Energy Equip. Sys./ Vol. 5/No. 3/September 2017/ 219-226

Energy Equipment and Systems

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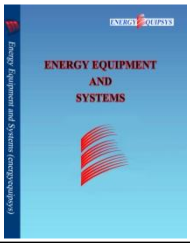

Determining the optimal size of a ground source heat pump within an air-conditioning system with economic and emission considerations

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Article history:

Received : 7 November 2016
Accepted : 8 April 2017

ABSTRACT

One of the most challenging issues in modern-day building energy management involves equipping the buildings with more energy efficient facilities. In this paper, a hybrid system for cooling/heating for a residential building is developed and optimized. The system consists of a ground source heat pump (GSHP) as well as an electric chiller (EC) and boiler. The model is implemented in MATLAB and optimized using NSGA-II. Two economic and environmental objective functions are considered: Net Present Cost (NPC) and Carbon Emission (CE); which are minimized simultaneously.

The results indicated that when the building load is completely met by GSHP, much less carbon is emitted to the environment, while when the majority of the load is provided by EC and boiler, NPC is lower and CE is much higher.

Keywords: Ground Source Heat Pump, Net Present Cost, Carbon Emission, Genetic Algorithm.

1. Introduction

In the recent decades, the world has faced an increasing need of energy, and since the dominant energy source is fossil fuel resources, greenhouse gases (GHG) emission has also increased. This has led to grave environmental issues threatening the planet. Numerous solutions have been proposed so far to reduce the energy consumption and consequently the GHG emission.

Among all energy consuming sectors, buildings account for a considerable share; for instance, about 40% of total energy in the US and Europe. The majority of building energy consumption is related to air conditioning systems [1]. Therefore, the energy proficiency of the building air conditioning system is very important and can provide a prominent emission reduction. Ground source heat pump (GSHP), is the most energy efficient air conditioning system that can provide cooling and heating, regarding the relatively constant temperature of the earth.

Numerous studies have been conducted to analyze the application and performance of the GSHPs. Zeng et al. [2] proposed a novel method to optimize the capacity and operation of a GSHP-CCHP coupling system using Multi Population Genetic Algorithm (MPGA). Zhou et al. [3] provided a scheme for the hybrid GSHP assisted by a cooling tower to alleviate underground heat accumulation. The research was done using TRNSYS software. Yousefi et al. [4]

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performed an economic and environmental feasibility study of a GSHP for cooling and heating purposes of a greenhouse. The results revealed significant air pollutant emission reduction. Barbieri et al. [5] conducted an optimal sizing of a multi-source energy system to fulfill electric, heating and cooling loads. GSHP is included in the system as well as in other air conditioning systems. Gabrielli and Bottarelli [6] implemented a thorough economic analysis to compare GSHP system with conventional systems. Noorollahi et al. [7] examined the ambient heat transfer of a greenhouse in Iran, equipped with a GSHP system. Huang and Mauerhofer [8] presented a sustainability evaluation method based on Life Cycle Theory and tested this new method by means of a case study on GSHP. Yousefi et al. [9] studied the exchange of GSHP with common systems in the building of a district in Tehran and assessed economic and environmental factors. Desideri et al. [10] carried out a feasibility study of the application of GSHP in a residential building and produced quantitative result using TRNSYS. Garber et al. [11] applied a probability-based approach to evaluate the economic feasibility of a hypothetical full-size GSHP system as compared to four alternative HVAC system configurations. The model was developed in TRNSYS based on real data.
In this paper, an optimization approach is applied to determine the optimal size of GSHP integrated with an electric chiller (EC) and natural gas boiler for a relatively large residential building. NSGA-II is used for the optimization and the codes are implemented in MATLAB.

Nomenclature

Symbols

P	Electrical power (kW)
Q	Thermal power (kW)
η	Efficiency (%)
t	Time step (h)
COP	Coefficient of performance
C	Cost related to the component
K	Single payment present worth factor
CRF	Capital recovery factor
r	Real interest rate (%)
L	Lifetime (years)
NG	Annual natural gas consumption (m^3)
y	Number of replacements
IN	Interest rate (%)
IF	Inflation rate (%)
EF	Emission factor (kg/kWh)
E	Electricity consumed (kW)

Subscripts

b	Boiler
$gshp$	Ground source heat pump
EC	Electric Chiller
nom	Nominal capacity
f	Fuel
c	Cooling load
h	Heating load
$grid$	Grid
cap	Capital cost
rep	Replacement cost
$o\&m$	Operation and maintenance cost
i	Index of components
ng	Natural gas
$bought$	Bought power from grid

Acronyms

NPC	Net Present Cost
CE	Carbon Emission
NSGA-II	Non-dominated Sorting Genetic Algorithm II

2. System Description

As stated previously, the system described here is comprised of a GSHP, EC and boiler. Fig. 1 illustrates the model of the system. As shown in Fig. 1, the role of GSHP is to provide both heating and cooling for the load, while EC and boiler act as cooling and heating sources, respectively. Technical data about the system components are presented in Table 1.

Table 1. Technical data of the system components [12]

COP of GSHP, cooling mode	4.5
COP of GSHP, heating mode	3.5
Boiler efficiency	80
COP of electric chiller	3

The model of the system is applied to a medium-sized residential building in Tehran. The heating/cooling loads of the building is calculated by Hourly Analysis Program (HAP) 4.51 and is depicted in Fig. 2. The

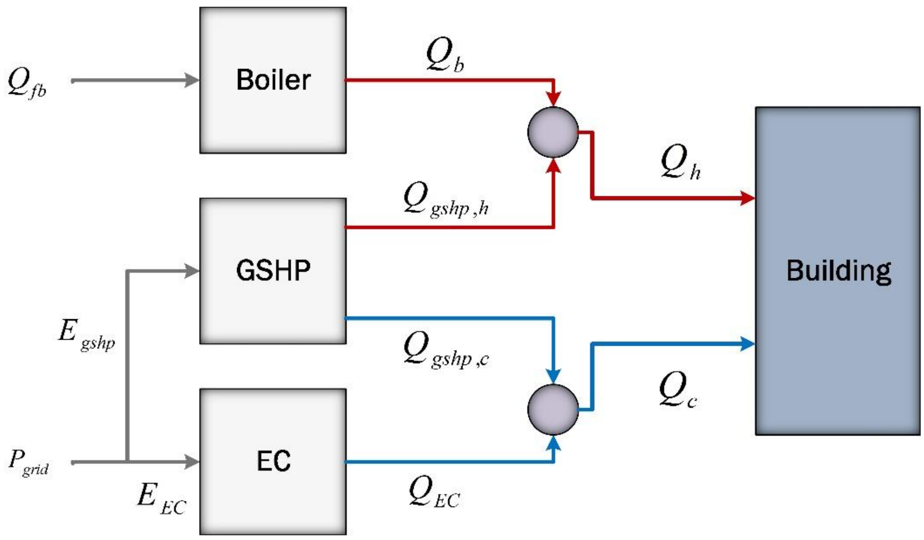

Fig.1. Schematic diagram of the system

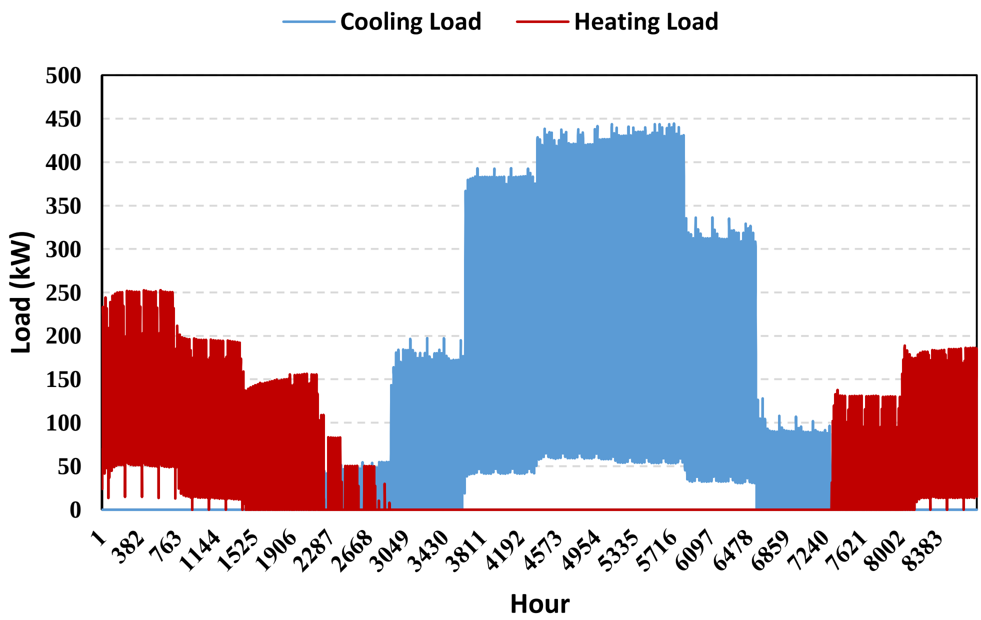

Fig.2. Heating and cooling load of the building

peak loads of heating and cooling is approximately 253 kW and 444 kW, respectively.

3. Mathematical Models

The mathematical model of the system is presented in this section. The model was implemented and run in MATLAB for a whole year with time steps of an hour (8760 hours). Non-dominated Sorting Genetic Algorithm-II (NSGA-II), proposed by Deb et al. [13], was used to solve the problem. Table 2 provides the values of parameters of the algorithm. The goal was to find the best system capacities in order to minimize Net Present Cost (NPC) and Carbon emission of the system.

The decision variable of the problem is the cooling capacity of the GSHP and it changes from 0 to 500 kW. The capacities of the EC and boiler can be found according to the capacity of the GSHP.

3.1. System model

As shown in Fig. 1, the cooling load was provided by GSHP and EC. In this model, it was considered that GSHP comes prior to EC, therefore, in time steps where the GSHP can

Table 2. NSGA-II Characteristics

Population size	30
Number of generations	100
Selection Method	Roulette Wheel
Selection Pressure	8
Crossover percentage (%)	70
Mutation percentage (%)	20
Mutation probability (%)	10

satisfy the load (the cooling load is less than the nominal cooling capacity of GSHP), the EC was turned off:

$$Q_{gshp,c}(t) = Q_c(t) \tag{1}$$

$$Q_{EC}(t) = 0 \tag{2}$$

On the other hand, when the cooling load of the building exceeds the capacity of the GSHP, the EC covers the deficiency:

$$Q_{gshp,c}(t) = Q_{gshp,c}^{nom} \tag{3}$$

$$Q_{EC}(t) = Q_c(t) - Q_{gshp,c}(t) \tag{4}$$

As a whole year of simulation is done, the required capacity for the EC can be obtained as:

$$Q_{EC}^{nom} = \max\{Q_{EC}\} \tag{5}$$

In cooling mode, the electricity consumption of the GSHP is determined as:

$$E_{gshp,c}(t) = \frac{Q_{gshp,c}(t)}{COP_{gshp,c}} \tag{6}$$

For the heating balance of the system, nominal heating capacity of the GSHP is required. This can be found as follows:

$$Q_{gshp,\mathrm{h}}^{nom} = Q_{gshp,\mathrm{c}}^{nom} \times \frac{COP_{gshp,h}}{COP_{gshp,c}} \tag{7}$$

Similar to the cooling mode, in heating mode, it is considered that the GSHP is the main source of heating. Therefore, in cases where the heating capacity of the GSHP is sufficient to meet the load, the boiler will not operate:

$$Q_{gshp,h}(t) = Q_h(t) \tag{8}$$

$$Q_b(t) = 0 \tag{9}$$

If the heating demand is more than the capacity of the GSHP, then the boiler compensates for the deficiency:

$$Q_{gshp,h}(t) = Q_{gshp,h}^{nom} \tag{10}$$

$$Q_b(t) = Q_h(t) - Q_{gshp,h}(t) \tag{11}$$

Hence, the nominal capacity of the boiler can be obtained as follows:

$$Q_b^{nom} = \max\{Q_b\} \tag{12}$$

For heating mode, the electricity consumption of the GSHP can be calculated as:

$$E_{gshp,h}(t) = \frac{Q_{gshp,h}(t)}{COP_{gshp,h}} \tag{13}$$

In this system, the only natural gas consuming component is boiler. The fuel consumption of the boiler can be calculated as follows:

$$Q_{fb}(t) = \frac{Q_b(t)}{\eta_b} \tag{14}$$

Both GSHP and EC consume electricity (Fig.1). Thus, total electricity consumption of the system is the sum of GSHP and EC consumptions. The EC consumption can be found from its operating status. The total GSHP consumption is comprised of both cooling and heating modes. These are stated in Eqs. (15) to (17):

$$P_{grid}(t) = E_{gshp}(t) + E_{EC}(t) \tag{15}$$

$$E_{EC}(t) = \frac{Q_{EC}(t)}{COP_{EC}} \tag{16}$$

$$E_{gshp}(t) = E_{gshp,h}(t) + E_{gshp,c}(t) \tag{17}$$

3.2. Objective functions

Two objective functions are considered to be optimized simultaneously using NSGA-II. The first objective function is an economic NPC index, to be minimized. Here, NPC is comprised of total capital, replacement and operating/maintenance costs as well as the natural gas and electricity charges. Therefore, NPC is defined as:

$$NPC = \sum_i \left[C_{cap,i} + C_{rep,i} \times K_i + C_{o\&m,i} \times \frac{1}{CRF(r,L)} \right] \times P_{nom,i} + \left(C_{ng} \times NG + C_{grid} \times P_{bought} \right) \times \frac{1}{CRF(r,L)} \quad (18)$$

where, NG and P_{bought} are total annual natural gas and electricity consumption in m^3 and kWh, respectively. K_i and $CRF(r, L)$ are single payment present worth factor and capital recovery factor, respectively, and can be calculated as follows [13]:

$$K_i(r, L_i, y_i) = \sum_{n=1}^{y_i} \frac{1}{(1+r)^{nL_i}} \quad (19)$$

$$CRF(r,L) = \frac{r(1+\mathrm{r})^L}{(1+\mathrm{r})^L - 1} \quad (20)$$

where, L_i is the lifetime of component i, y_i is the number of replacements of component i during the project lifetime, and r is the real interest rate and is calculated by:

$$r = \frac{IN - IF}{1 + IF} \quad (21)$$

Economic details of the system are provided in Table 3.

The second objective function is considered as an environmental index and it is the carbon emission (CE) of the system. This is a result of the consumption of natural gas and electricity and is calculated by:

$$CE = EF_{grid} \times \sum_{t=1}^{8760} P_{grid}(t) + EF_{ng} \times \sum_{t=1}^{8760} Q_{fb}(t) \quad (22)$$

EF_{grid} and EF_{ng} are the emission factors of grid electricity and natural gas consumption, and are 0.598 and 0.202 kg/kWh, respectively [14-15].

Table 3. Economic details of the system

Project lifetime (years)	20
Inflation rate (%)	12
Interest rate (%)	20
Grid electricity purchase price ($/kWh)	0.055
Natural gas price ($/m3)	0.043
Capital cost ($/kW)	GSHP= 350 Boiler= 48 EC= 180
Replacement cost ($/kW)	GSHP= 350 Boiler= 48 EC= 180
Operating/maintenance cost ($/kWh)	GSHP= 0.015 Boiler= 0.008 EC= 0.008
Components lifetime (years)	GSHP= 20 Boiler= 20 EC= 10

4. Optimization Results

As the simulation and optimization is accomplished, the results can be assessed. Fig. 3 illustrates the Pareto Front (PF) obtained from the optimization. As shown in Fig. 3, some answers have been repeated. Two answers, shown in blue, are selected at the two ends of the front. In answer 1, most of the load is met by EC and boiler, thus emission is high while having a lower NPC. In answer 2, all of the load is met by the GSHP and no EC and boiler is installed. Here, emission is lower with an increase in NPC. Details of these two answers are presented in Table 4.

From Table 4, it is derived that with an increase of about 19% in NPC value, more than 27% carbon emission can be avoided. In other word, if the GSHP is used for heating/cooling instead of conventional components, about 48.3 tons of CO_2 emission can be avoided.

Figure 4 illustrates monthly electricity consumption of the system for both answers. In the middle of the years, i.e. summer months, when the country consumption is too high, the system with GSHP draws less electricity from the grid than the system with EC and boiler. This is due to better energy conversion performance of GSHP and is clearly an important advantage.

In answer 2, all emission here is due to electricity consumption since there is no natural gas consumption. But in answer 1, emission takes place due to the consumption of both natural gas and electricity. Monthly emission of the system for both answers is depicted in Fig. 5 and 6. Less emission of the GSHP system is clearly shown in Figs. 5 and 6.

5. Conclusion

In this paper, a hybrid system for heating/cooling of a building was optimally sized. The system included a ground source heat pump as well as electric chiller and boiler. Two objective functions, economic and environmental, were considered and NSGA-II was utilized to solve the problem.

The results showed that as the capacity of GSHP increases within the system, lowering the share of EC and boiler, amount of carbon emission decreases considerably while NPC grows. Comparing the answers at the two ends of the range, with a 19% increase in NPC, 27% emission reduction can be accomplished.

The system with GSHP drew much less electricity from the grid in peak months of the year, since the energy conversion performance is better than EC. This would be another merit of the GSHP system.

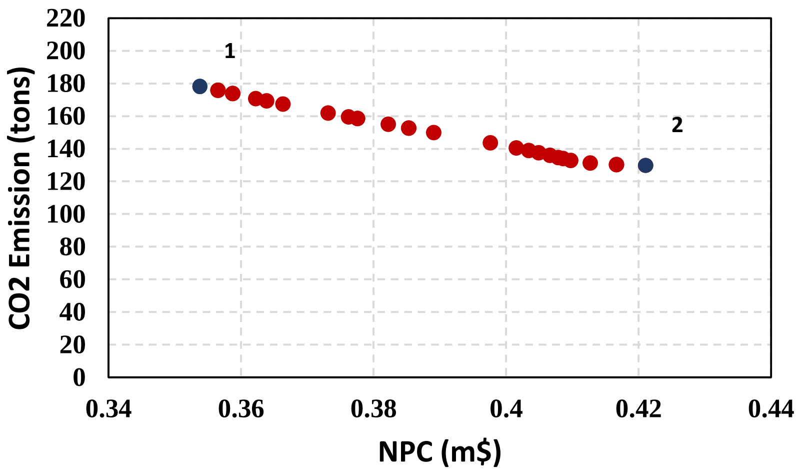

Fig.3. Pareto front of the optimization

Table 4. Details of two answers

	GSHP capacity (kW)	EC capacity (kW)	Boiler capacity (KW)	CE (tons)	NPC (m$)
Answer 1	35	410	225	178.1035	0.3538
Answer 2	445	0	0	129.8075	0.4211

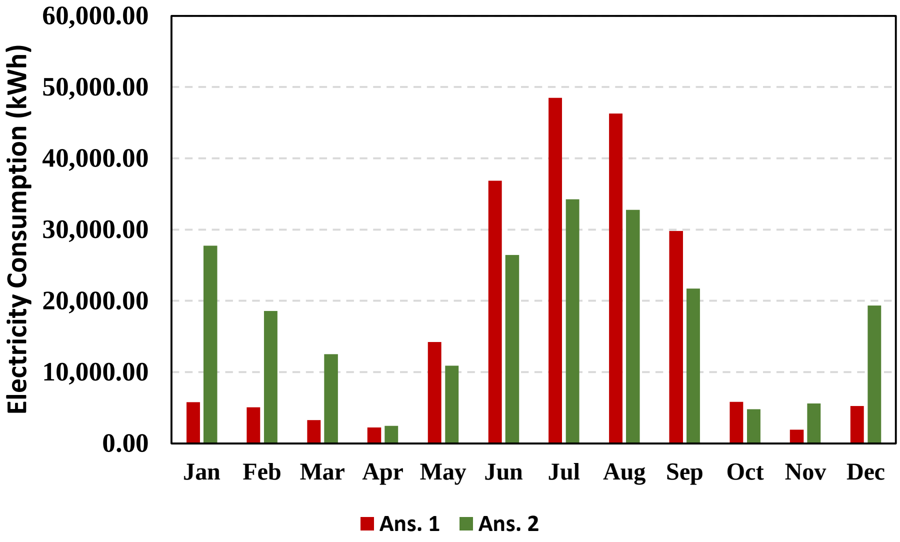

Fig.4. Electricity consumption of two answers

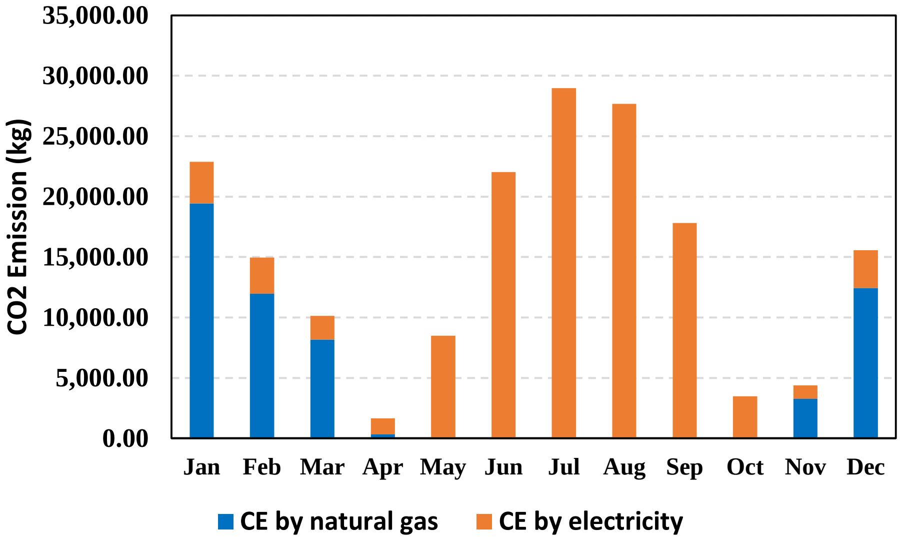

Fig.5. Monthly CO2 emission by source for answer 1

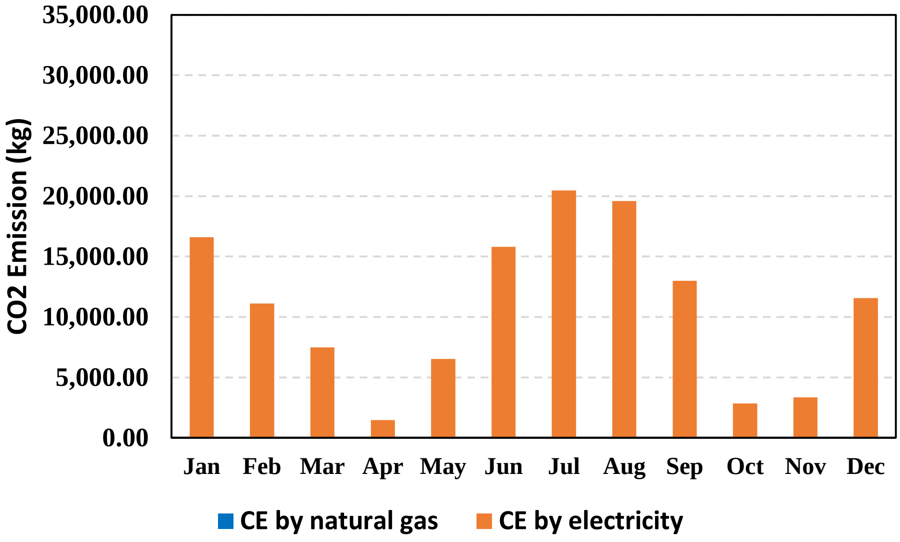

Fig.6. Monthly CO2 emission by source for answer 2

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