OPEN ACCESS

The 4th World Sustainability Forum
1 - 30 November 2014

http://www.sciforum.net/conference/wsf-4

*World Sustainability Forum 2014 – Conference Proceedings Paper*

# ECONOMIC AND ENVIRONMENTAL ASSESSMENTS OF ENERGY CONSERVATION IN RESIDENTAIL BUILDING TO MEET THE ELECTRICAL, HEATING AND COOLING LOADS WITH MICRO GAS TURBINE UNITS

S. Mohammdreza Heibati[1], Farideh Atabi[2], Morteza Khalaji Assadi[2], M. A.Ehyaei [1], Mohammad Hossein Ahmadi[3*]

[1] Department of Mechanical Engineering, Pardis Branch, Islamic Azad University, P.O. Box 16555/135, Tehran, Iran
[2] Department of Energy Engineering, Graduate School of Environment and Energy, Science and Research Branch, Islamic Azad University, Tehran, Iran, P.O. Box: 14155/4933
[3] Department of Renewable Energies, Faculty of New Science and Technologies, University of Tehran, Tehran, Iran

E-Mails: mrheibati@gmail.com; far-atabi@jamejam.net; rakhassadi@yahoo.com; Aliehyaei@yahoo.com ; mohammadhosein.ahmadi@gmail.com

* Corresponding author: Tel: +98-9122866205; Fax: +98 21 76281213.
E-mail address: mohammadhosein.ahmadi@gmail.com

*Received: 18 June 2014 / Accepted: 31 October 2014 / Published: 3 November 2014*

---

**Abstract:** The present study deals with the economic and environmental assessment of energy conservation in residential buildings. In this approach, the heating and cooling loads of a typical residential building in Tehran with micro gas turbine units have been considered. This 8000 m$^2$ area building possesses 10 floors with 4 units per floor. Five distinguished scenarios, wall insulation, roof insulation, shading, triple glazing and all of the four energy conversation methods have been proposed concerning the decrease in the energy usage. Each of the energy conservation methods was studied separately in four former scenarios and all of these methods were investigated simultaneously in the fifth latter scenario. To achieve the heating, cooling and electrical loads, a number of 30 kW combined heat and power (CHP) micro gas turbine units have been taken into consideration without energy conversation methods. The results show that the best scenario concerning the minimum value of energy loss is that for which the mean heating and cooling loads were 514.58 and 519.08 kW, respectively. Also the number of CHP micro gas turbine units reduces from 30 to 11 and also the total electricity cost decrease from 0.32 to 0.16 US$/kWh with consideration social cost of air pollution.

**Keywords:** optimum scenario; CHP micro gas turbine; residential building; energy conservation methods.

---

## 1. Introduction

In the last decade, related to energy factors and ecological problems, electric demand and financial raised worldwide. These difficulties are continuously increased, so technological alternatives are considered. One of these alternatives is distributed generation (DG). Distributed generation is defined generating electricity as near as possible to consumption [1]. In addition to efficiency promotion and lower environmental pollutions, these technologies provide other advantages such as elimination of power distribution lines, lower system initial cost and higher security [1]. Distributed generation (DG) technologies are divided into two main objects including renewable and non- renewable technologies [1]. Non-renewable systems consist many technologies such as: Micro gas turbine; internal combustion engine, Fuel cell, etc. [1]. Among these technologies, cogeneration system systems play an important role. Cogeneration systems are employed where both electricity and heat are required, in these systems waste heat produced during electricity generation. Thus, an economical benefit is gained in comparison to the systems where electricity and heat are separately produced [2]. Since combined heat and power (CHP) systems produce thermal (hot water or steam) and electrical energies simultaneously. System efficiency is increased from 35%-55% to over 90% in CHP systems [3]. Among cogeneration systems which are used in residential building, micro gas turbines play a crucial role because of their cost effectiveness, mobility, and high efficiency [4]. The use of internal combustion engines, micro gas turbines or fuel cells for on-site combined heat and power plant (CHP) in residential building, has been studied by several by authors of this paper [5-8]. Ren etal. [9] Performed the cost-effective operating strategy for the residential micro CHP plant. Onovwiona et al. [10] assessed a design and techno-economic evaluation model for residential internal combustion engine system including the power generator, electrical and thermal storage systems. Ren et al. [9,11] discussed optimal sizing for residential CHP system. They developed the technical, economic and institutional uncertainties in the design and operation of micro CHP plants while applying a comprehensive framework for uncertainty analysis. Azmy et al. [13,14] developed a techno-economic model for the control and design of fuel cell micro CHP plant. Babus'Haq [15] suggested the energy and CO2 emissions performances of various micro CHP plants for some residential building types, by considering different electricity generation mixes. Ren et al. [11] in another paper presented the economic and environmental evaluation of micro CHP systems with different operating modes for residential buildings in Japan. They analyzed two typical micro CHP alternatives, namely, gas engine and fuel cell for residential buildings. The results of that paper showed that the fuel cell system is recognized as a better option for the examined residential building from both economic and environmental points of view. The objective was to minimize annual cost of the energy system for a given residential customer equipped with the CHP plant, combining with a storage tank and a back-up boiler. More details about CHP and micro turbines are discussed in references [16-19].

Heibati and safaripour [20] in a research simulated and optimized CHP plant by multi-objective thermo-environmental method. In this method all of optimization program was based on evolutionary algorithm.

In a new study, a model have been developed based on mathematical equations of mass and energy balance between different parts of a building and the designed model for a case study XYZ building located at north of Tehran has been evaluated [21,22].

In summary, followings are the specific contribution of this paper in the subject matter area:

Five different scenarios have been proposed to energy saving (heating and cooling loads of the building) and based on these scenarios, number of micro gas turbine units is calculated and it shows by using each scenario what percent of energy usage is reduced and its effect on cost of electricity with respect to social cost of air pollution is considered.

## 2. ESTIMATION OF THE ELECTRICAL, HEATING AND COOLING ENERGY NEEDS OF A RESIDENTIAL BUILDING

The studied building is ten floors with 40 units. Each floor area is 200 $m^2$. The building height is 30 m; its length and width are 40m and 20m, respectively. The window areas are 30% of the south and north walls and 20% of east and west walls. Thicknesses of external and internal walls are 22 and 12 cm thick, respectively. They are made of brick with gypsum plaster on the interior walls. Thickness of roof is 22 cm and it is made of brick and roofing materials. Thermal insulation is not used in walls or roof of the building [5]. To calculate the electrical, heating and cooling loads of residential building located in Tehran, it was assumed that the $15^{th}$ day of each month represented all days of that month [5]. Electrical, heating and cooling energy needs of this building are calculated from reference 5, a paper that was written by M.A. Ehyaei et.al. In this paper, the total electrical energy consumption in each month was compared with the electricity bill received by the family in each month of the past year. The maximum deviation is 5%, in July, and the minimum is 0.8%, in December. The mean annual deviation was 2.34%.

Fig. 1 shows the ambient air temperatures for Tehran, during the months of January, April and July [5]. Figs. 2 and 3 show the total electrical power requirement of the residential building in a 24-hour period on January 15, and July 15, respectively. It should be mentioned that Figs. 2 and 3 do not include the electrical power and energy needed to operate the electrical motors used for the central heating and cooling systems of the building [5]. Fig. 4 shows the heating and cooling loads of the building (in kW), which is located in Tehran, on January 15, April 15 and July 15, respectively. To determine the hourly energy needs for the domestic hot water consumed in the residential building of 40 units, we assumed that all units have similar hot water consumption rate. We further assumed that the hot water consumption was uniformly distributed between 5 am to 11 pm, with no hot water consumed in the building between 11 pm and 5 am. Fig. 5 shows the daily energy needs of the building for domestic hot water [5].

**Figure. 1.** The ambient air dry-bulb and wet-bulb temperatures for Tehran, during the months of January, April and July [5].

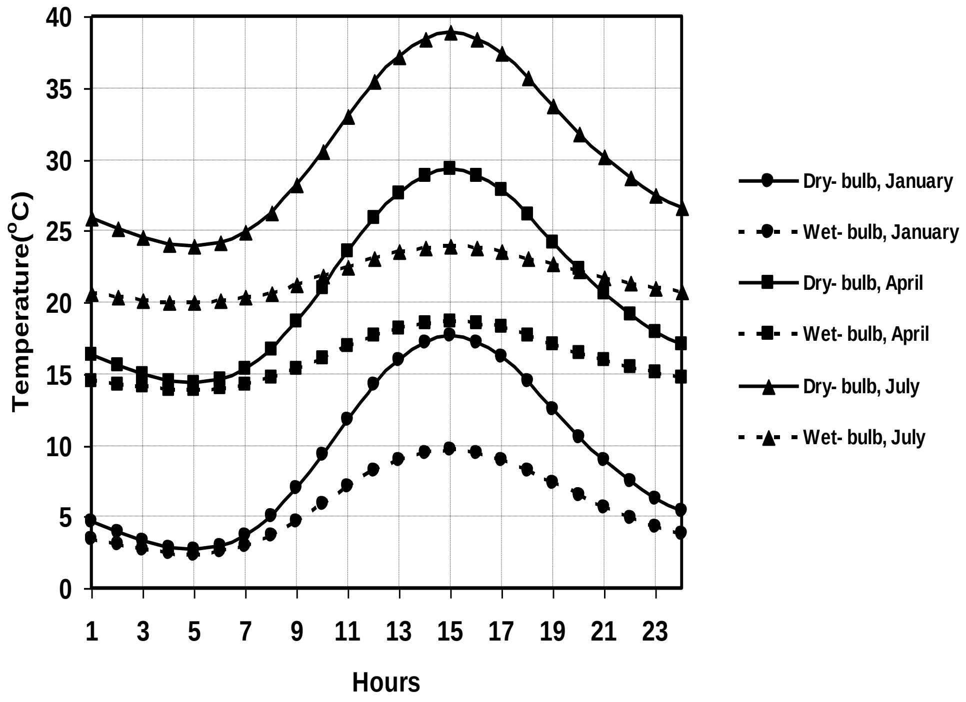



**Figure. 2.** Total electrical power requirement of the residential building in a 24-hour period, estimated on January 15 [5].

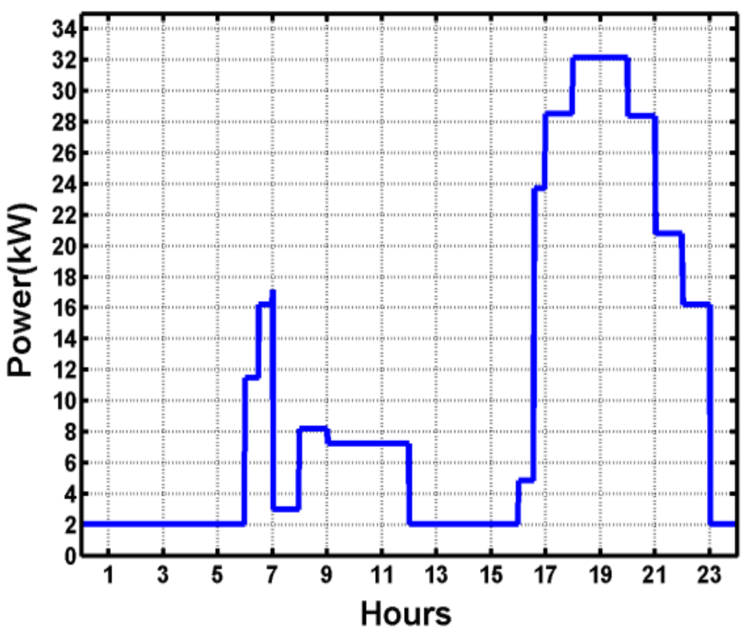



**Figure. 3.** Total electrical power requirement of the residential building in a 24-hour period, estimated on July 15 [5].

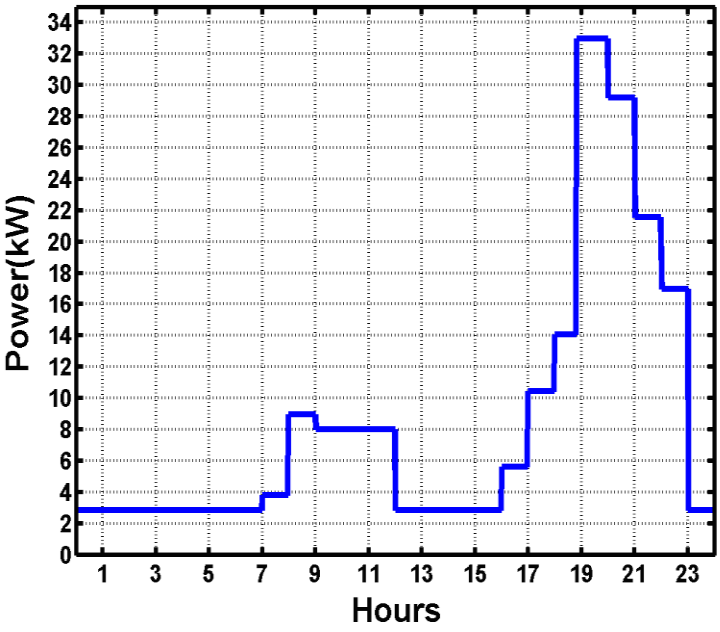



**Figure. 4.** The heating and cooling loads of the building located in Tehran, estimated on January 15, April 15 and July 15 [5].

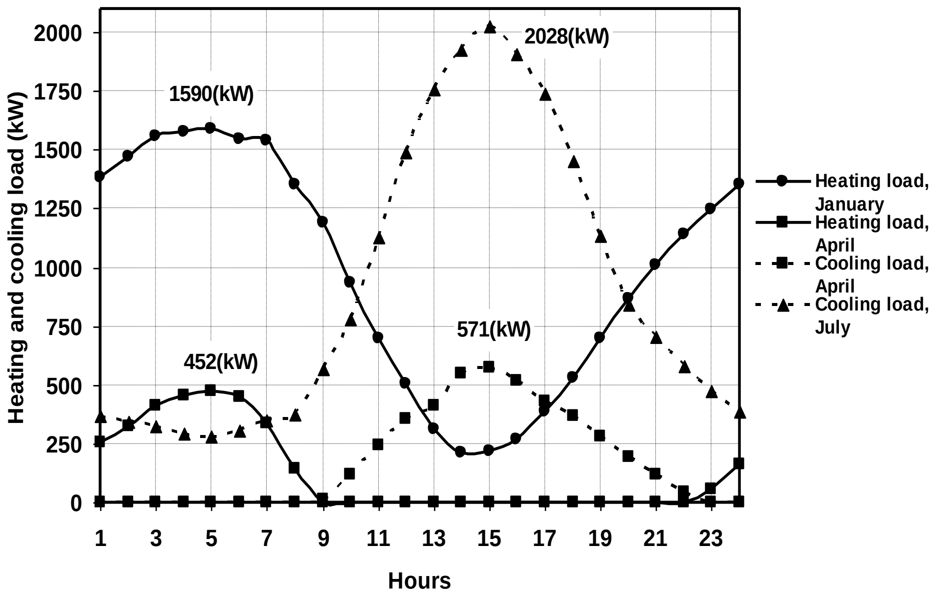
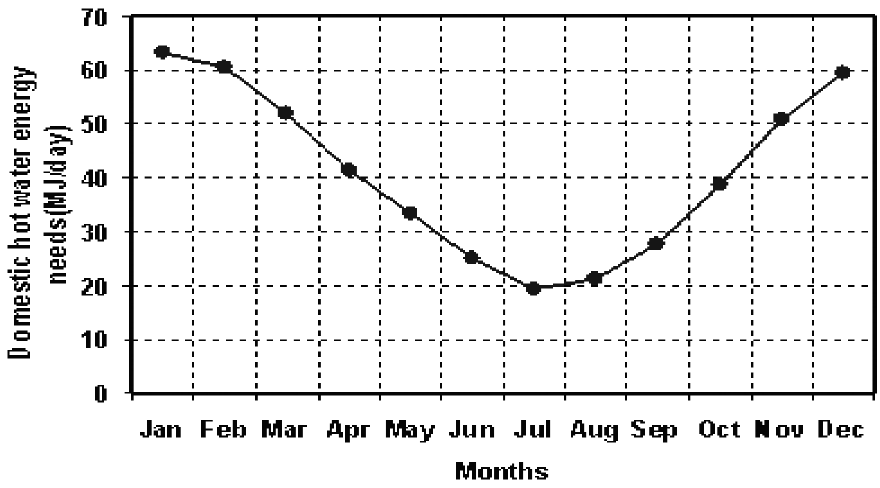



**Figure. 5.** Domestic hot water energy needs of the residential building [5].




## 3. ENERGY CONSERVATION SCENARIO TO REDUCE HEATING AND COOLING LOADS OF THE RESIDENTIAL BUILDING

In assumed building model, five different scenarios to reduce the energy consumption have been considered as follows:

Scenario “A”: wall insulation

Scenario “B”: roof insulation

Scenario “C”: shading

Scenario “D”: triple glazing

Scenario “E”: all of four energy conservation methods

### *3.1.A Scenario “A”*

In this scenario it is assumed that the external walls are isolated to reduce the energy losses. According to Table 1, the base case is composed of three layers: 25 mm stucco on the outside and 203 mm concrete block in middle, 16 mm gypsum board on the inside of wall. The overall *U*-value (overall heat transfer coefficient) is 1.485 W/m$^2$ K. In scenario “A” in addition to layer used in the base case between gypsum board and concrete block, a 152.4 mm mineral fiber insulator is used. In this case the overall *U*-value is reduced from 1.485 to 0.274 W/m$^2$K.

**Table 1.**Comparison of the material specifications and thickness for the external walls of the base case and scenario “A”

| Building cases | Layers and materials (from outside to inside) | Overall $U$-value ($W/m^2K$) |
|---|---|---|
| Base case | 25 mm Stucco + 203 mm concrete block + 16 mm gypsum board | 1.485 |
| Scenario A | 25 mm Stucco + 203 mm concrete block + 152.4 mm mineral fiber insulation + 16 mm gypsum board | 0.247 |

*3.2. B Scenario "B"*

In this scenario, the insulation is considered just for the last stage of the building. It was seen that a drastic reduction in thermal and energy losses is occurred by using this method. This is due to the fact that the last stage of the building is in the contact with ambient. Regarding to Table 2, building roof is made up of three layers: 9.5 mm built-up roofing in the outside, 13 mm plywood in the middle, 13 mm gypsum board on the inside layer. The overall $U$-value is 1.69 $W/m^2K$. Using 50.8 and 304.8 mm mineral fiber insulator between base case layers from outside to inside, the $U$-value is reduced from 1.69 to 0.102 $W/m^2K$.

**Table .2.**Comparison of the material specifications for the building roof of the base case and scenario "B"

| Building cases | Layers and materials (from outside to inside) | Overall $U$-value ($W/m^2K$) |
|---|---|---|
| Base case | 9.5 mm built-up roofing + 13 mm plywood + 13 mm gypsum board | 1.69 |
| Scenario B | 9.5 mm built-up roofing + 50.8 mm mineral fiber insulation + 13 mm Plywood + 304.8 mineral fiber insulation + 13 mm gypsum board | 0.102 |

*3.3. C. Scenario "C"*

One of the common methods to reduce the thermal losses in building especially in hot seasons is using the sunshade. In this building according to the geographical situation of Tehran sunshade is an overhang type. Table 3 shows its details. In this case, 152 mm reveal depth, 1016 mm projection from surface, 304 mm height above window and 2209 mm extension past right and left hand sides of window.

**Table 3**.Specifications of the window outer shading for scenario "C"

| Type | Specifications | Length (mm) |
|---|---|---|
| Overhang | Reveal depth | 152 |
| | Projection from surface | 1016 |
| | Height above window | 304 |
| | Extension past right hand side of window | 2209 |
| | Extension past left hand side of window | 2209 |

*3.4. D. Scenario "D"*

One of the heat losses in building is windows. This loss for single glazing windows is due to the higher U-value in building. If the low- triple emissivity windows are used in this scenario, the thermal losses will be minimized. Table 4 shows the comparison of two windows for base case and scenario “D”. It is obvious that U-value in triple glazing in comparison with single glazing reduced from 5.387 to 1.383 W/m2K. It is due to krypton gas between three glazings.

**Table.4.**Comparison between the specification of the single and triple glazing for the base case and scenario “D”

| Building cases | Glass details (from outside to inside) | Overall *U*-value ($W/m^2K$) |
|---|---|---|
| Base case | 6 mm clear glass, (single glazing) | 5.387 |
| Scenario D | 6 mm clear low emissivity glass + 13 mm Krypton gas + 6 mm clear low emissivity + 13 mm krypton gas + 6 mm blue -green reflective,(triple glazing) | 1.383 |

*3.5.E. Scenario “E”*

The optimum strategy to reduce the energy loss in the buildings is used for four energy conservation methods which they are proposed by scenario “E”. Target of these mentioned scenarios is reduction heating and cooling loads.

## 4. ESTIMATION OF ELECTRICAL, HEATING AND COOLING NEEDS OF RESIDENTIAL BUILDING WITH ENERGY CONSERVATION METHOD Main text paragraph (M_Text).

Table 5 shows the annual mean heating and cooling loads of the residential building with and without energy conservation methods. Regarding this table, it can be concluded that energy conservation methods such as wall insulation, roof insulation, triple glazing and accumulation of these methods, can reduce the annual average heating loads from 982.8 to 537.64, 532.26, 548.84 and 514.58 kW, respectively, except shading which increases the heating loads in the building, also cooling loads reduce from 891.3 kW to 555.4, 542.8, 566.53, 569.9 and 519.08 kW for wall and roof insulations, triple glazing, shading and all of the four energy conservation methods, respectively.

Table 6 shows the maximum heating loads for the residential building at 5 am, 15$^{th}$ January with and without energy conservation methods. Due to this table, it can be concluded that energy conservation methods such as wall insulation, roof insulation and triple glazing can reduce the maximum heating loads of residential which they effects on number of micro gas turbine units in order to meet the loads of the residential building. Table 7 shows the maximum cooling loads for the residential building at 3 pm, 15$^{th}$ July with and without energy conservation methods.

**Table 5**. Annual mean heating and cooling loads of the residential building.

| | Base case | Wall insulation | Roof insulation | Triple glazing | Shading | All |
|---|---|---|---|---|---|---|
| $Q_{h\ mean}$ (kW) | 982.8 | 537.64 | 532.26 | 548.85 | - | 514.58 |
| $Q_{c\ mean}$ (kW) | 891.3 | 555.48 | 542.85 | 566.53 | 569.90 | 519.08 |

**Table.6.** Maximum heating loads for the residential building at 5 am, 15th January with and without energy conservation methods.

| | Base case | Wall insulation | Roof insulation | Triple glazing | All |
|---|---|---|---|---|---|
| $Q_{h\ max}$ (kW) | 1590 | 898.20 | 887.90 | 916.80 | 874 |

**Table.7.** Maximum cooling loads for the residential building at 3 pm, 15th July with and without energy conservation methods.

| | Base case | Wall insulation | Roof insulation | Triple glazing | Shading | All |
|---|---|---|---|---|---|---|
| $Q_{c\ max}$ (kW) | 2018 | 1188.50 | 1154.70 | 1202.70 | 1209.70 | 1073 |

## 5. CALCULATION OF MICRO GAS TURBINE UNITS TO MEET THE ELECTRICAL, HEATING AND COOLING LOADS OF THE RESIDENTIAL BUILDING

CHP 30 kW capstone micro gas turbine units are employed to meet the electrical, heating and cooling loads of residential building. Fig. 6 shows the power and efficiency variations versus inlet air temperature for 30 kW capstone micro gas turbines. Figs. 7 and 8 show schematic diagrams of the micro gas turbines operating in winter and summer, respectively [5]. Gas turbines are used to produce electricity to meet the electrical and part of the heating and cooling energy needs through a heat pump. The energy in the exhaust gases is to meet the rest of the heating and cooling energy needs. In winter, heating loads are employed with heat pumps and recovering exhaust gas energy in CHP heat exchanger. In summer, cooling loads are employed with heat pump and recovering exhaust gas energy in heat exchanger. Recovered energy is used in absorption chiller to meet a part of cooling loads.

**Figure. 6.** Variations of power and efficiency of capstone C-30 micro gas turbines with ambient air temperature

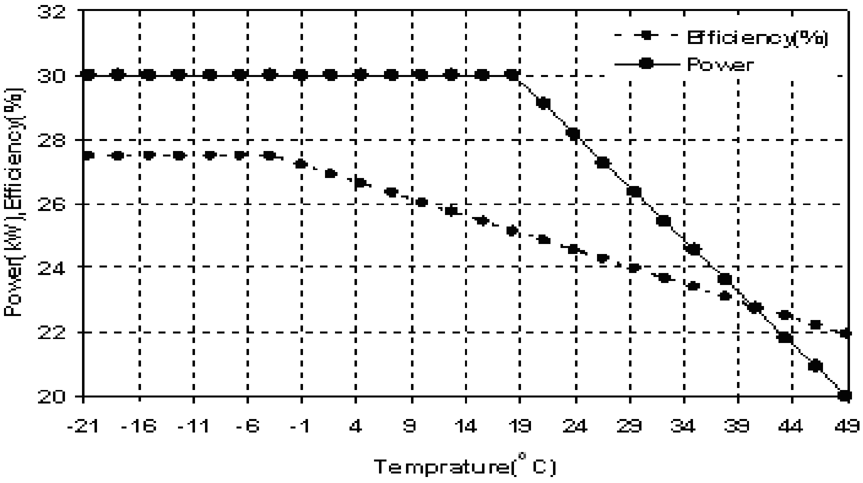



**Figure. 7.** Schematic diagram of the micro gas turbines meeting the energy needs of the building in winter

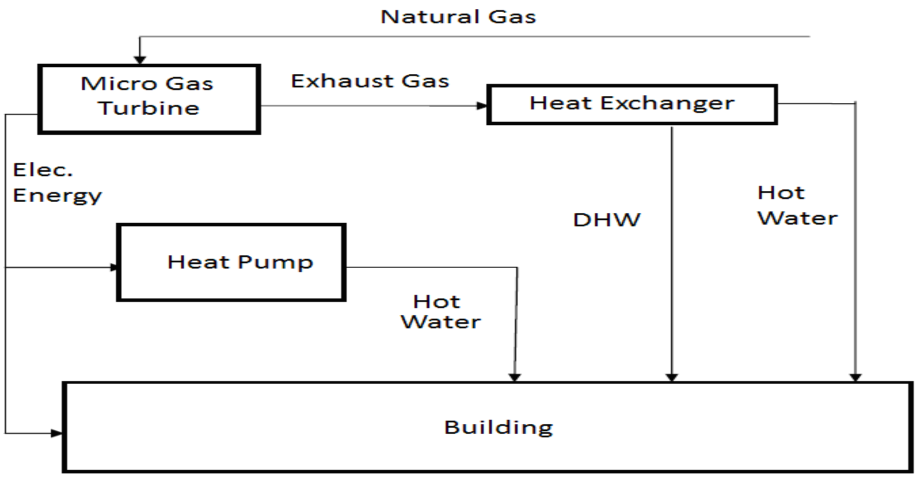
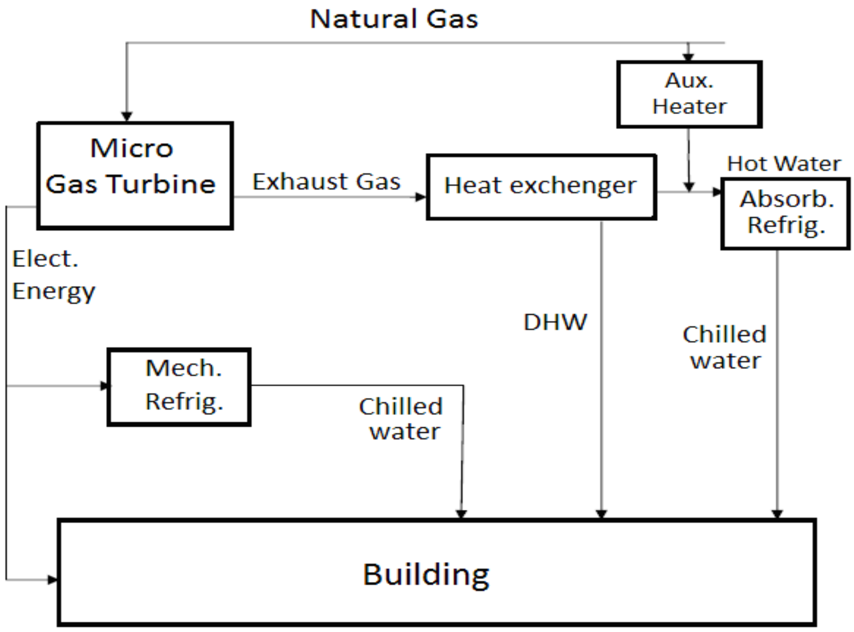


**Figure. 8.** Schematic diagram of the micro gas turbines meeting the energy needs of the building in summer




The following equations are used to determine the number of identical micro gas turbine units in winter and summer respectively [5]:

$$(ne-e')\beta_{hp}+nq\alpha-q'=Q_h \tag{1}$$

$$(ne-e')\beta_{ref}+(nq\alpha-q')\beta_{abs}=Q_c \tag{2}$$

In case there is no energy saving preparation. We first use Eq. (1) in order to find n for 15 January at 5 a.m. Referring to Table 6 and Figs. 1, 6 and 8, we obtain the following values: $T_a$ = 2.88C, $e_0$ = 2.05 kW, $Q_h$ = 1590 kW, $q_0$ = 0.926 kW, e = 30 kW and η = 27%. With these values we find from Eq. (1), n = 10.31 or n = 11 units. For 15 January at hour 20 (8 p.m.) we have $T_a$ = 10.5 8C,$e_0$ = 32.18 kW, $Q_h$ = 865 kW, $q_0$ = 0.926 kW, e = 30 kW and η = 26%. Then from Eq. (1) we obtain n = 6.08, or n = 6 units. For 15 July at hour 15, we have $T_a$ = 39 8C, $e_0$ = 2.83 kW, $Q_c$ = 2018 kW, $q_0$ = 0.285 kW, e = 23.8 kW and η = 23%. From Eq. (2) we obtain n = 30.03 or n = 30. For 15 July at hour 19, we have $T_a$ = 34 8C, $e_0$ = 32.96 kW, $Q_c$ = 1136 kW, $q_0$ = 0.285 kW, e = 24.8 kW and η = 23.5%. From Eq. (2) we obtain n = 11.37 or n = 12 units. It is obvious from the above calculations that, main task of the micro turbine in this case meets the cooling and heating energy needs of the residential building. With a total of 30 Capstone C30 micro turbines selected, all the energy needs of the building can be met at all the time. For Scenarios A to E same method should be considered. Table 8 shows the number of identical 30 kW Capstone micro gas turbine units to meet all of the loads of the building with and without energy conservation methods.

**Table.8.** Number of identical micro gas turbine.

| | Base case | Wall insulation | Roof insulation | Triple glazing | Shading | All |
|---|---|---|---|---|---|---|
| n | 30 | 12 | 12 | 12 | 12 | 11 |

## 6. ELECTRICITY COST ESTIMATION OF CHP MICRO GAS TURBINE

The electricity cost can be calculated by the following equation [6]:

$$C_E = C_I + C_O + C_F + C_A \tag{3}$$

In which $C_E$, $C_I$, $C_O$, $C_F$, $C_A$ are the cost of electricity, the cost associated with the initial investment (including the installation cost), the cost associated with the operation and maintenance, the cost associated with the fuel consumption and the externalized social cost of air pollution, respectively.

For $C_I$ :

$$C_I = \frac{C.I}{8760 C_f} \tag{4}$$

C: the total capital cost of the installed power generation system (US$/kW),I: capital salvage factor to be paid on the unit of borrowed capital, $C_f$: the capacity factor. The capital salvage factor (I) can be estimated by the following equation [23]:

$$I = \frac{i(1+i)^L}{(1+i)^L - 1} \tag{5}$$

Where L is the lifetime of the power generation system. We assumed this parameter to be 20 years and "*i*" is the annual interest rate assumed to be constant during the lifetime of the system, or the period of the loan repayment. The capacity factor ($C_f$) can be calculated form the following relation [6]:

$$C_f = \frac{e'_{mean}}{n e'_{nominal}} \tag{6}$$

Where $e'_{mean}$ is an annual average consumption of electrical power by the building (kW) and $e'_{nominal}$ is the micro gas turbine nominal power (kW). For the fuel cost used by the system ($C_F$), the following equation can be applied [6]:

$$C_F = \frac{Fuel\ \cos t(US\$/kWh)}{\eta_I} \tag{7}$$

Also, the external costs of air pollution ($C_A$) can be obtained from the following equation [6]:

$$C_A = [\dot{m}_{NO}(C_{A,NO}) + \dot{m}_{CO}(C_{A,CO}) + \dot{m}_{CO_2}(C_{A,CO_2})]\frac{1}{3600\ \ e_{no\min al}} \tag{8}$$

Where $\dot{m}_{NO}$ is the exhaust mass flow rate of nitrogen monoxide; $\dot{m}_{CO}$ is carbon monoxide and $\dot{m}_{CO2}$ is carbon dioxide. Also, $C_{A,NO}$; $C_{A,CO}$; $C_{A,CO2}$ are the externalized social cost of air pollution for nitrogen monoxide, carbon monoxide and carbon dioxide, respectively. For the CHP micro gas turbine, which produces power as well as heat, a boiler is assumed to produce the same amount of heat and as a result the costs of initial investment, operation and maintenance, fuel and finally externalized costs of air pollution of the assumed boiler could be reduced from the cost electricity as following: [6]:

$$C_E = (C_I + C_O + C_F + C_A) - (C_I + C_O + C_F + C_A)_{assumed\ boiler} \tag{9}$$

For calculation of the energy available in the exhaust gases, the following equation can be used [6]:

$$q = e(\frac{1}{\eta} - 1) \tag{10}$$

Where $q$ is the energy in the exhaust gases and $\eta$ is the thermal efficiency of micro gas turbine. For electricity cost of micro gas turbine without any energy conservation, regarding Eq. (3), the capacity factor ($C_f$), can be calculated as following:

$$C_f = \frac{144.69 + 10.18 + 0.48}{11 \times 30} = 0.47 \tag{11}$$

The capital salvage factor (I) can be calculated as following:

$$I = \frac{i(1+i)^L}{(1+i)^L - 1} = \frac{0.1(1+0.1)^{20}}{(1+0.1)^{20} - 1} = 0.117 \tag{12}$$

And the cost of initial investment ($C_I$) is calculated as following:

$$C_I = \frac{1300 \times 0.117}{0.47 \times 8790} = 0.036 \text{ US\$/kWh} \tag{13}$$

The cost of operation and maintenance for CHP micro gas turbine is 0.03 US$/kWh [6]. For the cost of the fuel consumption ($C_F$), assuming the gas fuel cost 0.0297 US$/kWh [6], the following equation can be applied:

$$C_F = \frac{0.0297}{0.23} = 0.129 \text{ US\$/kWh} \tag{14}$$

And external cost of air pollution produced by CHP micro gas turbine is calculated as following:

$$\begin{aligned} C_A &= \left(\frac{11}{30}\right) \times (8.175 \times 2.2197 \times 10^{-4} + 6.424 \times 5.54 \times 10^{-5} + 0.024 \times 0.028) \\ &= 0.001041 \text{ US\$/kWh} \end{aligned} \tag{15}$$

Regarding Eq. (10), the annual average energy in the exhaust gases is about 106.4 kW. The efficiency of boiler which produces heat equal to the CHP heat exchanger energy recovery is assumed to be about 60%, with the initial and operation and maintenance costs of about 75.7 and 0.002 US$/kWh, respectively. Electricity cost produced by CHP micro gas turbine can be calculated via the Eq. (9) as following [6]:

$$C_E = (0.036 - 0.0126) + (0.03 - 0.002) + (0.129 - 0.014) + (0.001041 - 0.0003) = 0.167 \text{ US\$/kWh} \quad (16)$$

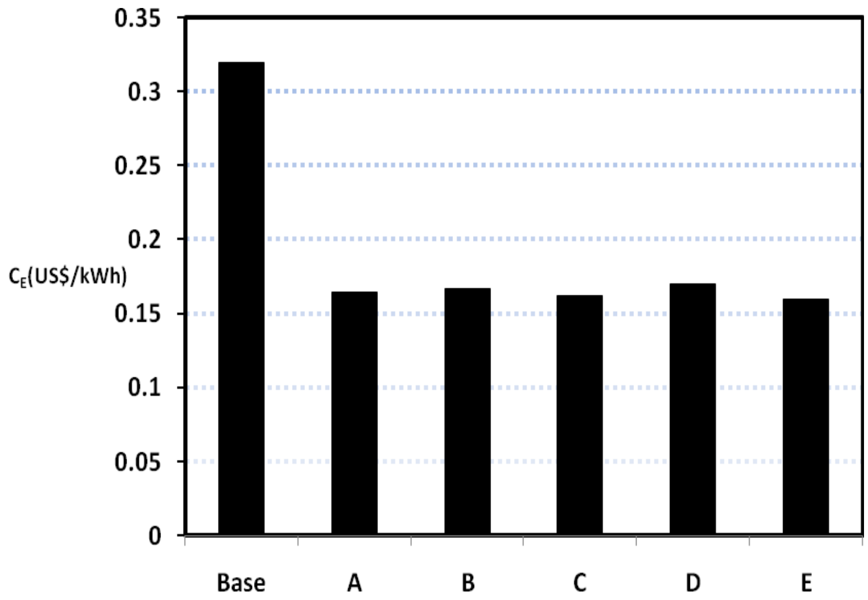
Table.9 shows initial cost for energy saving scenarios A to E.

**Table.9.**Initial cost for energy saving scenarios A to E

| **Scenarios** | **Initial cost (US$)** |
|---|---|
| A | 48000 |
| B | 3533 |
| C | 15000 |
| D | 172800 |
| E | 2393333 |

Figure.9.shows electricity cost for scenarios (A to E).

**Figure.9.**Eelctrcity cost of scenarios (A to E) to meet electrical, heating and cooling loads of residential building




## 7. CONCLUSION

In this research, various energy saving methods were proposed in different approaches according to considerable energy loss in residential buildings. Among the approaches investigated, the scenario "E", in which all the applied methods (wall insulation, roof insulation, triple glazing and shading) led to superior improvement in energy saving, was recognized as the optimum case. As the aim of this study was utilizing micro gas turbines for residential application, applying energy saving with respect to different scenarios led to decrease in the number of micro turbines employed. According to the results, the optimum building design is one whose proposed scenario has the lowest heating and cooling load. The results reveal that the best method for energy saving is using all the energy saving methods like wall insulation, roof insulation, triple glazing and shading. This approach leads to the lowest heating load for the buildings. Thus, the best scenario applied was the "E" case in which the $Q_{h\ mean}$ and $Q_{c\ mean}$ were 514.58 and 519.08 kW, respectively having the lowest energy loss in comparison with other methods. In this part, the electricity cost including initial, maintenance, social and fuel costs in two cases, namely base case and selected case, were compared with each other. Comparing the base cases in scenario "E", the initial cost reduced from 0.1 to 0.036 US$/kWh, the external costs decreased from 0.00284 to 0.00104 US$/kWh due to the reduction in environmental impacts, and also the maintenance and fuel costs remained constant at 0.03 and 0.129 US$/kWh, respectively. Consequently, the total electricity cost decreased from 0.321 to 0.16 US$/kWh. The results indicate that the number of CHP micro gas turbine units reduced from 30 to 11 and also total electricity and external costs decreased about 47% and 63.34%, respectively.

## References and Notes

1. Willis, H.L., Scott, W.G. Distributed Power Generation: Planning and Evaluation, 1st ed., Marcel Dekker, New York, USA, 2000.
2. Coelho, M. Nash, F. Linsell, D. Barciela, J.P. Cogeneration – the development and implementation of a cogeneration system for a chemical plant, using a reciprocating heavy fuel oil engine with a supplementary fired boiler, *Journal of Power and Energy* 217 (2002) 493–503.
3. Rosen, M.A. , Le M.N, Dincer, I. Efficiency analysis of a cogeneration and district energy system, *Applied Thermal Engineering* 25 (2005) 147–159.
4. Silveira, J.L.. Walter, A.C.S Luengo, C.A. A case study of compact cogeneration using various fuels, *Fuel* 76 (1997) 447-451
5. Ehyaei, M.A. Bahadori, M.N. Selection of micro turbines to meet electrical and thermal energy needs of residential buildings in Iran, *Energy and Buildings* 39 (2006) 1227–1234.
6. Ehyaei, M.A. Mozafari, A. Energy, economic and environmental (3E) analysis of a micro gas turbine employed for on-site combined heat and power production, *Energy and Buildings* 42 (2010) 259–264.
7. Saidi, M.H. Ehyaei, M.A. Abbasi, A. Exergetic optimization of a PEM fuel cell for domestic hot water heater, *ASME journal of fuel cell technology* 2 (2005) 284-289.
8. Saidi, M.H. Ehyaei, M.A.. Abbasi, A Optimization of a combined heat and power PEFC by exergy analysis, *Journal of Power Sources* 143 (2005) 179–184.
9. Ren, H. Gao, W. Ruan, Y. Optimal sizing for residential CHP system, *Applied Thermal Engineering* 28 (2008) 514–523.
10. Onovwiona H.I., Ugursal V.I., Residential cogeneration systems: review of the current technology, *Renewable and Sustainable Energy Reviews* 10 (5) (2006) 389–431.
11. Ren, H. Gao, W. Economic and environmental evaluation of micro CHP systems with different operating modes for residential buildings in Japan, *Energy and Buildings* 42 (2010) 853–861.4.
12. Arcuri, P. Florio, G. Fragiacomo, P. A mixed integer programming model for optimal design of trigeneration in a hospital complex, *Energy* 32 (2007) 1430–1447.

13. Azmy, A.M. Dynamic simulation of hybrid fuel cell/micro turbine units integrated into large power systems, *Applied Thermal Engineering* 18 (1998) 320–332.
14. Babus'Haq, R.F. Probert, S.D. O'Callaghan, P.W. Assessing the prospects and commercial viabilities of small-scale CHP schemes, *Applied Energy* 31 (1988) 19–30.
15. Babus'Haq, R.F. Pearson, J.P. Probert, S.D. O'Callaghan P.W., Economics of mini-combined heat and power packages for use in hotels, *Heat Recovery Systems and CHP* 10 (3) (1990) 269–275.
16. Bruno J.C., Valero A., Coronas A., Performance analysis of combined micro gas turbines and gas fired water/LiBr absorption chillers with post-combustion, *Applied Thermal Engineering* 25 (2005) 87–99.
17. Cardona E., Piacentino A., Cardona, F. Matching economical, energetic and environmental benefits: An analysis for hybrid CHCP-heat pump systems, *Energy Conversion Management* 47 (2006) 3530–3542.
18. Cardona E., Sannino P., Piacentino A., Cardona F., Energy saving in airports by trigeneration. Part II: Short and long term planning for the Malpensa 2000 CHCP plant, *Applied Thermal Engineering* 26 (2006) 1437–1447.
19. Dorer V., Weber A., Energy and $CO_2$ emissions performance assessment of residential micro-cogeneration systems with dynamic whole-building simulation programs, *Energy Conversion and Management* 50 (2009) 648–657.
20. Heibati, S. M., Safaripour, M, (2013). Modeling and multi-objective thermo-environmental optimization of CHP plant for residential application, *Proceedings of the International Conference on Environmental Pollution and Remediation*, Publisher: International ASET Inc. Paper number: 225, Conference: 3rd International Conference on Environmental Pollution and Remediation (ICEPR'13) Toronto, Canada; 15 – 17 July 2013.
21. Heibati, S. M., Atabi, F. (2013). Integrated dynamic modeling for energy optimization in the building: Part 2: an application of the model to analysis of XYZ building. *Journal of Building Physics*. , 37 (2) **153-169.** DOI: 10.1177/1744259112474873.
22. Heibati, S. M., Atabi, F., Khalajiassadi, M., & Emamzadeh, A. (2013). Integrated dynamic modeling for energy optimization in the building: Part 1: The development of the model. *Journal of Building Physics*, *37*(1), 28-54. DOI: 10.1177/1744259113475543.
23. Horngren C.T., Cost Accounting a Managerial Emphasis, Prentice-Hall, Englewood Cliffs, NJ, USA, 1997.