\cdot \quad (25)$$

3.2.2. Not selling electricity

When there is no excess electricity available for selling to utility, in addition to the constraints describe by Eqs. (14–24) for CCHP system and Eqs. (14–25) for CHP system, the following constraint is applied

$$E_{d,h,sale}^{PM}=0 \quad d=1,\ldots,7 \quad h=1,\ldots,24 \quad (26)$$

3.3. System components modeling

For optimization purposes, the models for reciprocating engine (RE), gas turbine (GT), and microturbine (MT) as prime movers, absorption chiller, compression chiller, supplementary boiler, and heat storage tank are necessary, as discussed below.

3.3.1. Reciprocating engine prime mover

Parameters used in the performance optimization are functions of RE capacity and they include capital cost, maintenance cost coefficient, nominal electrical efficiency, electrical efficiency at partial loads, and *HPR* or thermal efficiency (Firestone, 2004),

$$\eta_{nom}^{RE}=0.0175\,ln(Cp^{RE})+0.215 \quad (27)$$

$$CM^{RE}=-0.0024\,ln(Cp^{RE})+0.277 \quad (28)$$

$$Cc^{RE}=-76.21\,ln(Cp^{RE})+1303.3 \quad (29)$$

$$HPR=-0.2342\,ln(Cp^{RE})+3.17 \quad (30)$$

Maximum and minimum capacity of the RE described by Eqs. (27–30) is assumed 5000 kW (Firestone, 2004) and 1000 kW, respectively. RE useful life is 20 years (Firestone, 2004). Heat to power ratio is recoverable *HPR* and RE output TE is given by

$$H_{d,h}^{RE}=HPRE_{d,h}^{RE}\eta_{HX} \quad (31)$$

The electrical efficiency under different partial loads is approximated by a cubic polynomial, given by (Environmental Protection Agency (EPA), 2002)

$$\eta_{d,h}^{RE}=(0.04552\left(\frac{E_{d,h}^{RE}}{Cp^{RE}}\right)^{3}-0.03827\left(\frac{E_{d,h}^{RE}}{Cp^{RE}}\right)^{2}+0.6488\left(\frac{E_{d,h}^{RE}}{Cp^{RE}}\right)+0.6881)\eta_{nom}^{RE} \quad (32)$$

3.3.2. Gas turbine prime mover

The parameters for GT are given by (EPA, 2002)

$$\eta_{nom}^{GT}=0.04049\,ln(Cp^{GT})-0.0687 \quad (33)$$

$$CM^{MT}=-0.001386\,ln(Cp^{GT})+0.0185 \quad (34)$$

$$Cc^{GT}=\begin{cases}-108.8\,ln(Cp^{GT})+1953 & Cp^{GT}>1000\\ 1780 & Cp^{GT}=1000\end{cases} \quad (35)$$

$$\eta_{nom,th}^{GT}=\begin{cases}-0.025\,ln(Cp^{GT})+0.64 & Cp^{GT}>1000\\ 0.46 & Cp^{GT}=1000\end{cases} \quad (36)$$

Maximum and minimum capacity for installation of a GT in the industrial dairy unit is assumed as 10,000 and 1000 kW, respectively. GT useful life is 20 years (EPA, 2002). Electrical

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efficiency at different part loads can be approximated by (EPA, 2002)

$$\eta_{d,h}^{GT} = \left(0.8264\left(\frac{E_{d,h}^{GT}}{Cp^{GT}}\right)^3 - 2.334\left(\frac{E_{d,h}^{GT}}{Cp^{GT}}\right)^2 + 2.329\left(\frac{E_{d,h}^{GT}}{Cp^{GT}}\right) + 0.1797\right)\eta_{nom}^{GT} \quad (37)$$

Net recovered TE for GT is given by (EPA, 2002)

$$H_{d,h}^{GT} = \frac{E_{d,h}^{GT}}{\eta_{d,h}^{GT}(E_{d,h}^{GT})}\eta_{nom,th}^{GT} \quad (38)$$

3.3.3. Microturbine prime mover

Because the electrical demand in the industrial dairy unit is higher than available MT maximum capacity, several MTs are needed to operate in parallel. In this study, the maximum capacity of MT is 350 kW and the number of paralleled MT is determined through the optimization procedure. It is assumed that the operational strategies of all MTs are similar.

MT useful life is 10 years and other parameters of 350 kW MTs as given by EPA (2002) are

$$\eta_{nom}^{MT}(350\ kW) = 0.29 \quad (39)$$

$$CM^{MT}(350\ kW) = 0.01(\$/kW\ h) \quad (40)$$

$$Cc^{MT}(350\ kW) = 1339(\$/kW) \quad (41)$$

$$\eta_{nom,th}^{MT}(350\ kW) = 0.48 \quad (42)$$

where $\eta_{nom,th}^{MT}$ is the thermal efficiency of MT. Electrical efficiency at different part loads can be approximated by (EPA, 2002)

$$\eta_{d,h}^{MT} = \left(0.8838\left(\frac{E_{d,h}^{MT}}{numCp^{MT}}\right)^3 - 2.182\left(\frac{E_{d,h}^{MT}}{numCp^{MT}}\right)^2 + 2.0\left(\frac{E_{d,h}^{MT}}{numCp^{MT}}\right) + 0.29\right)\eta_{nom}^{MT} \quad (43)$$

Net recovered TE for the 350 kW MT (EPA, 2002) is

$$H_{d,h}^{MT} = \frac{E_{d,h}^{MT}}{\eta_{d,h}^{MT}(E_{d,h}^{MT})}\eta_{nom,th}^{MT} \quad (44)$$

The general relation for all three prime mover gas consumption and produced power is (Ren et al., 2008)

$$Gas^{PM} = \frac{E_{d,h}^{PM}}{\eta_{d,h}^{PM}HV} \quad (45)$$

3.3.4. Absorption and compression chillers

For CHP system, there is no capital cost for the existing compression chillers in the industrial dairy unit, however, for CCHP system, an absorption chiller must be added and its capital cost is described by (Firestone, 2004)

$$Cc^{abs-chill} = \begin{cases} -81.552\ ln(Cp^{abs-chill}) + 778 & Cp^{abs-chill} > 1000 \\ -35.4\ ln(Cp^{abs-chill}) + 431 & Cp^{abs-chill} < 1000 \end{cases} \quad (46)$$

The absorption chiller capacity is assumed equal to peak cooling demand with negligible maintenance cost (Wang et al., 2009).

It should be noted that utilization of heat energy varies with the type of prime mover used. For GT and MT prime movers, all recoverable heat is in the form of high temperature exhaust. For RE prime move, however, the recoverable heat is utilized from both the high temperature exhaust and lower temperature radiator loop (Firestone, 2004). Because better performance could be achieved by means of double effect absorption chillers for GT and MT and single effect absorption chillers for RE, the coefficient of performance (*COP*) for absorption chiller is assumed 1.2 for GT and MT and 0.7 for RE (Firestone, 2004). In addition, the *COP* of compression chiller is assumed 3.5 (Chen et al, 2009). The amount of cooling produced by each chiller is the product of *COP* and the input energy.

3.3.5. Supplementary boiler

The existing boilers in the industrial dairy unit are in satisfactory conditions and there is no need for additional investment for new boilers. The relation between boiler gas consumption and produced TE is given by (Ren et al., 2008)

$$Gas^{boiler} = \frac{H_{d,h}^{boiler}}{\eta^{boiler}HV} \quad (47)$$

The constant boiler efficiency is assumed 0.8 for all operational conditions.

3.3.6. Heat storage tank

The capital cost of heat storage tank is assumed negligible, as noted earlier.

The relation between entering, leaving, and stored TE in the storage tank is (Ren et al., 2008).

$$E_{d,h}^{tank} = E_{d,h-1}^{tank} + H_{d,h}^{tank} \quad (48)$$

H^{Tank} is positive when TE is stored and negative when TE is retrieved from the storage tank. Minimum and maximum heat storage capacities are assumed zero and 4000 kW h, respectively.

4. Optimization

The PSO algorithm is a population based optimization method inspired by social behavior of flocks of birds and fish looking for food (Kennedy and Eberhart, 1995). Observations show that birds use the information of whole group for finding their direction. Hence, during each flight (iteration), birds as particles update their velocities and positions by the best experience of whole group $p_g(k)$ and their own $p_i(k)$. The number of variables in each problem determines the dimension of particles. At each iteration, velocities and positions of particles are updated according to (Hassan et al., 2005)

$$V_i(k+1) = \omega V_i(k) + c_1 r_1(p_i(k) - X_i(k)) + c_2 r_2(p_g(k) - X_i(k)) \quad (49)$$

$$X_i(k+1) = X_i(k) + V_i(k+1) \quad (50)$$

where ω is the inertia weight and ranges from 0.2 to 1.0. $V_i(k)$ and $X_i(k)$ are current velocity and position of particle *i*, respectively. Learning factors or acceleration coefficients c_1 and c_2 range from 1.5 to 2.0 and, r_1 and r_2 are random numbers between 0 and 1.0.

Both $p_i(k)$ and $p_g(k)$ are updated in each iteration according to

$$if\ f(X_i(k+1)) < f(p_i(k)) \rightarrow p_i(k+1) = X_i(k+1) \quad (51)$$

$$if\ f(X_i(k+1)) < f(p_g(k)) \rightarrow p_g(k+1) = X_i(k+1)$$

where $f(x)$ is the optimization objective function (Hassan et al., 2005).

In this study, the values of c_1, c_2 and ω are assumed to vary during each iteration. Their initial values are 2.5, 1.5, and 1, respectively, and their final values are 1.5, 2.5, and 0.1, respectively. Population size (i) is 500 particles and the number of iterations (k) is 1000. Variables to be optimized include 168 (=7 days/week × 24 h/day) operation variables, capacity of prime mover (1) and capacity of absorption chiller (1). Therefore, the dimension of each particle is 169 for CHP system and 170 for CCHP system. Note that each particle is a potential solution that optimizes the objective function.

The input to the algorithm is electricity, cooling, and heat loads hourly data, gas price, electricity selling and purchasing tariffs,

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variables maximum and minimum values, effective interest rate, project lifetime, and specification of each component (contains capital cost, maintenance cost, efficiency, and useful life).

PSO algorithm is initialized within an allowable range with a random vector X which contains the initial positions of the particles. Dimension of X for CCHP system is 500×170 (500×169 for CHP system). The velocity vector for the next iteration V is also produced randomly. Velocity vector is restricted to be not more than a predetermined value. The objective function introduced in Eq. (1) is calculated for every particle.

The convergence of PSO algorithm for RE-based CCHP system and under the conditions of selling electricity for current energy policy is shown in Fig. 3.

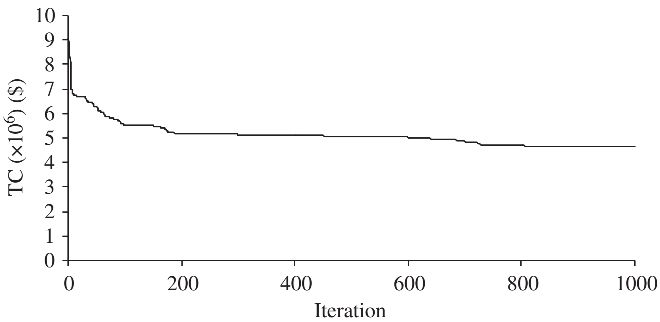

Fig. 3. Convergence of PSO algorithm for optimization of RE CCHP system.

5. Results and discussion

The results for simulation of various prime mover technologies for both CHP and CCHP systems under the conditions of subsidized and unsubsidized energy price policies are given and discussed in this section.

5.1. Current energy policy

Based on the current subsidized prices, optimization results are shown for different capacities of RE, GT, and MT prime movers in Fig. 4 for CHP system and Fig. 5 for CCHP system. The optimal configurations of CHP and CCHP systems for RE, GT, and MT prime movers under conditions of selling and not selling electricity are presented in Table 2. Whenever CCHP system is not economical, absorption chiller capacity selected is zero and system behaves as

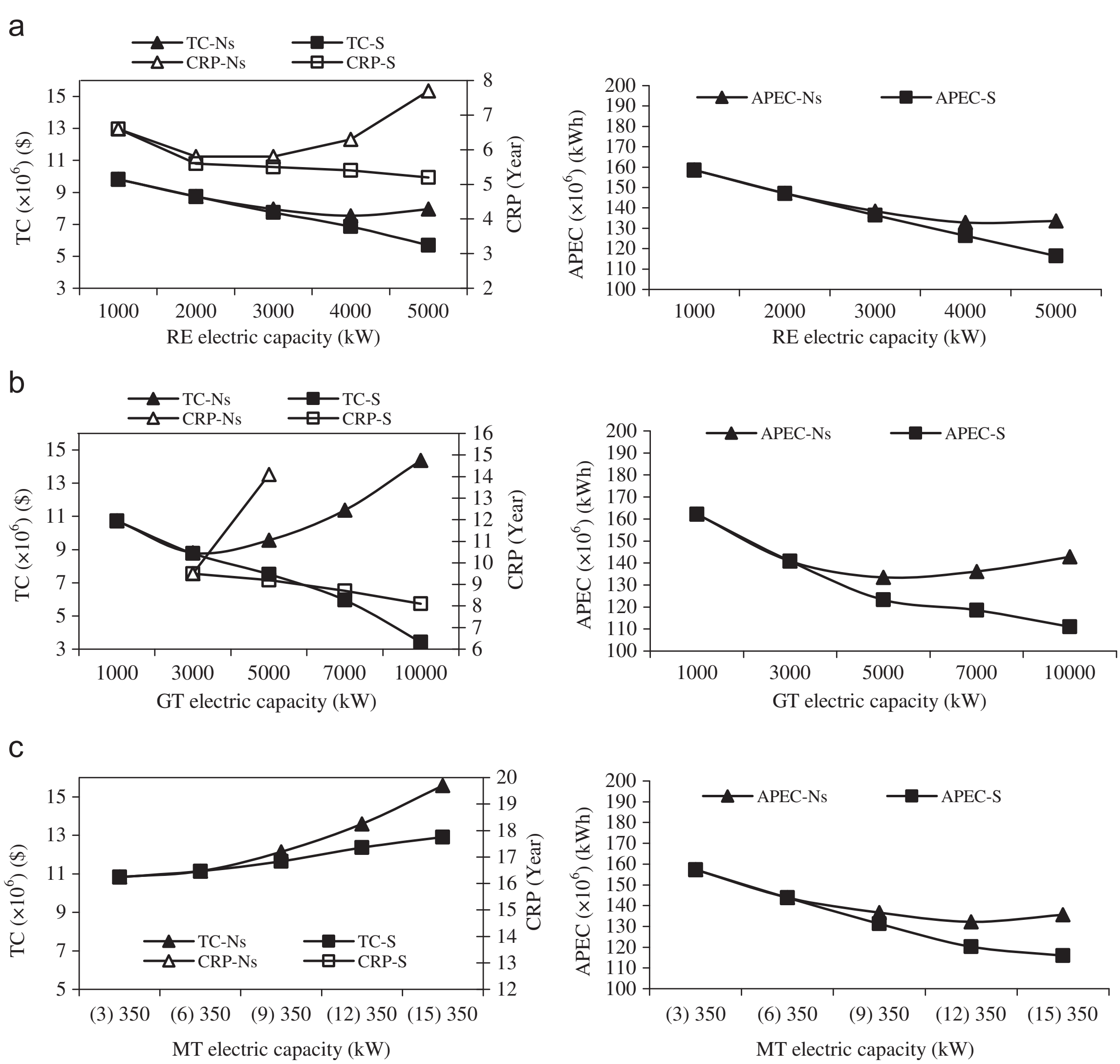

Fig. 4. Total cost (TC), capital recovery period (CRP), and annual primary energy consumption (APEC) of CHP system for various prime mover generation capacities for 20 year system useful life under conditions of selling (S) and not selling (Ns) electricity to the national network. For MT, the number of 350 kW units required is shown in parenthesis on the horizontal axis.

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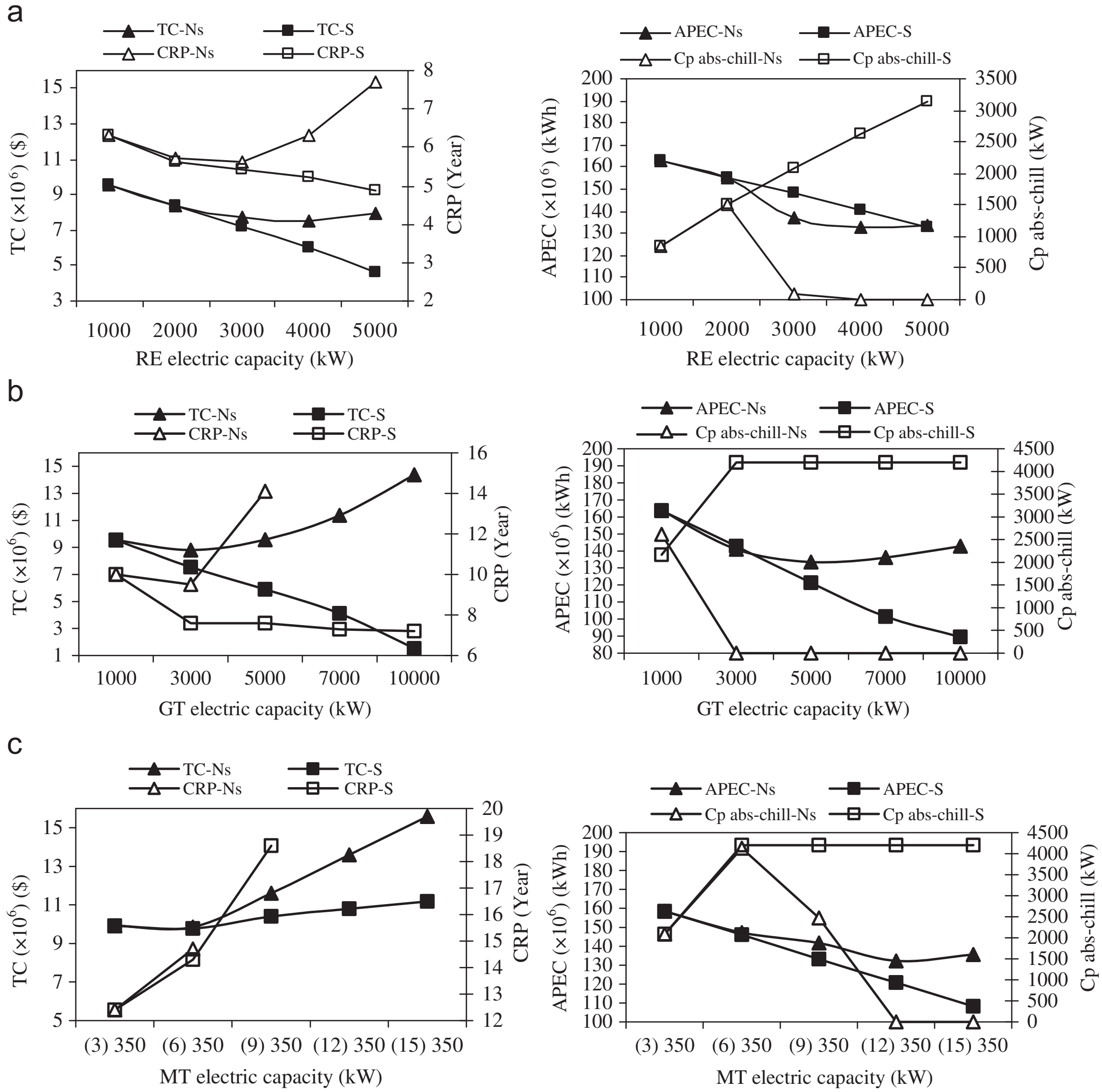

Fig. 5. Total cost (TC), capital recovery period (CPR), annual primary energy consumption (APEC), and absorption chiller optimal capacity of CCHP system for various prime mover generation capacities for 20 year system useful life under conditions of selling (S) and not selling (Ns) electricity to the national network. For MT, the number of 350 kW units required is shown in parenthesis on the horizontal axis.

Table 2
Simulation results for optimal configuration of CHP, CCHP, and SHP systems for current subsidized energy price policy for selling and not selling electricity to national electrical network.

Parameter		Electricity						SHP
		Selling			Not-selling			
		RE	GT	MT	RE	GT	MT	
Prime mover capacity (kW)	CHP	5000	10,000	–	3730	3024	–	0
	CCHP	5000	10,000	(5) 350	3730	2093	(5) 350	
Absorption chiller capacity (kW)	CHP	N/A	N/A	–	N/A	N/A	–	0
	CCHP	4200	4200	3454	0	3999	3454	
Annual primary energy consumption ($\times 10^6$) (kW h)	CHP	116.4	111	–	132.3	140.7	–	170.8
	CCHP	118.7	89.4	150.3	132.3	152.5	150.3	
Total cost present value ($\times 10^6$) ($)	CHP	5.7	3.4	–	7.5	8.8	–	10.6
	CCHP	4.2	1.5	9.7	7.5	8	9.7	
Capital recovery period (years)	CHP	5.2	8.1	–	5.9	9.5	–	N/A
	CCHP	4.6	7.2	13.2	5.9	7.1	13.3	

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a CHP system. For MT-based CHP system, the total cost is higher as compared with SHP system and hence this choice is not economical and the values are not shown (Table 2).

From an economic point of view, when it is allowed to sell electricity to utility, it is better to choose a system with higher capacity and that is true for both CHP and CCHP systems. As shown in Figs. 4 and 5, the total investment and energy costs as well as capital recovery period are lower when the system is allowed to sell electricity to utility. Selling electricity to utility results in decreasing the operational cost and ultimately resulting in shorter capital recovery period. For example, for RE-based CCHP system, the optimal capacities under the conditions of selling and not selling are 5000 and 3730 kW, where the corresponding capital recovery periods are 4.9 and 5.9 years, respectively (Table 2). However, it is not true about MT prime mover because of high capital cost (lower useful life requires replacement after 10 years into 20 years of system operation life). Note that whenever CHP or CCHP system installation is not economical, capital recovery period is not shown in Figs. 4 and 5.

As in Fig. 5, when selling electricity to utility is allowed for the CCHP system, the absorption chiller optimal capacity increases with increase of prime mover capacity to allow the CCHP system to sell and provide more revenue. However, when not selling excess electricity to utility, increasing the prime mover capacity more than a specified value (for instance 2000 kW for RE shown in Fig. 5) causes a decrease in absorption chiller optimal capacity to allow the system to supply cooling load via compression chiller and CCHP system prime mover is operated under higher partial load. Note that in this study, because only TE can be dissipated not electricity, the CCHP system should never produce power more than electricity load and unsatisfied cooling load via absorption chiller. When the absorption chiller optimal capacity becomes zero, CCHP system behaves as CHP system.

The employment of CCHP systems has resulted in lower total annual primary consumption, as compared with SHP system (170.8 GWh) (Table 2). Therefore, CCHP system widespread installation can lead to limited reduction of primary energy resources with current subsidized prices in Iran. The major reason for decrease in annual primary energy consumption is higher efficiency for fuel utilization by CHP and CCHP systems. As shown in Figs. 4 and 5, when selling electricity to utility is allowed, the annual primary energy consumption decreases with an increase in prime mover capacity. When selling electricity is not allowed, increase in capacity more than a specified value (4000 kW for RE-based CCHP system) causes primary energy consumption to increase (primary energy consumption for 4000 and 5000 kW RE-based CCHP system are 132.9 and 133.6 GWh, respectively) due to heat loss (caused by decrease in the capacity of absorption chiller) and lower power production of CCHP system (to avoid producing power more than electricity and unsatisfied cooling loads).

Optimal operation results for RE-based CHP and CCHP systems under the conditions of selling and not-selling electricity to utility are depicted in Figs. 6 and 7. It is observed that during the beginning hours of day, when electricity price is low, RE does not produce power and, as electricity price increases, the power production reaches maximum value. However, for higher electricity price at the beginning of Friday (weekend), RE produces power to meet electricity load only.

When selling electricity is not allowed, optimal capacity for RE-based CHP system (3730 kW) is equal to its CCHP system (3730 kW) counterpart. However, GT-based CHP system optimal capacity (3024 kW) is higher than its CCHP system (2093 kW) counterpart. The difference is due to absorption chiller *COP* of 0.7 for RE-based systems and 1.2 for GT-based system. As CCHP system does not produce power more than load demand and prime mover may never operate below 30% of its rated capacity,

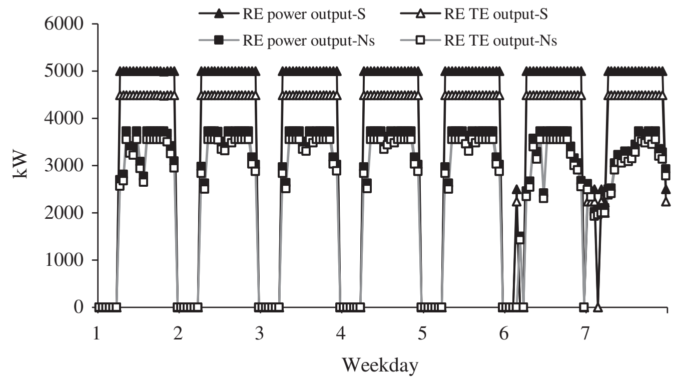

Fig. 6. Optimal operation for optimal RE-based CHP system under conditions of selling (S) (5000 kW) and not selling (Ns) (3730 kW) for one week that is typical for the entire year.

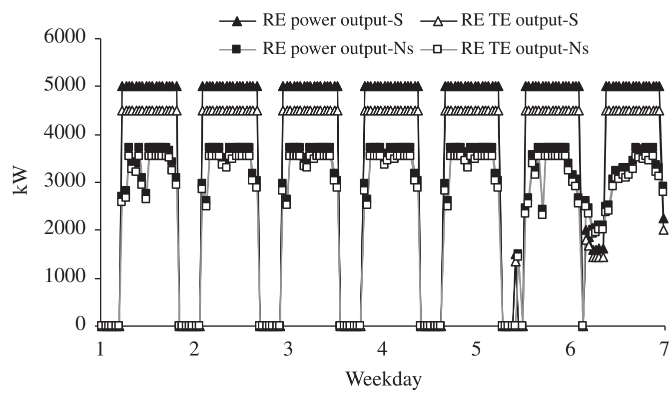

Fig. 7. Optimal operation for optimal RE-based CCHP system under conditions of selling (S) (5000 kW) and not selling (Ns) (3730 kW) for one week that is typical for the entire year.

CCHP system can be operated in two ways, when not selling electricity: (i) using lower prime mover capacity and meeting cooling load by means of heat driven absorption chiller and (ii) using higher prime mover capacity and meeting cooling load by means of electric compression chiller. However, for CHP system, cooling load is fulfilled by compression chiller and prime mover capacity is therefore greater.

Since CCHP system meets whole or part of the cooling load via TE and absorption chiller *COP* is lower than that of electric compression chiller, higher gas consumption by CCHP system, as compared with CHP system, is observed as annual energy consumption of CHP system is lower than CCHP system (for 5000 kW RE and selling electricity, CHP and CCHP system's annual primary energy consumptions are 116.9 and 132.8 GWh, respectively).

When selling electricity is allowed, for optimal configuration of RE, using CCHP system ($ 4.6 $\times 10^6$ and capital recovery period of 4.9 years) under Iran current energy policy is more favorable than CHP system ($ 5.7 $\times 10^6$ and capital recovery period of 5.2 years). Since CCHP system utilizes output TE of prime mover to meet cooling load, the CCHP system is able to sell more electricity to utility as compared to CHP and, because revenue from selling electricity is more than natural gas cost, CCHP can be considered more effective.

Based on the simulation results, it is determined that for Iran, under current subsidized energy price policies, RE-based CCHP system is economically more effective for use in the industrial dairy unit, due to lower total cost and shorter capital recovery period. When selling electricity is possible, 5000 kW RE-based

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CCHP system is the optimal choice. However, when the system sell electricity is not allowed, 3730 kW RE-based CHP system is the best option.

5.2. Future energy policy

Once the RE-based CHP and CCHP systems are determined as optimal, it is of interest to examine the effects of higher gas prices on system parameters against current and future estimated electricity prices. Therefore, in this section, the results of gradual increase in natural gas and electricity prices to international market prices for RE for both CHP and CCHP systems are discussed. As in Tables 3 and 4, for both CHP and CCHP systems, results show that when the electricity price is fixed and gas price is increased, the capital recovery periods become very long and installation of CHP and CCHP systems is not favorable. It is worth noting that when selling electricity is not allowed, for CHP and CCHP systems, doubling and tripling gas prices decrease prime mover optimal capacity (3730 kW to 3182 and 3183 kW, respectively) and this behavior is reasonable.

As is shown in Tables 3 and 4, the benefits realized from electricity unsubsidized price can overcome the negative effects of unsubsidized natural gas price on CHP and CCHP systems operation costs (for example difference between SHP and CCHP system total 20 year present value cost becomes $\$17.3\times10^6$). The capital recovery periods for unsubsidized electricity price are shorter for both subsidized and unsubsidized gas price, (under the conditions of not selling electricity, 1.4 and 1.5 years for CCHP system for subsidized and unsubsidized gas price, respectively) and, adoption of CHP and CCHP systems becomes more attractive. In this case, for current gas price ($\$0.017/m^3$) and under the condition of not selling, comparing the results in Table 2 with those in Tables 3 and 4 confirms that higher electricity prices increase both CHP and CCHP systems prime mover capacities (3730–3999 kW) and CCHP system behave as CHP system.

6. Conclusions and recommendations

In this study, the effects of current and future energy price policies in Iran on optimal configuration of CHP and CCHP systems are investigated. It is determined that the choice of prime mover plays an important role in economic feasibility of CHP and CCHP systems. It is confirmed that the economic benefits of CHP and CCHP systems are highly dependent on optimal sizing and operating conditions. For CCHP systems, utilization of all three prime movers is economically preferred over SHP system. For CHP system, MT installation is uneconomical as compared with SHP system. In this study, RE is determined as the best choice for prime mover and the capital recovery periods for the best case for subsidized and unsubsidized energy prices are 4.9 and 1.3 years, respectively. The utilization of CHP and CCHP system is effective in lowering total energy consumption for both current and future energy policies. Under the current energy price policies, CCHP systems utilization is economically more favorable than their CHP counterparts. For future, it is hypothesized that industrial units with high demand for primary energy resources, similar to the industrial dairy unit, are suitable for utilization of CHP and CCHP systems, when the policy of selling electricity to utility is considered. It is concluded that current energy price policies hinder promotion of installing CHP and CCHP systems and, the policy of selling electricity to utility as well as eliminating subsidies are prerequisites to successful widespread utilization

Table 3
Simulation results for RE-based CHP system operating under current and future estimated electricity price policies and different scenarios for gas prices.

Electricity price ($/kW h)	Gas price ($/m^3)	Selling (S) or not-selling (Ns)	Selling price ($/kW h)	Optimal RE capacity (kW)	CHP total 20 years present cost ($\times10^6$) ($)	SHP total 20 years present cost ($\times10^6$) ($)	Capital recovery period (year)
Current policy (Table 1)	0.073	S	0.035	5000	12.7	14.6	9.2
	0.073	Ns	0	3179	13.4	14.6	9.8
	Double (0.034)	S	0.035	5000	7.8	11.8	6
	Double (0.034)	Ns	0	3182	9.4	11.8	6.4
	Triple (0.051)	S	0.035	5000	9.8	13	7
	Triple (0.051)	Ns	0	3183	11.1	13	7.5
Future policy (Table 1)	0.017	S	0.035	5000	5.7	27.9	1.5
	0.017	Ns	0	3999	8.1	27.9	1.4
	0.073	S	0.081	5000	5.6	31.9	1.3
	0.073	Ns	0	3963	14.6	31.9	1.5

Table 4
Simulation results for RE-based CCHP system operating under current and future estimated electricity price policies and different scenarios for gas prices.

Electricity price ($/kW h)	Gas price ($/m^3)	Selling (S) or not-selling (Ns)	Selling price ($/kW h)	Optimal RE capacity (kW)	Optimal absorption chiller capacity (kW)	CCHP total 20 year present cost ($\times10^6$) ($)	SHP total 20 year present cost ($\times10^6$) ($)	Capital recovery period (year)
Current policy (Table 1)	0.073	S	0.035	5000	0	12.7	14.6	9.2
	0.073	Ns	0	3179	0	13.4	14.6	9.8
	Double (0.034)	S	0.035	5000	3142	7.3	11.8	6
	Double (0.034)	Ns	0	3182	0	9.4	11.8	6.4
	Triple (0.051)	S	0.035	5000	0	9.8	13	7
	Triple (0.051)	Ns	0	3182	0	11.1	13	7.5
Future policy (Table 1)	0.017	S	0.035	5000	3159	4.6	27.9	1.6
	0.017	Ns	0	3999	0	8.1	27.9	1.4
	0.073	S	0.081	5000	3142	2.9	31.9	1.3
	0.073	Ns	0	3963	0	14.6	31.9	1.5

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of such systems. For future works, accounting for electricity network constraints such as nodes voltages, environmental effects, and investigating feasibility of using district heating for optimal configuration and operation of CHP and CCHP systems with consideration for different energy price policies are recommended.

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