International Journal of
Energy & Technology
www.journal-enertech.eu
ISSN 2035-911X
International Journal of Energy & Technology 6 (4) (2014) 1–10

# EVALUATION OF OPTIMUM PERFORMANCE AND ECONOMIC ANALYSIS OF MICRO CHP SYSTEMS IN DIFFERENT SECTORS IN IRAN

Eslam Ezzatneshan[a,*], Mitra Arami[b], Tarannom Parhizkar[b],
Ali Hosseni Kordkheili[a], Sourena Sattari[a]

[a] Sharif Energy Research Institute (SERI), Sharif University of Technology, Azadi Ave., Tehran, Iran
[b] Energy Engineering Faculty, Sharif University of Technology, Azadi Ave., Tehran, Iran
[*] Corresponding Author, Email Address: ezzatneshan@ae.sharif.edu

## ABSTRACT

In this paper, the optimal operation strategy and economic study of Micro Combined Heat and Power (CHP) systems are performed in residential, commercial and health center sectors. The optimization model has been developed by a nonlinear programming (NLP) method. The objective function of this model is to minimize annual energy cost of the buildings. The optimum capacity and operating schedule of the Micro CHP systems are determined from the economic point of view. The annual cost saving and the rate of return of the Micro CHP systems are evaluated in the different buildings and compared with those of existing systems. A sensitivity analysis has been performed to investigate the effects of the key parameters on the adopting the Micro CHP systems to meet the energy demands of the buildings considered. This analysis indicates the profitability of Micro CHP systems is strongly sensitive to energy prices. Results obtained show if the surplus electricity sales is not considered, applying the Micro CHP systems are not economical in the buildings with the low electrical and heating demands. With considering electricity buyback, the profitability index increases for the all buildings. As well as, the annual cost is decreased by increasing the electricity buyback price. Study shows payback periods for the health, commercial and residential buildings studied are 2.5, 4.9 and 5.4 years, respectively.

**Keywords:** Micro CHP system, optimization model, nonlinear programming, economic study, residential and commercial and health buildings.

## 1. INTRODUCTION

In the last decade, applying Micro Combined Heat and Power (Micro CHP) technologies has been increased due to rising energy prices, environmental issues, reliability and power quality enhancement, and reduction of transmission losses [1]. Recently in Iran, using Micro CHP systems in commercial and residential sectors has been considered by legislators and energy customers as well. Moreover, it is crucial to prioritize the installation of Micro CHP systems in the different sectors because of different energy tariffs and different thermal and electrical loads demands in each sector.

Micro CHP systems have to fulfill the thermal demands and part of the electrical demands, or gratify the electrical demands and part of the thermal demand, or fulfill both in buildings. Therefore, the CHP system ought to be run at part-load conditions according to the magnitude of the electrical and thermal loads. On the other hand, deficiency of the electrical or thermal demand have to be made up by purchasing electricity or heat from other sources such as the electrical grid or a boiler plant. The surplus electricity or heat ought to be stored or sold. Thermal storage device such as a water tank is used to store the extra heat produced by the CHP system. In addition, surplus electricity can be stored in batteries or capacitors or sold to the grid. The performance of the Micro CHP systems is subjected not only to the variation of load demands, but also it can be dependent on other parameters such as electricity and natural gas price and other energy policies [2]. As a result of hourly and seasonal fluctuation in buildings demands, developing an efficient economic model to determine the optimal operational strategies and sizing system throughout the year is necessary. Several researches have been investigated mathematical models and great deal of studies has been reported on this significant topic.

Dorer and Weber [3] assessed performance of Micro CHP systems with dynamic building simulation. They considered fluctuation of the building loads by using the TRNSYS software. Also, the different Micro CHP technology, namely fuel cell, stirling and internal combustion engine (ICE) for single and multi-family houses compared and results showed ICE system in the single-family house can achieved maximum reduction in primary energy demand. Wang et al. [4] investigated the technical, economical and environmental performance of the combined cooling and heating power (CCHP) system base on the operation strategy and they develop an optimization model by genetic algorithm. The objective function of Wang et al.'s study consists of primary energy consumption, carbon dioxide emission, and annual energy cost. Tveit et al. [5] worked on multiperiod mixed integer nonlinear programming (MINLP) model to analysis the effect of long term thermal storage at long term operation of the CHP system in a district heating network. Ren and Gao [6] presented a multi-objective optimization model to minimize energy cost with respect to the environmental impact. In that study, the distributed technologies include photovoltaic (PV), fuel cell and gas engine are considered. The results revealed that the operation of the distributed energy resource system was highly sensitive to environmental objective. Tichi et al. [7] examined energy price policies before and after subsidizing for the optimal configuration of the CHP and CCHP systems based on particle swarm optimization algorithm in Iran. Fumo et al. [8] worked on economic evaluation of the CHP system base on primary energy. They believe that economic evaluation of the CHP systems based on site energy usage can lead to misleading conclusions about energy savings. In addition, this study evaluates the effect of the power generation unit efficiency over the primary energy reduction when a CHP system is utilized. Mago et al. [9] presented a comparison of CCHP and CHP systems based on primary energy consumption (PEC), operation cost, and carbon dioxide reduction (CDE) for different climate conditions. Results show that more PEC reduction is achieved for cities that required more heating during the year. They concluded both the CCHP and CHP systems operated based on thermal load reduce the PEC for all the evaluated cities. On the other hand, CHP systems operated based on electrical load always increases the PEC.

Ren and Gao [10] worked on different operating modes of Micro CHP systems in residential sectors in Japan. In that study, gas engine and fuel cell are utilized for residential buildings. From economic and environmental points of view, the results revealed that fuel cell system is better option for the residential building. Feasibility study of installation Micro CHP systems in different sectors are performed by Mago and Smith [11]. They evaluated the primary energy consumption (PEC) reductions from the use of CHP systems in Full Service Restaurant, Large Hotel, Primary School, Outpatient, Supermarket, Small Hotel Hospital, Small Office buildings. They conclude that using of a CHP system reduces the PEC for all the buildings except for the primary school and the small office buildings and the maximum PEC reduction was obtained for the outpatient building. Climate impacts on Micro CHP systems usage are investigated by Teymouri Hamzehkolaei and Sattari [11]. They discussed the technical and economic study of using Micro CHP in the different climate zones of Iran for the residential buildings. In their work, the building energy demand is calculated using a degree-day method to estimate annual heating and cooling loads in residential buildings. The results revealed that two climate zone of Iran namely Ardebil and Tehran with the highest annual energy saving respectively are the best locations to install the Micro CHP systems.

In this study, economic analysis of using the Micro CHP system is executed in the different building users (sectors) in Iran. The present study focuses on Tehran climate zone, because of some market penetration reasons and the financing potential of this metropolis for the adaption of the Micro CHP systems in Iran. The sectors studied are categorized in residential, commercial and health centers. Evidently, the performance and economic feasibility of the Micro CHP systems extremity depended on hourly and seasonally fluctuation of the buildings demand loads. Hence in this study, the hourly cooling, heating and electricity end-use demand have been calculated for all the buildings. Sensitivity analysis on the natural gas and electricity prices is investigated; furthermore, the study of cost optimization is performed with two scenarios involve the possibility of electricity sales to the grid and without that. The optimization model has been developed by nonlinear programming (NLP) method and it is applied to the real data from Iran. The objective is to minimize annual cost of buildings which are equipped with the Micro CHP plant and the optimal capacity and operating schedule of the system is investigated as well.

The paper is organized as follows: at the first, system components are described. In the second section, the nonlinear mathematical model, including objective function and constraints of the model is explained in detail. Next, the problem description is expressed. Economic analysis for installation of Micro CHP systems in the three different sectors is performed and the results are discussed at the final section.

## 2. DESCRIPTION OF SYSTEM

The Micro CHP system under investigation in all the buildings surveyed consists of an internal combustion engine, a supplementary boiler and an air conditioner. The internal combustion engine is driven by natural gas and produces electricity and hot exhaust gas to accommodate building electrical and thermal demand. If electricity produced by prime mover cannot cover the electrical demand, the remaining electrical demand is supported by purchasing from the grid. Otherwise, surplus electricity is returned to the grid to be sold. In similar manner, if heat that produced by prime mover cannot cover building thermal demand, supplementary boiler is used to meet the remaining thermal demand; otherwise, the excess heat is dissipated to outdoor air.

## 3. DESCRIPTION OF THE MODEL

In order to maximize profitability and minimize payback period of a Micro CHP system, it is essential to determine the optimal capacity. To achieve this goal, it is necessary to take local conditions, energy requirements, as well as technical and economic information into full consideration. In this study, the Micro CHP optimization is formulated based on hourly electricity and thermal loads; electricity and natural gas prices; as well as Micro CHP performance characteristics; and further constraints to minimize the annual cost as the objective function. The economic analysis model is developed in general parameters and can be adapted to various systems with different technology and performance.

### 3.1. OBJECTIVE FUNCTION

The objective of this model is to minimize buildings annual cost of energy. The objective function consists of running and investment cost of the Micro CHP and supplementary boiler, cost of purchasing electricity from grid and income from surplus electricity sales to the grid [13].

$$\begin{aligned} C_{total} = {} & C_{Purch}^{Utility} + C_{run}^{IC} + C_{run}^{Boiler} \\ & + C_{invest}^{IC} + C_{invest}^{Boiler} - I_{Sale}^{Utility} \end{aligned} \tag{1}$$

In order to annualize investment costs of the system components, a capital recovery factor (CRF) used to convert a present value into a stream of equal annual payments over a specified time, at a specified interest rate. The CRF is defined as follow:

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{2}$$

In Eqs. (3) and (4), the annual capital costs of back-up boiler and the Micro CHP system are described. This is the process of spreading the initial cost (based on accounting the time value of money) across the lifetime of the system.

$$C^{IC}_{invest} = Cc^{IC} \times Cp^{IC} \times CRF \tag{3}$$

$$C^{Boiler}_{invest} = Cc^{Boiler} \times Cp^{Boiler} \times CRF \tag{4}$$

In Eqs. (5) the running costs of the Micro CHP system are presented. As presented below, running costs consist of operation and maintenance costs. The operating cost is calculated by multiplying the fuel price with fuel consumption by Micro CHP system. In a similar approach, the maintenance cost is calculated by multiplying a constant maintenance cost coefficient with the generated electricity.

In Eqs. (6) the running costs of boiler are presented. As discussed before, running costs consist of operation and maintenance costs. The operating cost is calculated by multiplying the fuel price with fuel consumption by back-up boiler. Also, the maintenance cost is calculated by multiplying a constant maintenance cost coefficient with heat energy. Furthermore, the boiler efficiency (η) is constant for different part loads.

$$\begin{aligned} C^{IC}_{run} = 30 \times (&\sum_{d=1}^{12}\sum_{h=0}^{24} \frac{E^{IC}_{self}(d,h) + E^{IC}_{sale}(d,h)}{\alpha(d,h) \times HeatRate} \times P_{gas} \\ &+ \sum_{M=1}^{12}\sum_{h=0}^{24} ((E^{IC}_{self}(d,h) + E^{IC}_{sale}(d,h)) \times c^{IC}_{m}) \end{aligned} \tag{5}$$

$$\begin{aligned} C^{Boiler}_{run} = 30 \times (&\sum_{d=1}^{12}\sum_{h=0}^{24} \frac{H^{Boiler}(d,h)}{\eta_{Boiler} \times HeatRate} \times P_{gas} \\ &+ \sum_{d=1}^{12}\sum_{h=0}^{24} H^{Boiler}(d,h) \times c^{Boiler}_{m}) \end{aligned} \tag{6}$$

Unlike the boiler efficiency, it is assumed that the electricity efficiency (α) of the Micro CHP plant varies in different part loads. As displayed in table 1, electrical efficiency is calculated by linear interpolated method based on the efficiencies for the load factors of 25%, 50%, 75% and 100%, respectively.

**Table 1:** Efficiency of prime mover of the Micro CHP at different load factor [13]

| Load factor (%) | 25 | 50 | 75 | 100 |
|---|---|---|---|---|
| Electricity efficiency (%) | 30.5 | 33.8 | 34.8 | 35.4 |

In Eq. (7), cost of purchased electricity is calculated by multiplying the utility electricity rate with the amount of electricity purchase as:

$$C^{Utility}_{purch} = 30 \times (\sum_{d=1}^{12}\sum_{h=1}^{24} E^{Utility}(d,h) \times P(d,h)) \tag{7}$$

Eq. (8) describes the income by surplus electricity sales to utility. It is calculated by multiplying the electricity buyback price with the amount of electricity delivered to the grid.

$$I^{Utility}_{sale} = 30 \times (\sum_{d=1}^{12}\sum_{h=0}^{24} E^{IC}_{sale}(d,h) \times P^{Sale}) \tag{8}$$

### 3.2. CONSTRAINTS

Heat and electricity supply ought to be balanced with buildings heat and electricity demands at each time. As shown in Eqs. (9) and (10), at each point in time, buildings electrical demands should be covered by the produced electricity in site and electricity purchased from utility. In the same manner, produced heat by prime mover and boiler should fulfill space heating and hot water demands at all times.

$$E^{Utility}(d,h) + E^{IC}_{self}(d,h) \geq D_{elec}(d,h) + \frac{D_{cooling}(d,h)}{\eta_{cooling}} \tag{9}$$

$$H^{IC}(d,h) + H^{Boiler}(d,h) \geq D_{heating}(d,h) + D_{hotwater}(d,h) \tag{10}$$

The Micro CHP system cannot generates more power than its installed capacity:

$$E^{IC}_{self}(d,h) + E^{IC}_{sale}(d,h) \leq Cp^{IC}_{rat} \tag{11}$$

The constraint of the recovered heat from internal combustion engine in each time is expressed in Eq. (12).

$$H^{IC}(d,h) \leq \frac{E^{IC}_{self}(d,h) + E^{IC}_{sale}(d,h)}{\gamma(d,h)} \tag{12}$$

Similar to supplementary boiler, heat is constrained by Eq. (13) to prevent heat supply more than its installed capacity.

$$H^{Boiler}(d,h) \leq Cp^{Boiler}_{rat} \tag{13}$$

### 3.3. ECONOMIC ASSESMENT

The Micro CHP system has usually higher capital cost and lower running cost compared with the conventional energy systems include utility electricity and gas boilers. Therefore, in the economic evaluation, the cost saving ratio (profitability index) and the payback period has been employed. The cost saving ratio expresses the profitability of the Micro CHP system and is defined as the ratio of total energy cost difference between the Micro CHP system and the conventional system to the annual energy cost of the existing system [10]:

$$CSR(\%) = (\frac{C_{CON} - C_{CHP}}{C_{CON}}) \times 100 \tag{14}$$

where, *CSR* indicates the cost saving ratio. $C_{CON}$ and $C_{CHP}$ are the annual energy cost of the conventional system and Micro CHP system, which are illustrated in Eqs. (15) and (16), respectively.

$$C_{CON} = C^{Utility}_{Purch} + C^{Boiler}_{run} + C^{Boiler}_{invest} \tag{15}$$

$$C_{CHP} = C^{Utility}_{Purch} + C^{IC}_{run} + C^{IC}_{invest} + I^{Utility}_{Sale} \tag{16}$$

The amount of cost saving is equal to the difference between annual energy costs of conventional systems and energy costs of Micro CHP system as shown in Eq. (17).

$$C_{save} = C_{CON} - C_{CHP} \tag{17}$$

Finally, the payback is the ratio of the Micro CHP installation cost to the cost saving. As illustrated in Eq. (18).

$$Payback = \frac{Cc^{IC} \times Cp^{IC}}{C_{save}} \tag{18}$$

## 4. PROBLEM DESCRIPTION

The economic studies have been conducted in three sectors of health, residential and commercial buildings with 259.9 $m^2$, 105.6 $m^2$ and 148.85 $m^2$ areas, respectively.

First of all, hourly space cooling and heating consumption, electricity loads and hot water supply of the buildings are calculated. Figures 1, 2 indicate hourly thermal (space heating + hot water) and electrical demands (space cooling + electricity load) for the three health (No. 1), residential (No. 2) and commercial (No. 3) buildings at a sample summer day. As shown in figure 2, the hourly heating load per unit area for the residential building is more than the other ones but the trend for the cooling load is vice versa. During noontime, the electrical load is relatively high for the both health and commercial buildings compared to the residential buildings. Due to the hot climate in the summer season, electrical load in that season has a huge share of total building electrical loads. The other load characteristic is the heating and cooling peak loads which do not occur at the same time.

The investment and maintenance costs of the Micro CHP are based on the available commercial technologies by internal combustion engines. The gas and electricity tariffs are the key factors in the economic study for the Micro CHP systems. The electricity tariff varies hourly for the health building (Table 2) during a day. The electricity tariff for the residential and commercial buildings is also presented in table 3. Electricity prices increase based on monthly electricity consumption for these two buildings [15].

Detailed technical and cost information as well as some other main assumptions for this analysis are summarized in Table 4.

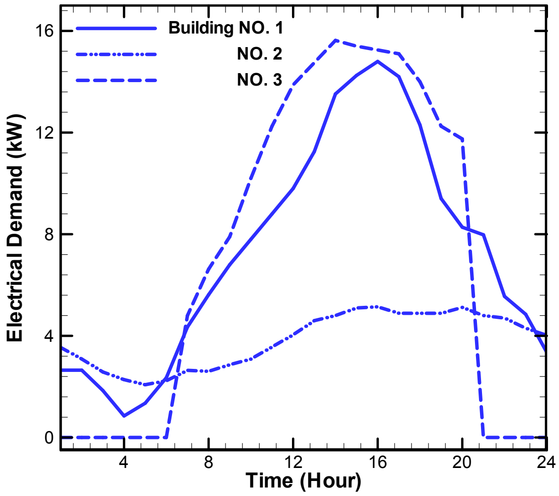

Fig. 1. Hourly electrical loads for a sample summer day in the health building (No. 1), residential building (No. 2) and commercial Building (No. 3).

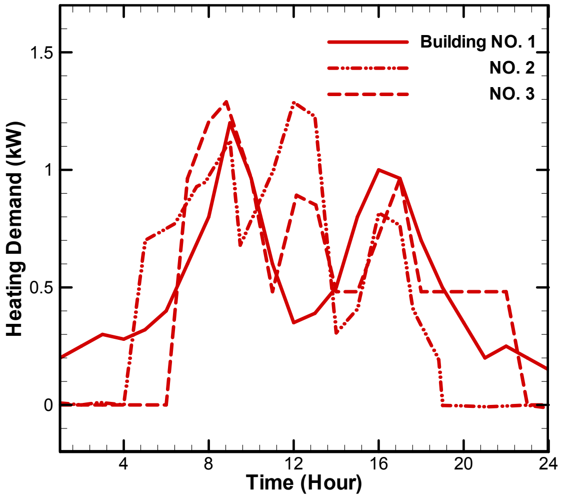

Fig. 2. Hourly heating loads for a sample summer day in the health building (No. 1), residential building (No. 2) and commercial Building (No. 3).

**Table 2:** Electricity tariff for health building [15]

| Health building | Off-peak ($/kWh) | Peak ($/kWh) | Mid-peak ($/kWh) |
|---|---|---|---|
| Electricity tariff | 0.17 | 0.680 | 0.34 |

**Table 3:** Electricity tariff for the residential and commercial buildings [15]

| Monthly electricity consumption (kW) | Residential building ($/kW) | Commercial building ($/kW) |
|---|---|---|
| 0-100 | 0.03 | 0.11 |
| 101-200 | 0.035 | 0.115 |
| 201-300 | 0.075 | 0.120 |
| 301-400 | 0.135 | 0.125 |
| 401-500 | 0.155 | 0.14 |
| 501-600 | 0.195 | 0.16 |
| Up 600 | 0.215 | 0.18 |

**Table 4:** Data assumption for the analysis

| | | |
|---|---|---|
| Micro CHP | Annual maintenance cost ($) | 1% of the investment cost |
| | Life time (year) | 15 |
| | Heat/electricity ratio | 2 |
| | carbon intensity (kg/kWh) | 0.18 |
| | Electricity efficiency | [14] |
| Boiler | Annual maintenance cost ($/kWh) | 0.001 |
| | Life time (year) | 20 |
| | carbon intensity (kg/kWh) | 0.18 |
| | Efficiency (%) | 85 |
| | carbon intensity of powerhouse (kg/kWh) | 0.66 |
| | Air conditioner COP | 4 |
| | Interest rate (%) | 10 |

## 5. RESULTS AND DISCUSSIONS

The nonlinear mathematical programming model described in the present paper is applied to study the optimal capacity and operating schedule of Micro CHP systems in the residential, commercial and health center buildings from the economic point of view. The results are organized in two parts: The first study presented is the sensitivity analysis to examine the effects of the energy tariffs on adopting the Micro CHP systems in the three buildings considered. Next, the analysis is performed to study the annual cost and profitability percent of the Micro CHP systems in each sector. These analyses are made for two cases; with electricity buyback and without electricity buyback. A comparison of the payback period and annual saving cost for the buildings studied are also carried out.

## 5.1. SENSITIVITY ANALYSIS

A sensitivity analysis has been performed to evaluate the effects of the key parameters on adopting the Micro CHP systems in the three buildings studied. The present study shows that the economic parameters are more sensitive to energy tariffs. The optimal capacity of the Micro CHP systems are computed by using sensitivity analysis on natural gas and electricity prices and the annual cost per unit area is evaluated for all the sectors considered. The profitability of Micro CHP system and the rate of return on investment are computed for each building compared to the conventional system (boiler and utility electricity). Two scenarios involve with- and without possibility of electricity sales to utility have been studied. In Iran, the electricity buyback price has not been announced for surplus electricity of the Micro cogeneration systems. In the present study, reasonable electricity buyback prices are assumed to perform sensitivity analysis. The base price for electricity buyback is considered 0.15 $/kWh and the sensitivity analysis of this parameter is performed with two different prices, 0.2 and 0.3$/kWh.

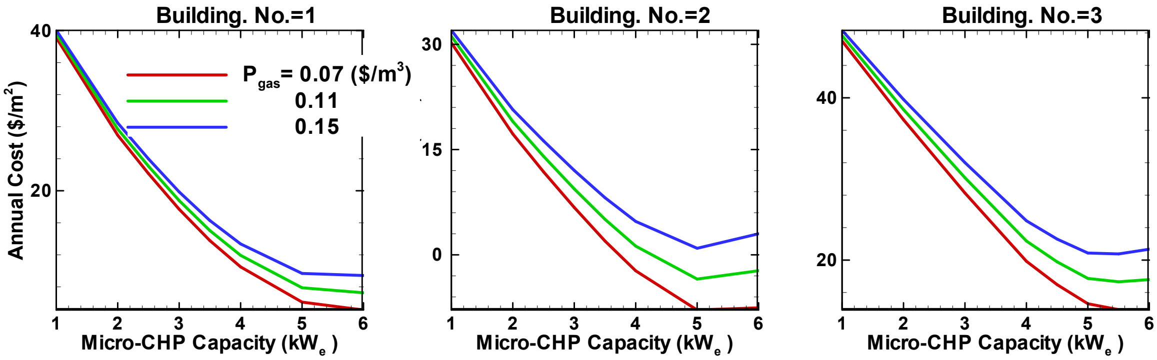

Fig. 3. Annual cost sensitivity analysis with respect to the gas price

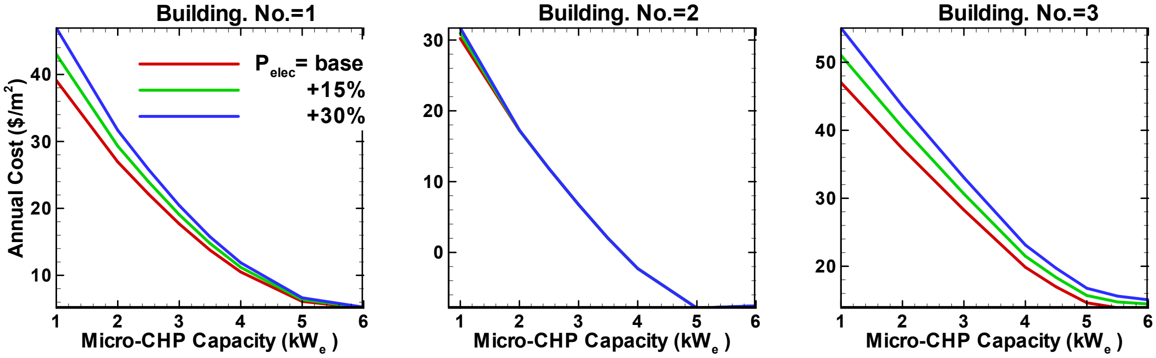

Fig. 4. Annual cost sensitivity analysis with respect to the electricity price

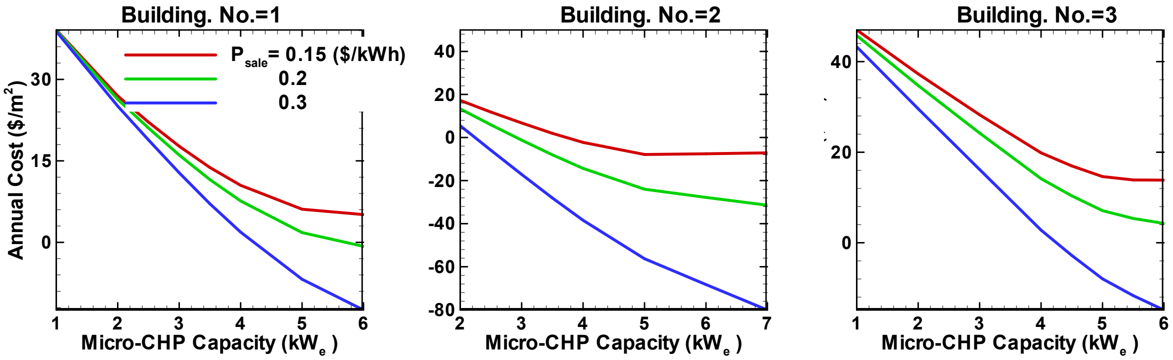

Fig. 5. Annual cost sensitivity analysis with respect to the electricity buyback

Natural gas price greatly affects the cost of supply cooling and heating loads of the buildings. For the gas price sensitivity study, electricity price is calculated from the table 2 and 3. Electricity buyback price is set to be 0.15 \$/kWh and three different prices 0.07, 0.11 and 0.15 \$/m$^3$ are considered for natural gas to perform a sensitivity analysis. Figure 3 shows the sensitivity of the annual cost per unit area of the health, residential and commercial buildings with respect to the capacities of Micro CHP systems and different prices for the natural gas. As shown in this figure, by increasing the Micro CHP capacities the annual cost per unit area of the buildings are reduced because of the amount of surplus electricity increased to sell to the utility. Although, the reduced annual cost for the higher Micro CHP system capacities is not always justified economically. Because the higher system capacities need higher capital costs and can further decrease the rate of return of investment.

From Fig. 3 it can be observed that the annual costs per unit area of all three buildings are reduced by increasing the gas price. The reason can be explained by high efficiency of the Micro CHP systems compared to the conventional system (boiler and utility electricity). The annual cost study indicates the Micro CHP systems are not cost effective with low gas prices; because the capital cost of the Micro CHP systems are higher than the exciting systems. The average heating load of the residential building is more than the health and the commercial buildings. Therefore, the economic analysis in this building is more sensitive to the gas price changes. So that the annual cost reduction of the residential building is more with increasing the gas price.

Electricity purchase price is another significant factor that affects the total cost of the energy systems and shows economic benefits of installing Micro CHP systems in buildings. Figure 4 illustrates the sensitivity analysis on the electricity purchase price for the three buildings studied. In this study, the natural gas price and the electricity buyback price are set to be 0.07 \$/m$^3$ and 0.15 \$/kWh, respectively. Electricity base price (table 1 and 2) is increased 15% and 30% for this sensitivity analysis. As shown in Fig. 4, it can be found that a considerable amount of the required electricity is purchased from the grid for lower capacities of the Micro CHP system. Consequently, the annual cost per unit area of the buildings increases by increasing the electricity price. On the other hand, the annual costs per unit area are reduced by increasing the capacity of the Micro CHP system because of the surplus electricity sales to the utility increased. The electricity price has less effect on the annual costs when the purchased electricity from the grid decreases. As shown in Fig. 4, in the residential building, due to the low electricity consumption compared to the health and commercial buildings, changes in the electricity price has less effect on the annual cost.

The annual cost of the sensitivity analysis on the electricity buyback price is shown in Fig. 5. The natural gas and electricity tariffs are 0.07 \$/m$^3$ and 0.15 \$/kWh, respectively. The results show that the health and commercial buildings have higher electricity consumptions compared to the residential building. Thus, surplus electricity sold to the grid in these two buildings is less than the residential building. Consequently, the annual cost per unit area of the health and commercial buildings are more than the residential one. As well as, by increasing the buyback price from 0.15 \$/kWh to 0.3 \$/kWh, the annual cost is reduced by increasing the Micro CHP capacities.

## 5.2. ECONOMIC ANALYSIS WITH/WITHOUT ELECTRICITY BUYBACK

The present investigation shows that the economic justification of Micro CHP systems is extremely dependent on electricity sales to the grid, particularly in the residential buildings which have lower electrical loads compared to the other sectors. The electricity buyback for Micro cogeneration systems is still under consideration in Iran.

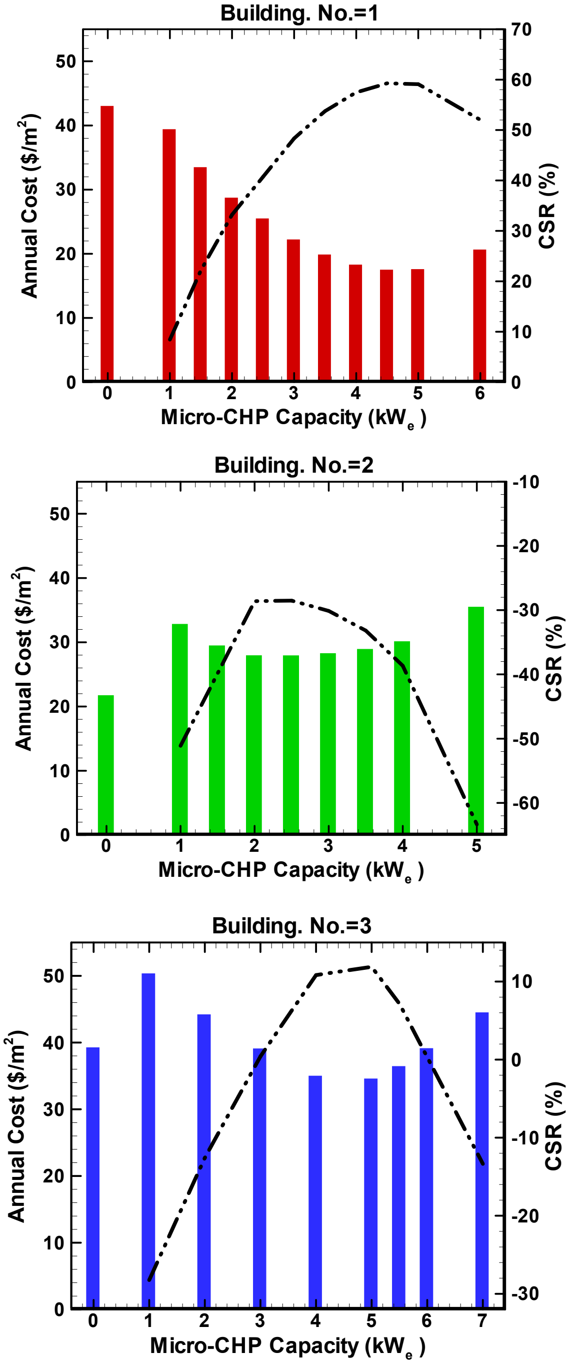

Fig. 6. Annual cost (bar) and profitability index (dash-dot line) for different Micro CHP capacities without electricity buyback for buildings No.=1, No.=2, No.=3.

Figure 6 indicates the annual cost per unit area and the profitability index changes for different Micro CHP capacities without electricity buyback compared to the existing system in the health, residential and commercial buildings. The existing system includes boiler and utility electricity determined by zero capacity for the Micro CHP.

In this study, the natural gas and electricity prices are set to be 0.07 $\$/m^3$ and the base prices, respectively. Since the health building has high electricity demand, the annual cost per unit area are lower than the cost of existing system for all the Micro CHP capacities in this sector. Without electricity buyback, a Micro CHP system with 4.5 $kW_e$ has the maximum profitability index which is close to 60% for this building. A similar assessment is performed to study of the annual cost and profitability index for the commercial building. Figure 6 illustrates the annual cost per unit area of the commercial building with the using of the low Micro CHP capacity is more than the existing systems. Hence, the profitability index for the low capacity Micro CHP systems is negative. This can be explained by the substantial share of purchased electricity from the utility and the capital cost of the installed system. Because of high electricity demand in the commercial building similar to the health building, the annual cost per unit area is reduced by increasing the Micro CHP capacity from 1 to 5 $kW_e$ which makes the electricity purchase from the utility decreased. Further increase in the Micro CHP capacity with the high capital cost and by an increase in surplus electricity without electricity buyback causes the annual cost to be increased again. Therefore, a system with 4.5-5 $kW_e$ has the maximum profitability index close to 11% for this building. The low profitability index in commercial building compared to the health building shows that the existing systems have low costs for the commercial buildings. This decline in costs by using existing systems is expected because of the higher heating loads in the commercial buildings compared to the health buildings.

The residential building has lowest electrical demand compared to the other ones. In this sector, the profitability index is negative for all the Micro CHP capacities and their annual costs are more than the existing systems. This result illustrates using the Micro CHP systems are not economical in the buildings with the low electrical and heating demands when the surplus electricity buyback is not considered.

Figure 7 shows the hourly operation trend for a Micro CHP system in the health building in situation where there is no electricity buyback. The electricity efficiency and output electrical power is indicated within 24 hours for a summer day. In the peak load hours, the Micro CHP system operates in the maximum power and efficiency. In off-peak load times, the output power and efficiency of the system are reduced. Although, the system efficiency decreases during the off-peak hours, but the developed economic analysis model keeps the system operation at optimum condition to minimize the annual cost. An economic analysis is also performed to study using the Micro CHP systems in different sectors with considering the electricity buyback. The electricity price of the buildings studied are given from the table 1 and 2 and the natural gas and electricity buyback prices are set to be 0.07 $\$/m^3$and 0.15 \$/kWh, respectively.

Figure 8 illustrates the annual cost per unit area and the profitability index for the three health, residential and commercial buildings. This study shows the profitability index increases for the all buildings with considering electricity buyback. This is because the electricity buyback allows more on-site generation, and then the Micro CHP systems with high efficiency can make more surplus electricity to sell to the utility grid. In the lower Micro CHP capacities, the electricity buyback has not significant value; on the other hand, the high capital cost of the system causes negative profitability index. Accordingly, the profitability index goes to decrease when the Micro CHP capacity is more increased. The maximum value of profitability index occurs for the residential buildings which have the lowest electrical consumption.

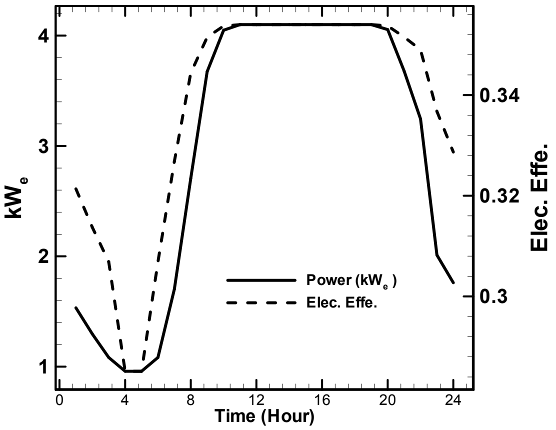

Fig. 7. Hourly efficiency and performance of Micro CHP system in a sample summer day for the health building without electricity buyback.

As shown in Fig. 8, with considering the electricity buyback, the annual cost is reduced when the capacity of the Micro CHP systems is increased. It is important to note that the higher system capacities need higher capital costs and can further increase the payback period time as well. Figure 9 shows comparison of the payback period of the Micro CHP systems with the existing systems in the three buildings studied. It can be observed that at low or high capacity of the systems adopted, the capital cost increases the payback period time. This study shows the systems with high capacities although reduce the annual costs with considering the electricity buyback but they are not cost effective. As shown in Fig. 9, the optimum capacity range of the Micro CHP systems are 4.5-5 $kW_e$ and the optimum payback period times for the health, residential and commercial buildings studied are 2.5, 5.4 and 4.9 years, respectively. At the optimum payback point, the Micro CHP system operates with high efficiency which it causes lower electricity purchase from grid and reduces the annual energy costs.

Using the economic analysis model developed and the optimum point of Micro CHP capacity in each building which has been estimated previously, the average amounts of annual saving costs per unit area are calculated with- and without electricity buyback situations. The electricity buyback and natural gas prices are set to be 0.07 $\$/m^3$ and 0.15 \$/kWh, respectively. The electricity prices are also given in table 1 and 2. In Fig. 10, annual saving costs obtained with using the Micro CHP system with electricity buyback and without that are compared in all buildings considered. This comparison shows that using the Micro CHP systems with considering electricity buyback in all sectors studied make a significant change in annual savings. Much surplus electricity sales to grid in the residential building compared with the two other sectors causes high cost saving in this building. Although, the annual costs increase if electricity sales to the grid is not possible. In this condition, the health and commercial buildings have nearly reasonable annual saving but using of the Micro CHP systems are not recommended for the residential buildings.

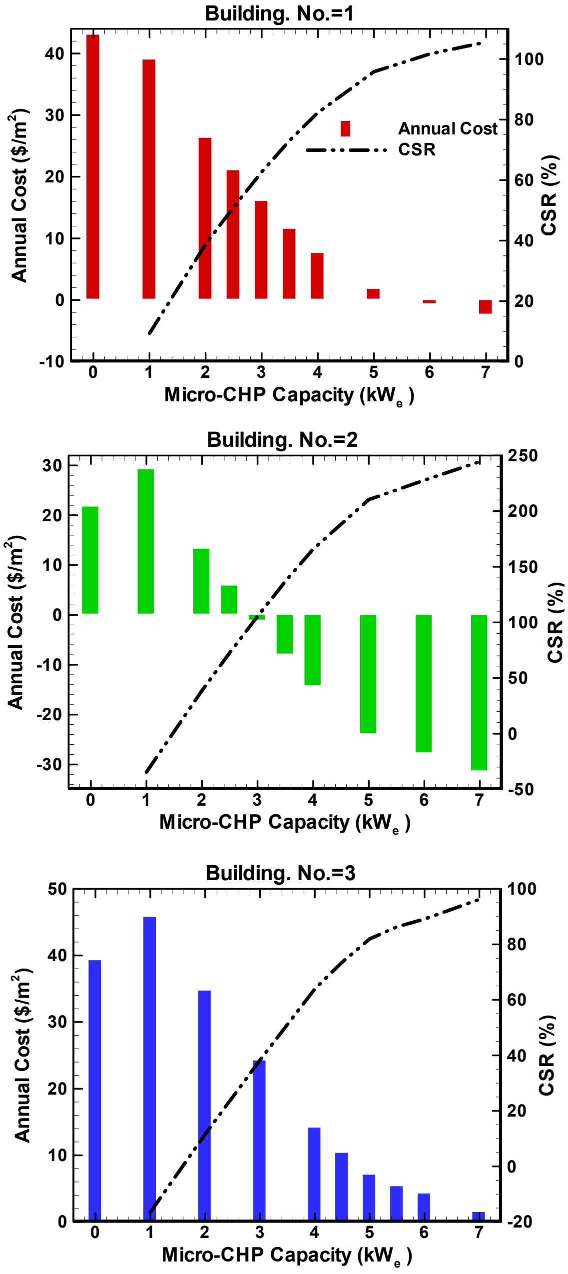

Fig. 8. Annual cost (bar) and profitability index (dash-dot line) for different Micro CHP capacities with electricity buyback for buildings No.=1, No.=2, No.=3.

A carbon tax is such a disincentive policy has been adopted in many countries to prevent consumption of energy forms with undesirable traits. In Iran, tax on carbon emissions is not legally arranged and still under consideration. In this paper, carbon intensity is considered in the model of economic analysis and the emission reduction is studied by using the Micro CHP units instead of the traditional systems. Figure 11 indicates the percent reduction of annual carbon emissions of the different sectors considered by using the Micro CHP system. The optimum capacity values calculated in situation without electricity buyback are used for each sector to study the emission reduction. As shown in this figure, emission is significantly reduced for all sectors studied with considering electricity buyback.

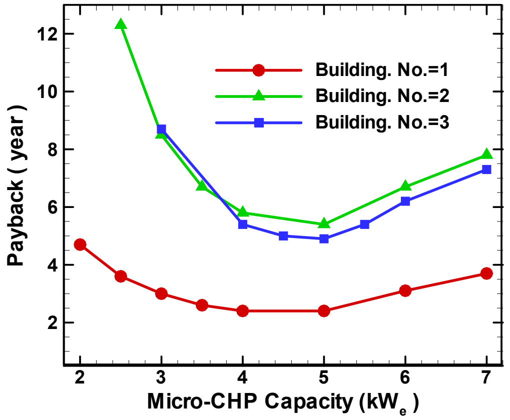

Fig. 9. Comparison of the payback period at electricity buyback situation for the buildings No.=1, No.=2, No.=3.

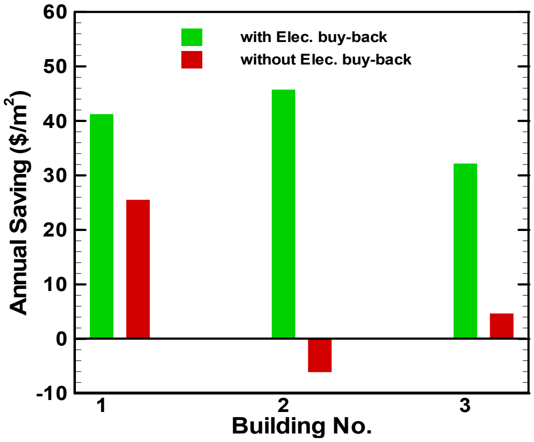

Fig. 10. Comparison of the annual saving cost for the optimum Micro CHP capacities of the buildings No.=1, No.=2, No.=3 with/without electricity buyback.

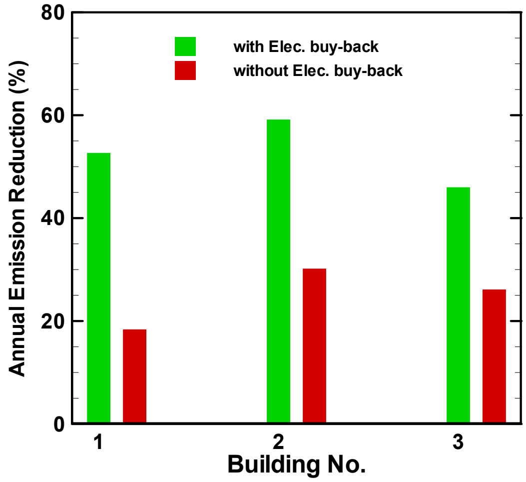

Fig. 11. Comparison of the annual emission reduction for the buildings No.=1, No.=2, No.=3 w/wo electricity buyback.

## 6. CONCLUSION

In the present study, an optimization model based on the nonlinear programing method are applied for investigation of the optimal operation strategy and economic study of Micro CHP systems in the residential, commercial and health center buildings. The annual cost saving and the rate of return of these systems are studied in the different sectors and compared with those of the existing systems.

A sensitivity analysis is performed to examine the effects of energy tariffs on the adopting the Micro CHP systems in the three sectors studied. The present study indicates that the economic parameters are sensitive not only to the energy tariffs but also to the capital cost of the Micro CHP systems and the heating and electrical demands of the buildings.

If the surplus electricity buyback is not considered, the annual cost with adopting the Micro CHP system for the residential building is higher than the existing systems (boiler and utility electricity). The results obtained by applying the optimization method presented show the profitability index is negative for all the Micro CHP capacities in the residential building which has lowest electrical demand compared to the commercial and health buildings. This result illustrates using the Micro CHP systems are not cost effective in the buildings with low electrical and heating demands if electricity sales to the grid are not possible. Without considering electricity buyback, it is concluded that adopting the Micro CHP systems in the health and commercial buildings studied have nearly reasonable annual savings but the Micro CHP systems are not recommended for the residential building.

On the other hand, annual cost saving is significantly increased with adopting the Micro CHP systems with electricity buyback in all buildings surveyed. The maximum value of profitability index occurs for the residential buildings which have the lowest electrical consumption and then the Micro CHP system adopted in this building can make more surplus electricity to sell to the utility grid. Although, the annual cost is reduced when the capacity of the Micro CHP systems is increased but the higher system capacities need higher capital costs and can further increase the payback period time as well. Study shows the optimum capacity range of the Micro CHP systems are 4.5-5 $kW_e$ and the optimum payback period times for the health, residential and commercial buildings studied are 2.5, 5.4 and 4.9 years, respectively. The study demonstrates that the emission is significantly reduced for all sectors studied by applying the Micro CHP systems with considering electricity buyback.

## REFERENCES

[1] M. Motevasel, A. Seifi and T. Niknam, Multi-objective energy management of CHP (combined heat and power)-based micro-grid, *Int. J. of Energy*; vol. 51, pp. 123-136, 2013.

[2] H. Ren, W. Gao and Y. Ruan, Optimal sizing for residential CHP system, *Applied Thermal Engineering*, vol. 28, pp. 514–523, 2008.

[3] V. Dorer and A. Weber, Energy and $CO_2$ emissions performance assessment of residential micro-cogeneration systems with dynamic whole-building simulation programs, *Energy Conversion and Management*, vol. 50, pp. 648–657, 2009.

[4] J. J. Wang, Y. Y. Jing and C. F. Zhang, Optimization of capacity and operation for CCHP system by genetic algorithm, *Applied Energy*, vol. 87, pp. 1325-1335, 2009.

[5] T. Tveit, T. Savola, A. Gebremedhin and C. Fogelholm, Multi-period MINLP model for optimizing operation and structural changes to CHP plants in district heating networks with long-term thermal storage, *Energy Conversion and Management*, vol. 50, pp. 639–647, 2009.

[6] H. Ren and W. Gao, A MILP model for integrated plan and evaluation of distributed energy systems, *Applied Energy*, vol. 87, pp. 1001–1014, 2010.

[7] S. G. Tichi, M. M. Ardehali and M. E. Nazari, Examination of energy price policies in Iran for optimal configuration of CHP and CCHP systems based on particle swarm optimization algorithm, *Energy Policy*, vol. 38, pp. 6240–6250, 2010.

[8] N. Fumo, P. J. Mago and L. M. Chamra, Energy and economic evaluation of cooling, heating, and power systems based on primary energy, *Applied Thermal Engineering*, vol. 29, pp. 2665–2671, 2009.

[9] P. J. Mago, N. Fumo and L. M. Chamra, Performance analysis of CCHP and CHP systems operating following the thermal and electric load, *Int. J. Energy Res.*, vol. 33, pp. 852–864, 2009.

[10] H. Ren and W. Gao, Economic and environmental evaluation of Micro CHP systems with different operating modes for residential buildings in Japan, *Energy and Buildings*, vol. 42, pp. 853–861, 2010.

[11] P. J. Mago and A. D. Smith, Evaluation of the potential emissions reductions from the use of CHP systems in different commercial buildings, *Building and Environment*, vol. 53, pp. 74-82, 2012.

[12] F. Teymouri and S. Sattari, Technical and economic feasibility study of using Micro CHP in the different climate zones of Iran, *Int. J. of Energy*, vol. 36, pp. 4790-4798, 2011.

[13] H. Cho, P. J. Mago, R. Luck and L. M. Chamra, Evaluation of CCHP systems performance based on operational cost, primary energy consumption, and carbon dioxide emission by utilizing an optimal operation scheme, *Applied Energy*, vol. 86, pp. 2540-2549, 2009.

[14] S. Higashiguchi, K. Hirai, N. Shinke, S. Ibe, O. Yamazaki and K. Yasuhara et al., Development of Residential PEFC Cogeneration Systems at Osaka Gas, Residential Cogeneration Development Department Osaka Gas Co., Ltd., Osaka, 2005.

[15] Electric Power Ministry of Iran, Tavanir Parent Specialized Company, October 2010. Available from: http://www.tavanir.org.ir

## NOMENCLATURE

| | |
|---|---|
| c | Cost coefficient($/kWh) |
| C | Cost($) |
| Cc | Capital cost($/kW) |
| Cp | Capacity(kW) |
| E | Electricity load(kW) |
| H | Heat load(kW) |
| Heat rate | $kWh/m^3$ |
| i | Interest rate % |
| D | Customer load(kW) |
| P | Energy price($/kWh) |

### *Greek symbols*

| | |
|---|---|
| α | Electricity efficiency% |
| γ | Heat to electricity ratio |
| η | efficiency % |

### Subscripts

| | |
|---|---|
| boiler | Supplementary boiler |
| Cooling | Cooling load |
| Hot water | Hot water load |
| Invest | Investment |
| d | Day |
| m | maintenance |
| rat | Rated capacity |
| run | running |
| Purch | Purchase |
| self | Self use |

### Superscripts

| | |
|---|---|
| IC | Internal combustion engine |
| Utility | Utility grid |