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ORIGINAL RESEARCH PAPER

Thermodynamic Analysis of Utilization of Horizontal Geothermal Heat Pump for Optimizing Energy Consumption and Reducing CO2 Emission (Case Study: Shahrood City, Iran)

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ABSTRACT

Today, energy efficiency is one of the global requirements. The purpose of this study is thermodynamic modeling of using a horizontal heat pump system in residential houses in Shahrood climate and to investigate its effect on optimal energy consumption. For this purpose, a heat pump system was designed. Through mathematical functions and modeling equations, the technical, environmental and economic aspects of conventional systems and the proposed model were compared. In order to calculate the hot and cold design loads required in the optimization, Carrier HAP software was used. Initially, a hypothetical residential unit with an area of 96 square meters was designed using Google Sketchup software. The modeling results show that the proposed system (GSHP) is superior to conventional systems in all aspects except one, which is the initial cost of design and construction. So that the reduction of electricity consumption is 11.7% and the reduction of energy consumption is 4.4% and the reduction of carbon dioxide emissions is about 83%. Also, the optimal consumption of heat pump for cooling and heating in Shahrood is 2.8 and 6.3, respectively. Finally, the energy efficiency is 77%. As a result, given the rise in fossil fuel costs, rise in concerns regarding the damages to the environment, and the need of countries for sustainable development, growing tendency to this technology is not far from mind.

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1. Background

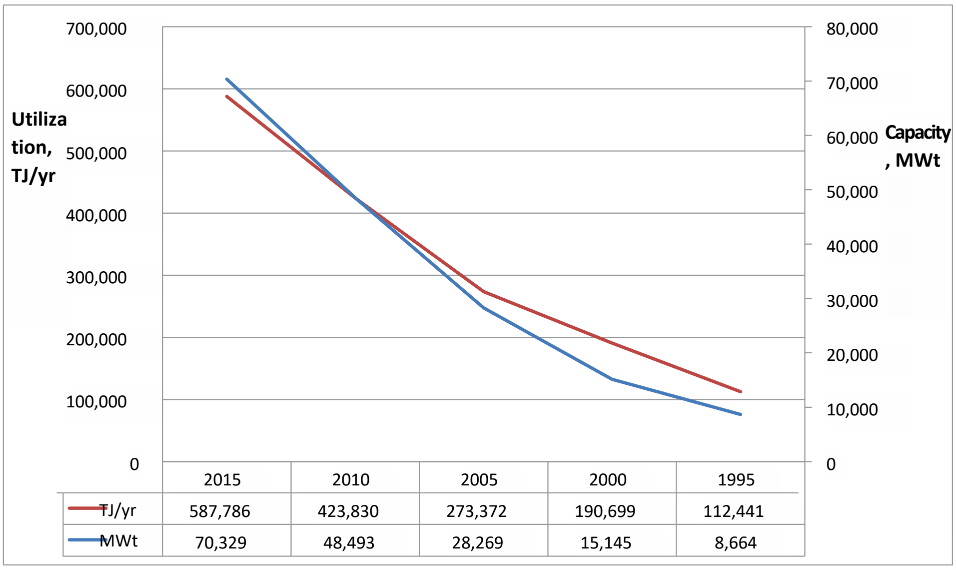
The economic strategy of sustainable development includes efficiency increase and optimal utilization of energy in building, as consumer of a large part of global energy. Buildings have the highest and most cost-efficient potential in energy consumption. Besides, the studies reveal that energy consumption saving is the most efficient method to reduce greenhouse gases (*GHG*) (Sarbu & Sebarchievici, 2014). About 12.5% of oil products, 46% of natural gas, and 46% of electricity of the country are consumed by buildings in residential, public, and commercial sectors which illustrates the need of paying attention to energy consumption in this section (Yazdan et al., 2012). Given the rising energy consumption in Iran and the very high share of energy consumption in Iran's building, energy saving in this field is of uttermost importance. In this regard, some measures have been taken such as requirement to observe the national building regulations.

However, the main step in reducing the energy consumption index to the desired level is using high-efficient cooling and heating technologies (Lund et al., 2015). Geothermal heat pump or ground source heat pump is novel technology that uses the earth heat (not the geothermal fluid) to provide desired condition for covered places. Since the heat pumps do not use the geothermal fluid, so, this method can be used all over the country. The capacity of a geothermal heat pump does not only depend on size, but also it is a function of earth condition, weather conditions, how designing the desired system, annual ratio of heating to cooling performance etc.

Due to their availability, high-efficiency, low cost, and simple design, the ground source heat pumps (GSHP) are among the other types of renewable energies (Liu et al., 2015). Furthermore, it should be noted that utilizing GSHPs for supplying heating and cooling will lead to a 15-77% reduction in CO_2 production (Blum et al., 2015). Geothermal systems have higher installation costs than air conditioning, aeration, and alternate heating systems. However, their repair and maintenance costs are low and its return on capital is lower than other systems. There is no need to replace the components of this system for nearly 20-30 years, and if needed, only the central unit needs to be replaced while its piping system remains intact. The most part of the installing costs of this system is related to digging costs. The air conditioning system of GSHP is very reliable and silent (Egg & Howard, 2010). Despite the advantages of GSHP systems, there are some disadvantages such as high installation cost, need to large land for installation, and lack of public awareness prevent the fast utilization of this technology in buildings (Karytsas & Theodoropoulou, 2014). Now, the energy needed for heating the buildings and supplying the hot water has dedicated nearly 80% of total energy required in the building field; on the other hand, the need for cooling is increasing every year (Sarbu & Sebarchievici, 2014). Direct utilization of geothermal energy is one of the oldest, most common and diverse of energies used for supplying this energy.

While China, USA, Sweden, Turkey, and Germany are respectively the five top countries in direct utilization of geothermal energy (total of 65%), Iran has only a capacity of 0.18%, rank 38, showing the lack of investment and using this type of system comparing with other countries, especially the neighboring country, i.e., Turkey (Luo et al., 2015).

Recent analysis of using this type of energy indicates the growth in usage of this energy globally. The installed capacity for direct using of GHG in the world from 1995 to 2015 is shown in Fig. 1. According to the figure, the installed capacity from 1995 to 2015 has increased from 112 to 588 . Furthermore, Fig. 2 shows the capacity installed by different methods from 1995 to 2015.



	2015	2010	2005	2000	1995
TJ/yr	587,786	423,830	273,372	190,699	112,441
MWt	70,329	48,493	28,269	15,145	8,664

Figure 1. Globally installed capacity of direct utilization of GHG from 1995 to 2015 (Lund et al., 2015)

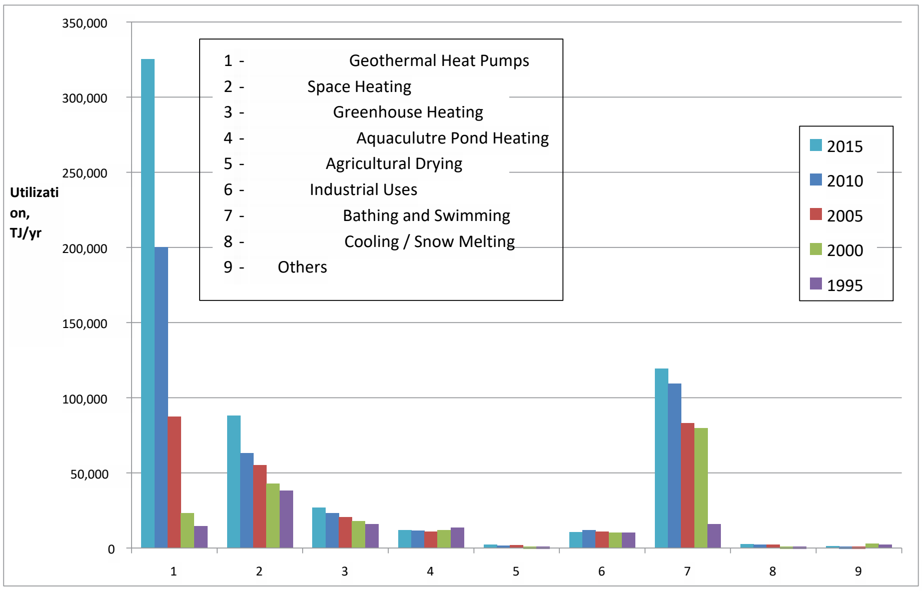


Figure 2. Comparison of direct utilization method of GHG from 1995 to 2015 (Lund et al., 2015)

It can be seen from the figure that utilization of GHG has the maximum growth than the other technologies, so that its capacity has increased to over 320 by the year 2015. The growth in using GHG, compares to other methods, is such that this includes 81% of total installed capacity, and 66% of total amount of direct usage (Soni et al., 2015).

Nearly the half of solar radiation reaching the earth are absorbed by the earth, which causing changes in earth surface temperature in different seasons up to the depth of 15m (Sanaye & Niroomand, 2010). From the depth below than 2, the earth temperature is nearly constant which is equal to the average annual temperature in that environment. With further increase in the depth, there is a constant temperature gradient in the earth (approximately 3 increase per 100). Fig. 3 is depicted to show the temperature variation in low depths in the lower layers of the ground. It can be found from the figure that the earth temperature near depth of 8m is approximately equal to the average earth temperature. Of course, the upper plot varies depending the geographical location, soil type etc.; this is why the efficiency of GSHP varies in different locations (Lapanje et al., 2013).

Based on the report of Oak Ridge National Laboratory, the valid statistical results show that there are 4003 heat pumps installed in Louisiana, US, that reduce the energy consumption by 24 million . This amount is equal to 32% of energy consumption for cooling and heating before installing these units, Therefore, 6445 electricity per a residential unit by installing such systems [16]. According to the report by National Renewable Energy Laboratory, US, the GSHP systems have lowest production and emission of GHG among all conditioning systems (USDOE, 2012).

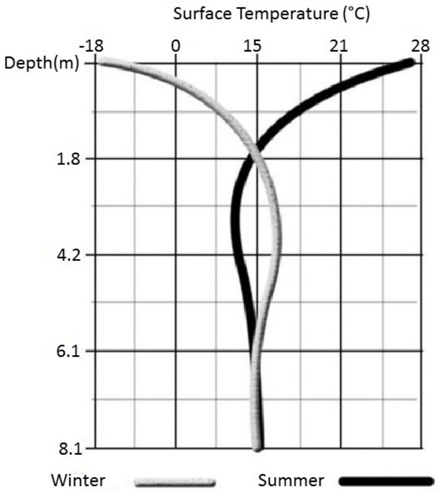


Figure 3. Variation of earth temperature in terms of depth for winter and summer (Lapanje et al., 2013)

The national renewable energy laboratory (NREL) has estimated that the utilization capacity of GSHP will be one million by the year 2050 (Green & Nix, 2013).

The present study aims at performing thermodynamic modeling of utilizing horizontal ground source heat pump systems in the residential buildings and investigating its effect on the optimal energy consumption.

2. Material and methods

To perform the thermodynamic modeling, a ground source heat pump system with following specifications is designed:

- In this system, refrigerant cycle is considered as vapor compression.
- R-22 is used as the refrigerant.
- Condenser and evaporator are considered as double-pipe heat exchangers in which the refrigerant and water flowing in central tube and shell, respectively.
- U-tube, which is made of high density poly ethylene, is considered as the underground heat exchanger.

Figures 4 and 5 represent a view of GSHP system for heating and cooling, respectively.

The temperature-entropy curve of the thermodynamic cycle under study is depicted in Fig. 6. In this figure, the 1-2 process is the refrigerant flow in compressor, 2-3 process is refrigerant flow in condenser, 3-4 process is refrigerant flow in expansion valve, and 4-1 process is refrigerant flow in evaporator. The refrigerant at stage 1 must be super heat to ensure that there are no liquid drops and the compressor is not damaged. The other specifications used for modeling are listed in Table 1.

In the first step, the temperature and pressure at point 1 are used to calculate the entropy at this point. The pressure at point 1 is equal to evaporator pressure and its pressure is equal to the sum of evaporator temperature and super heating temperature, which is equal to 2.

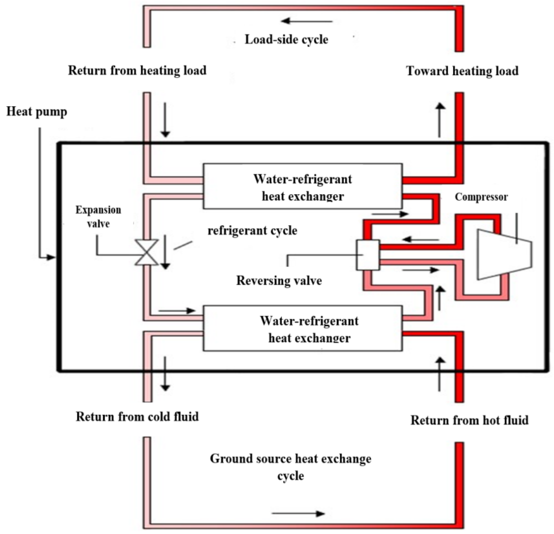


Figure 4. View of GSHP system for heating

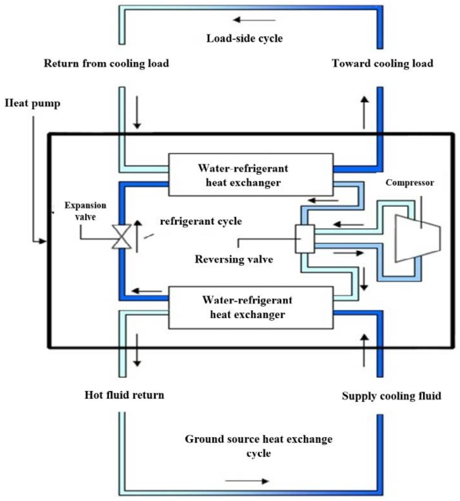


Figure 5. View of GSHP system for cooling

In the second step, by using both the entropy at point 2s, which is equal entropy at point 1, and the pressure at point 2, which is equal to condenser pressure, the enthalpy at point 2s is calculated. Now, by having the enthalpy at points 1 and 2s, as well as the compressor's isentropic efficiency, the enthalpy at point 2 is calculated. Then, by using the enthalpy and pressure at point 2, the entropy at point 2 is obtained.

In the third step, the temperature at point 3, which is condenser temperature minus the subcooling temperature, and the temperature at point 3, which is equal to pressure at point 2 (constant pressure condense process, (Lemmon et al., 2015)), the entropy and enthalpy at point 3 are calculated.

In the last step, since the temperature at point 4 is equal to the evaporator temperature, and enthalpy at point 3 is equal to that of point 3 (isentropic process in expansion valve (Kakac et al., 2012)), the entropy and quality at point 4 are calculated.

- ***Calculating water and refrigerant mass rates***

By using the first law of thermodynamics and by considering the boundary works equal to zero, the refrigerant flow mass rate is calculated by Eqs. (1) and (2) (Liu et al., 2015):

$$\dot{m}_{R,h} = Q_h/(h_{2,h} - h_{3,h}) \tag{1}$$

$$\dot{m}_{R,c} = Q_c/(h_{1,c} - h_{4,c}) \tag{2}$$

Where Q_c (kW) and Q_h (kW) are the heat transfer rate between water and refrigerant in the evaporator and condenser in cooling and heating scenarios, respectively.

To calculate the water flow mass rate, the water properties have been considered at the average temperature of inlet and outlet water at both cooling and heating scenarios. The underground water is passed through evaporator $Q_{w,h} = Q_{Eva,h}$ and condenser $Q_{W,c} = Q_{Con,c}$ in cooling and heating processes, respectively. $Q_{Con,c}$ (kW) and $Q_{Eva,h}$ (kW) are the heat transfer rate between refrigerant and underground water in heating and cooling processes, respectively.

By using the first law of thermodynamics and by considering the boundary works equal to zero, the water flow mass rate is calculated by Eqs. (3) and (4) (Egg & Howard, 2010):

$$\dot{m}_{W,h} = \frac{Q_{Eva,h}}{c_{p,W} \times (T_{W1,h} - T_{W2,h})} \tag{3}$$

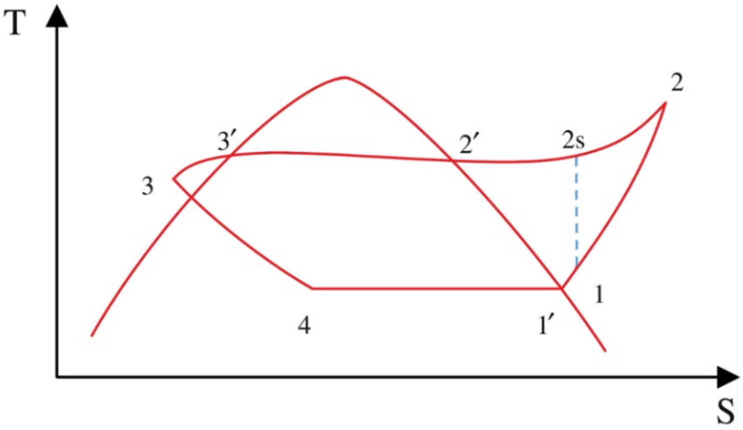


Figure 6. Temperature-entropy curve of thermodynamic cycle of GSHP under study

Table 1. Assumptions and data used in modeling

Parameter	Symbol	Value
Compressor isentropic efficiency	η_s	75%
Compressor electrical efficiency	η_{el}	80%
Pump electrical efficiency	η_{pump}	80%
Pump motor efficiency	η_M	80%
Internal radius of evaporator inner pipe	$D_{I,i,Con}$	0.0318 m
Internal radius of condenser inner pipe	$D_{I,i,Eva}$	0.0318 m
External radius of evaporator inner pipe	$D_{I,o,Con}$	0.0348 m
External radius of condenser inner pipe	$D_{I,o,Eva}$	0.0348 m
Thermal conductivity of evaporator inner pipe	K_{Con}	0.398 $kW/(m\,°C)$
Thermal conductivity of condenser inner pipe	K_{Eva}	0.398 $kW/(m\,°C)$
Thermal conductivity of GSHP pipe	$K_{p,GHX}$	0.3979 $W/(m\,°C)$
Depreciation period	n	20 y
Degradation rate	i	10 %

$$\dot{m}_{W,c} = \frac{Q_{Con,c}}{c_{p,W} \times (T_{W2,c} - T_{W1,c})} \quad (4)$$

- ***Calculating compressor electricity consumption***

By using the first law of thermodynamics and by considering the boundary heat transfer rates equal to zero, the compressor electricity consumption for cooling and heating cases is calculated by Eqs. (5) and (6) (Liu et al., 2015):

$$W_{com,c} = \dot{m}_{R,c} \times \Delta h_{Com,c} = \dot{m}_{R,c} \times \frac{h_{2,c} - h_{1,c}}{\eta_{el,c}} \quad (5)$$

$$W_{com,h} = \dot{m}_{R,h} \times \Delta h_{Com,h} = \dot{m}_{R,h} \times \frac{h_{2,h} - h_{1,h}}{\eta_{el,h}} \quad (6)$$

Finally, the following equation is used to select the compressor.

$$W_{Com} = Max\{W_{Com,c}, W_{com,h}\} \quad (7)$$

Since the maximum operational capacity is used for system in designing the cycle.

The heat transfer rate is calculated by Eq. (8), because the total heat transfer coefficient is equal to the ratio of unity to the total resistance (Yazdan et al., 2012).

$$Q_{GHX} = \frac{\Delta T}{R_{Total}} = \frac{|T_s - (T_{W1} + T_{W2})/2|}{R_w + R_p + R_s} \quad (8)$$

So, to calculate the length of underground heat exchanger in both cooling and heating cases, Eqs. (9) and (10) are used. Finally, the maximum calculated length is considered as the desired length.

$$L_{GHX,h} = \frac{Q_{Eva,h}}{T_s - \bar{T}_{W,h}} \left(\frac{1}{2h_{W,GHX,h}\pi D_{i,GHX}} + \frac{ln(D_{o,GHX}/D_{i,GHX})}{4\pi K_{p,GHX}} + \frac{1}{2U_s\pi D_{o,GHX}}\right) \quad (9)$$

$$L_{GHX,c} = \frac{Q_{Con,c}}{\bar{T}_{W,c} - T_s} \left(\frac{1}{2h_{W,GHX,c}\pi D_{i,GHX}} + \frac{ln(D_{o,GHX}/D_{i,GHX})}{4\pi K_{p,GHX}} + \frac{1}{2U_s\pi D_{o,GHX}}\right) \quad (10)$$

- ***Calculating pump electricity consumption***

The head needed for pump is equal to the length of underground pump plus 50% additional length for losses in the heat pump, joints, and pressure (Zhao et al., 2003). Then, the pump power is calculated for cooling and heating conditions from Eqs. (11) and (12), respectively. Finally, the maximum power calculated for cooling and heating from Eq. (13) is considered for design (Zhao et al., 2003).

$$W_{Pump,h} = \dot{m}_{W,h} \times H_{Pimp,h}/(\rho_{W,h} \times \eta_{Pump,h}) \quad (11)$$

$$W_{Pump,c} = \dot{m}_{W,c} \times H_{Pimp,c}/(\rho_{W,c} \times \eta_{Pump,c}) \quad (12)$$

$$W_{Pump} = Max\{W_{Pump,h}, W_{Pump,c}\} \quad (13)$$

The Carrier HAP software has been used to calculate cooling and heating design loads required for optimization. To this end, a unit of desired building was designed by Google Sketchup software. In this design, it has been tried to obey all national building regulations. A particular attention has been paid to article 19 of the national building codes. In following, the weather data of Shahrood city are provided using the default plot in Carrier HAP at the desired heating and cooling degree hours.

Designed unit has an area of 96 m^2 (). Besides, the calculations for single-, two-, and four-storey building have been included to consider different types of buildings, and the average value of loads for every unit has been used in design. According to Figure 7, the unit design under study has two 12 m standard bedrooms (1&2), a balcony (3), a bathroom (4), a kitchen (5), a living room (6), and a WC (7). The properties of materials used in the building are tabulated in Table 2.

The research flowchart is shown in Figure 8.

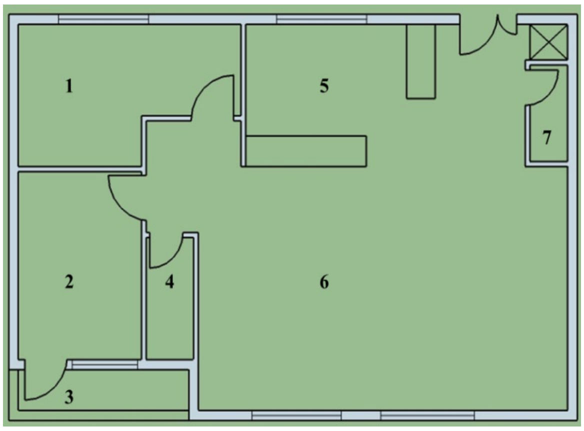


Figure 7. Design of residential unit under study

Table 2. Assumptions and data used in modeling

Case	Diameter (m)	Overall heat transfer coefficient (W/m^2.K)
External wall	0.279	1.789
Internal wall	0.127	2.315
External roof	0.345	0.322
Internal roof	0.330	0.337
Double-glazed glass	-	3.237
External door	0.130	3.925
Internal door	0.100	3.975

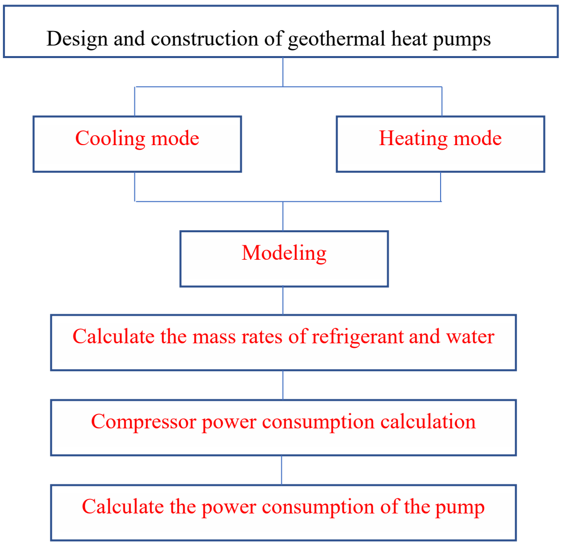


Figure 8. Research flowchart

3. Results

- ***Calculating load and operational hours***

In the first step, all spaces required for cooling and heating in the design, such as rooms, living room, and kitchen, is designed in Carrier HAP software. According to the article 19 of the national building codes, all double-glazed windows, external walls, and roof are selected to be sealed. A GSHP system was selected in the software. For further information one can refer to design file provided in the appendix.

For the summer design dry and wet bulb temperature, summer daily range, and winter design dry and wet bulb temperature, the calculated data for Shahrood city was used, and the required load of the GHSP system for the city was determined.

The annual cooling and heating operating hours are calculated as follows: the hours in which the air temperature is higher than the comfort temperature are added to the annual cooling operating hours; on the other hand, the hours in which the air temperature is less than the comfort temperature are added to the annual heating operating hours. According to the ASHRAE standard, the comfort temperature for cooling and heating is 27.8 and 19.4, respectively.

By a change in cooling values and one time by changing the heating values, the optimal annual costs values were calculated, that are respectively shown in Figs. 8 and 9. For every plot, the line equation is also calculated.

It can be seen that both plots have the same Y-intercept, while the slope of cooling design thermal load is steeper than that of heating; as a result, its total annual cost is higher than that of heating by . In fact, the same Y-interception of both plots is logical since there are the same independent costs of design thermal in both plots.

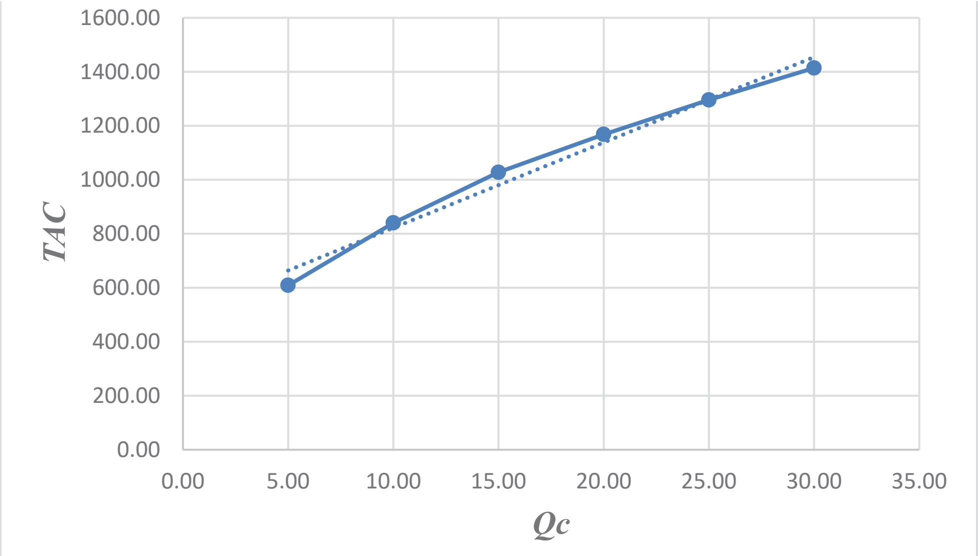


Figure 9. Annual optimal costs value in terms of cooling design thermal load $TAC=32.24\times Q_c+448$

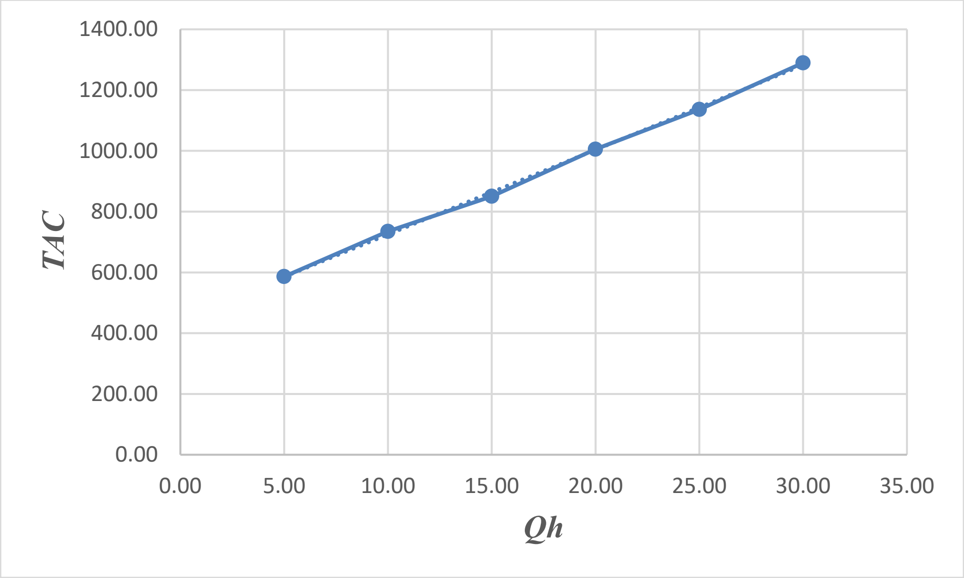


Figure 10. Annual optimal costs value in terms of heating design thermal load TAC=28.12×Q_h+445

The annual thermal load needed for Shahrood city in cooling (Q_c) and heating (Q_h) cases are shown in Table 3. As shown in the diagram, GSHP in all cases has a significant advantage over Common systems It is weaker in only one case, and that is the initial cost of design and construction. But since this cost is reimbursable in later years, it can be considered justifiable.

Table 3. Software outputs for optimal consumption of GSHP for Shahrood city

City	SDB	WDB	T_{Air}	T_S	t_c	t_h	t_{oc}	Q_c	Q_h
Shahrood	29.4	0.6	16.94	12.0	90.0	2850.0	36.5	2.8	6.3

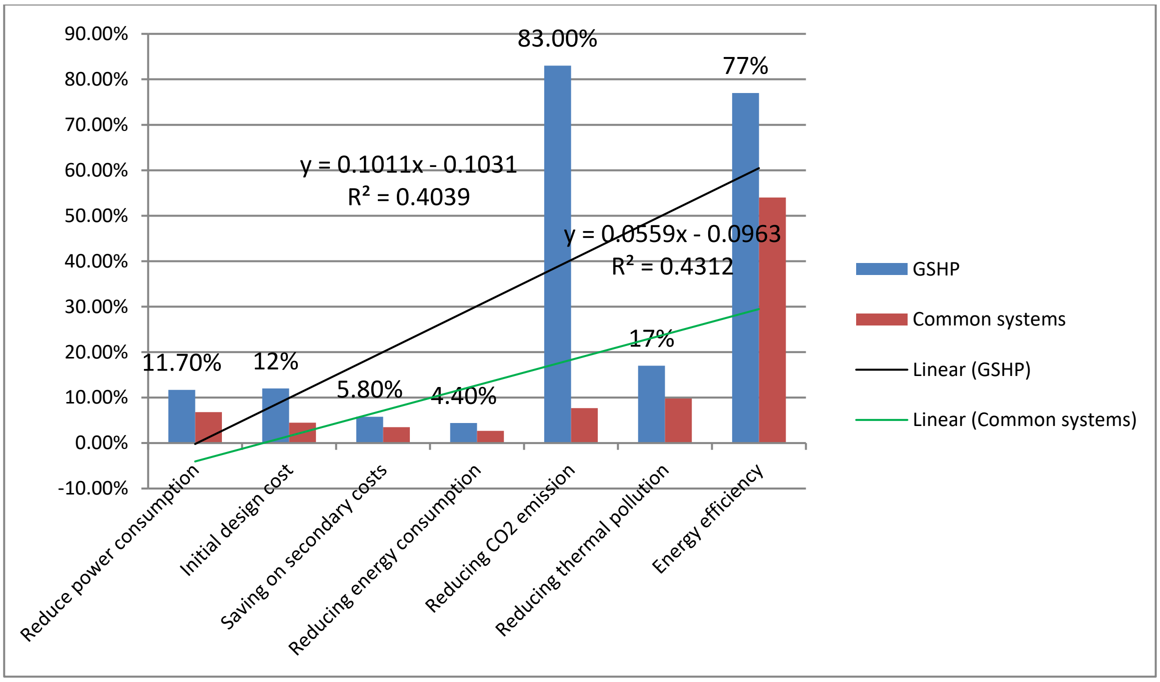


Figure 11. Comparison of technical aspects and costs of the two systems GSHP and Common systems

4. Conclusion

As it is clear from the results, utilizing horizontal GSHP can considerably reduce the consumption costs, and on the other hand, reduces the air pollutants emission. High installation cost is one of the most challenges for wide use of this system. So, in developing countries it is tried to overcome this problem by offering some discounts in electricity consumption costs or dedicating the subside. Daily increase desire to utilize shallow geothermal energy highlights the need for better knowledge about the factors affecting the efficiency of this system. Given that the increasing price of fossil fuels will encourage utilization of renewable energies, which is totally valid abut GSHP systems. The results of research in the study area showed that the use of GSHP system consumes 11.7% less energy than conventional energy systems in buildings. Also, interior design costs will be reduced by 12% and secondary costs will be saved by 5.80%. But its most important advantage is to reduce CO2 emissions by 83%, and ultimately the efficiency of this system compared to current systems is 77% vs. 54%.

The rise in fossil fuel costs, rise in concerns regarding the damages to the environment, and the need of countries for sustainable development, growing tendency to this technology is not far from mind. In fact, it is necessary to investigate the thermal characteristics of the earth such as heat transfer rate and other environmental properties to design optimal GSHP. Besides, the initial system costs include digging and piping depends on geological conditions and groundwater quality.

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