PROCEEDINGS, 42nd Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 13-15, 2017
SGP-TR-212

Economic and Thermodynamic Evaluations of Using Geothermal Heat Pumps in Different Climate Zone (Case Study: Iran)

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Keywords: *Geothermal Heat Pump, Climate zone, Economical analysis*

Abstract

Increasing in energy demand has led countries to find the most efficient way for supplying energy. According to many negative environmental impact of fossil fuels and of course the problem of diminishing, the idea of replacing renewables become more important among developing countries. Iran is one of the developing countries which has a high potential of renewable energies. Indeed, it has used a variety of renewables for the purpose of decreasing fossil fuels share. Geothermal energy is kind of renewables which are not widely used in Iran. It is mainly for this reason that, the feasibility and economic assessments have not truly considered in order to find best area around the country. In this study, we focused on geothermal heat pumps particularly. So, economic and thermodynamic analysis have been conducted in order to determine the best region based on three climate zone in Iran (high, low, and medium temperature). Regarding this circumstances, we analyzed 3 cities (Bushehr, Sarab, and Yazd) of these different regions and applied exergy and economic evaluations. Therefore, the second law efficiency calculated for the mentioned cities to compare the GSHP efficiency in different climates. As a result, the coldest city (Sarab) indicates the highest efficiency (around 1). Relating the economic analysis, the RETScreen software was chosen. Seemingly, it is clear cut that the cold region has the lowest payback time (3.5 years). Concequently, the cold region is the best location to implement geothermal heat pump as a replacement of fossil fuels.

1. INTRODUCTION

Increasing in energy demand and rising concern about fossil fuels limitation are compelling countries all over the world to deploy policies for adjustment of energy consumption structure. Moreover, greenhouse gasses (GHG) emitted from fossil fuels have become one of the most prominent world's problem in recent years. Therefore, many countries attempt to replace a kind of new source which can outweigh these drawbacks. Renewable energy development not only facilitates to decreasing environmental impacts and energy crisis but also promotes economic aspects [1]–[3]. While, a half percentage of installed renewable energy in the world is regarding residential, commercial and public purposes by 2012 [4]. Geothermal energy is one of those resources which has the high potential of using in order to decrease dependent on fossil fuels. Geothermal energy is the heat from the Earth. Resources of geothermal energy range from the shallow ground to hot water and hot rock found a few miles beneath the Earth's surface, and down even deeper to the extremely high temperatures of molten rock called magma [5]. Heat pumps are kind of technologies for the direct use of geothermal.

Geothermal heat pump systems consist of basically three parts: the ground heat exchanger, the heat pump unit, and the air delivery system [6]. The heat exchanger is basically a system of pipes called a loop, which is buried in the shallow ground near the building. A fluid (usually water or a mixture of water and antifreeze) circulates through the pipes to absorb or relinquish heat within the ground. Currently, ground source heat pump (GSHP) system is widely used for heating, cooling and supplying hot water demand of commercial and residential buildings [7] and [8], [9].The GSHP has many advantages such as reduction of electricity consumption, low cost of maintenance and the ability to reduce greenhouse gas emissions [10]. At present, energy demand is fulfilled by fossil fuels, but the future is dependent on sustainable energy technologies. Thereby contribute to emission reduction as well. In this direction, one of the promising technologies that can be used for space heating and cooling processes is ground source heat pump (GSHP) technology.

This technology is well developed in European countries, USA and Canada for space heating applications [11]. The majority of these systems are installed in North America (USA, Canada) and in Europe [12]. In Asia [13]–[15], China is the leading country in implementing the GSHP technology with the capacity to meet 20 million square meters of building area [16]–[20].

Iran's recent economic growth has increased the country's energy demand and most of its energy demands are met through fossil fuel. Considering Iran's statistics, geothermal resources as space heating and cooling applications for buildings has become popular in recent years [10]. An economic study carried out by Yousefi et al. [21] developed the use of GSHP in Tehran, Iran. The financial analysis shows that this source of energy is highly beneficial with the payback time of less than 2 years.

The present study identifies the impact of economic and thermodynamic parameters on GSHP installation considering the different climate in Iran. To shed more light on this issue, 3 cities were collected as the climate indicators separated by low, high, and medium temperature (Sarab, Bushehr, and Yazd respectively). Regarding the thermodynamic factor, the exergy analysis is applied due to finding the second law efficiency in each selected city. Then, the economic analysis developed using RETScreen software for financial parameters and the HAP Carrier 4.51 for the heating/cooling demand simulation.

2. MATERIALS AND METHODS

2.1. Iran status

Iran is one of the developing countries which consume high energy. According to International energy agency in 2014, the total final energy consumption calculated as 181124 Ktoe in Iran. In this regard, residential sector dominates the highest consumption (27.4%). On the other hand, the maximum energy consumption emerges from Industry sector in developed countries all around the world. Figure 1 shows Iran energy consumption by sectors. Due to this high energy consumption and diversification of renewable resources in Iran, the idea of using renewable energy become more popular [4]. Geothermal energy in particular heat pumps is kind of technology with high initial costs. Therefore, technical and economic assessments should be first developed in order to achieve more efficient energy source. Economic benefits are hinged on feasibility analysis whilst location climate can individually affect this target.

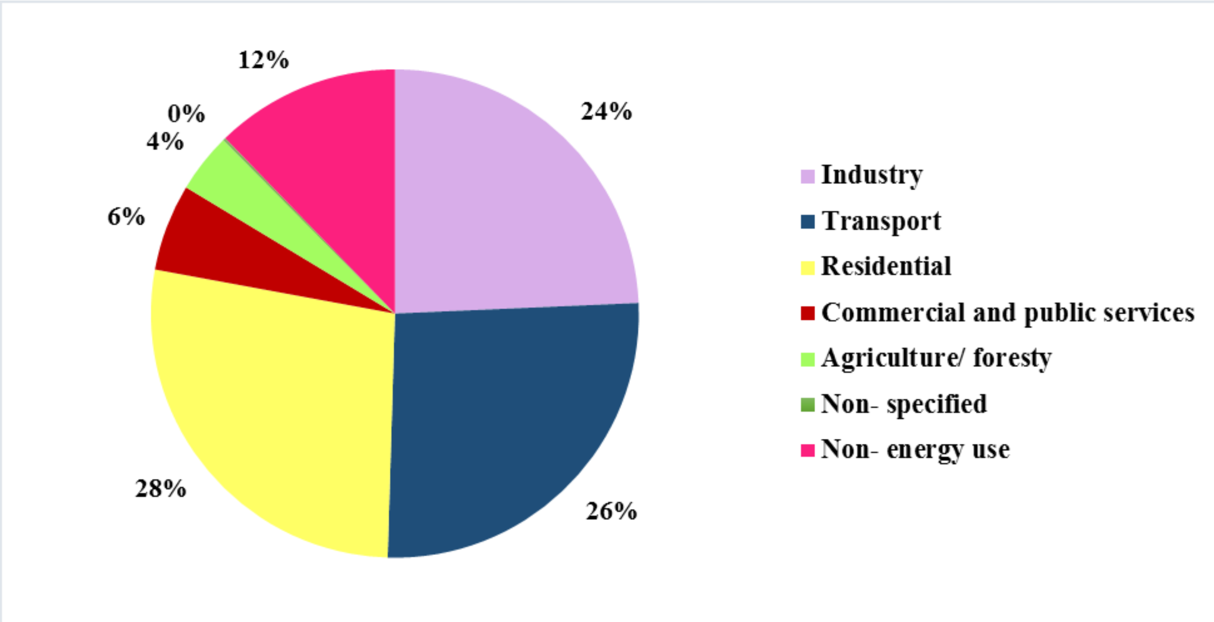


Figure 1. Iran energy consumption by sectors in 2014 [4]

As regards the situation, Iran is located in the continent of Asia and surrounded by 7 countries such as Iraq, Armenia, Azerbaijan, Turkmenistan, Afghanistan, Pakistan, and Turkey. Iran's climate is divided into 8 regions which illustrate in Figure 2. The warm and arid zones are known as long hot summers and short cool winters which mostly influenced by the Arabian Desert.

In this study, 3 climate zones (high, medium, and low temperature) were assumed in the whole country which is on the basis of temperature change. To elaborate more on this issue, high-temperature regions represents the dry and warm areas distributed in the southern part. Thus, low temperature located mostly in the north area of the country with cold weather, and medium are kind of tropical climate concentrated in the central area of the map. Three cities are chosen as the case study consist of Bushehr, Yazd, and Sarab as the high, medium, and low temperature respectively. Therefore, the impact of climate on the economic and technical aspects of GSHPs are analyzed.

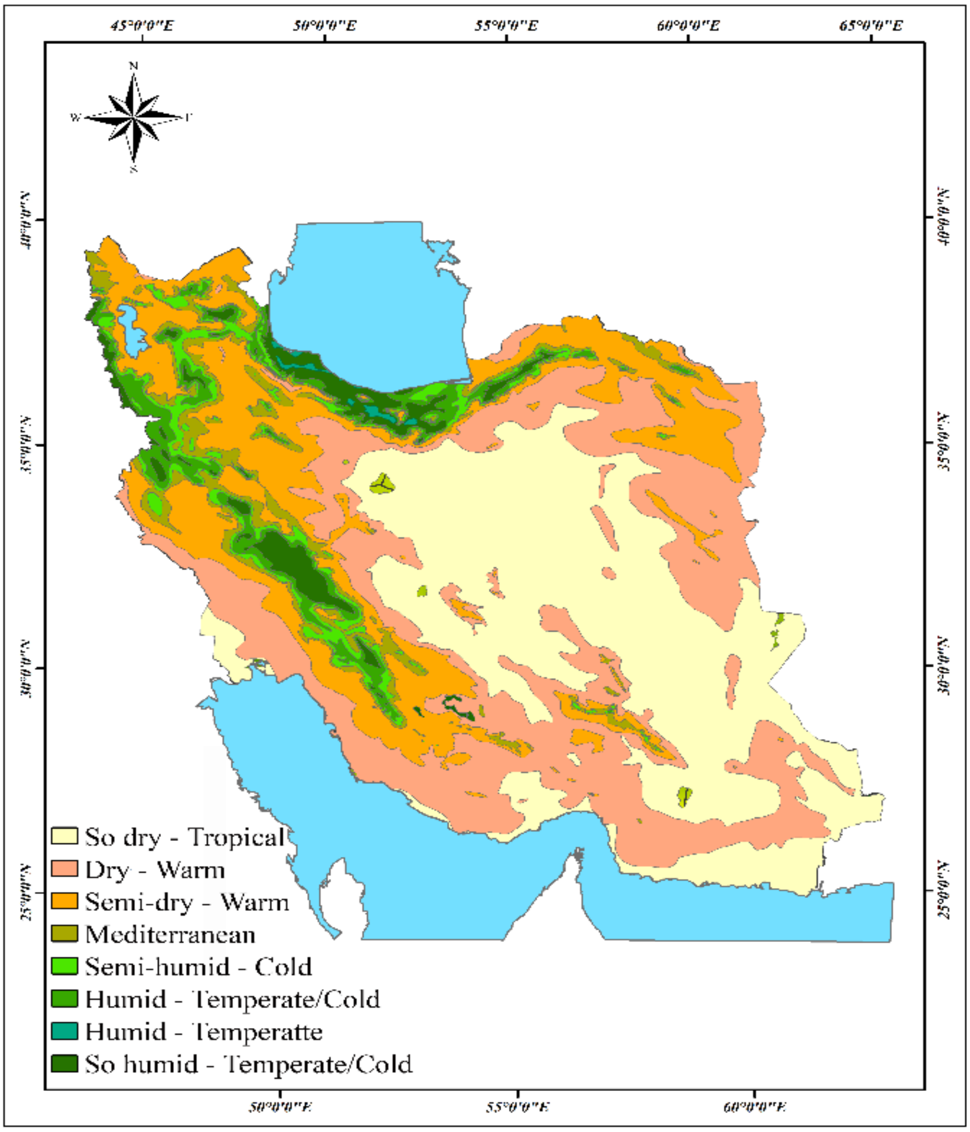


Figure 2. Iran's climatic map [22]

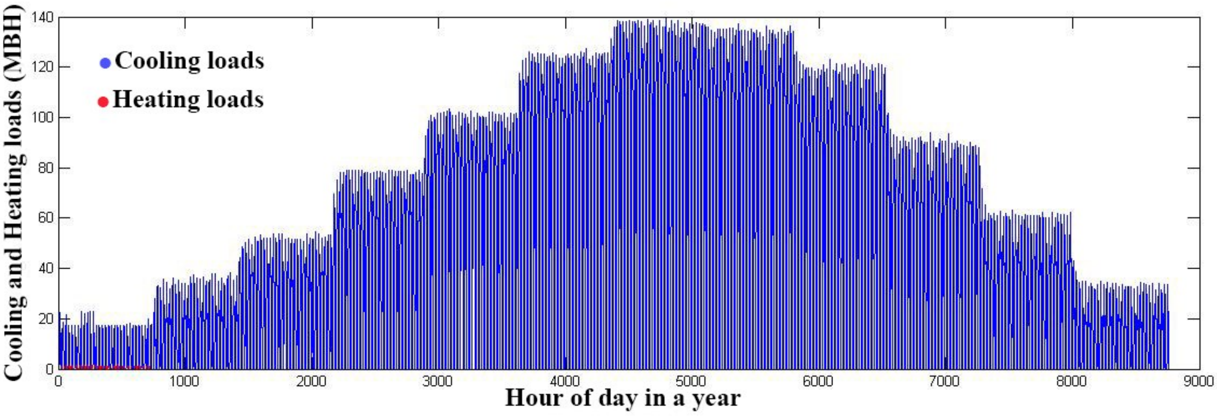
2.2. GSHPs in buildings

In order to reduce the dependent on fossil fuels in residential sector coincide with the energy consumption reduction, utilizing renewable energies is the best solution. Geothermal energy is commonly used as heat pumps in case of supplying heating and cooling demand for the residential sector. Importantly, the effect of region conditions and financial factors should be considered.

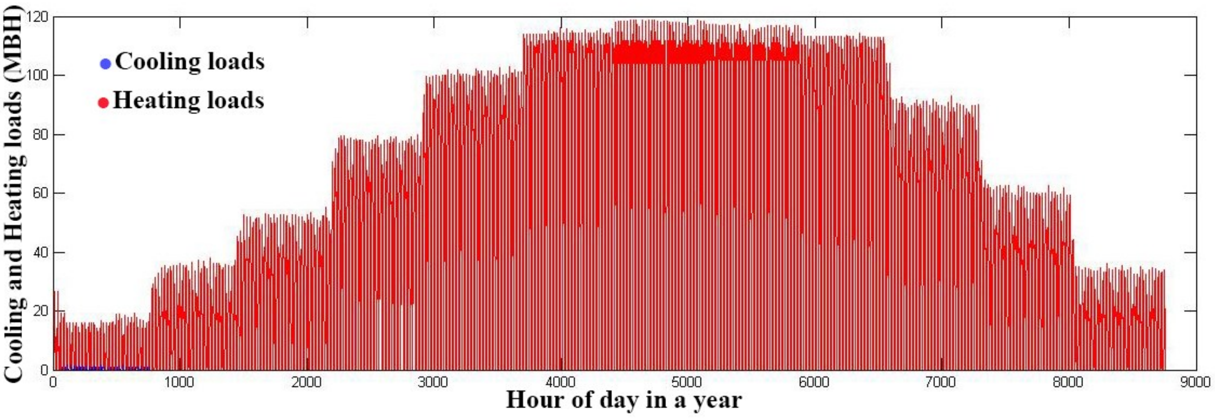
In this work, first of all, we considered a typical building with total area of 900 m^2 in order to estimate heating and cooling loads in the mentioned case studies. The assumed apartment is comprised of 4 floors equipped with a vertical GSHP as the proposed case replacement using four wells, non-glazing windows with 10 cm thickness, and 20 cm thickness for external walls.

Hourly heating/cooling loads are simulated using HAP Carrier 4.51software for the mentioned building considering the split and fan coil systems as the base case. Regarding the base case in Iran, it is clear cut that the heating demand is supplied from natural gas and the cooling demand consume electricity.

Figure 3 is illustrated the simulated hourly loads for the mentioned case studies. As it is demonstrated clearly by the Figure 4, the high temperature (Bushehr) city have considerable cooling loads with approximately zero heating loads whilst it is opposite for the low-temperature city (Sarab).



(a)



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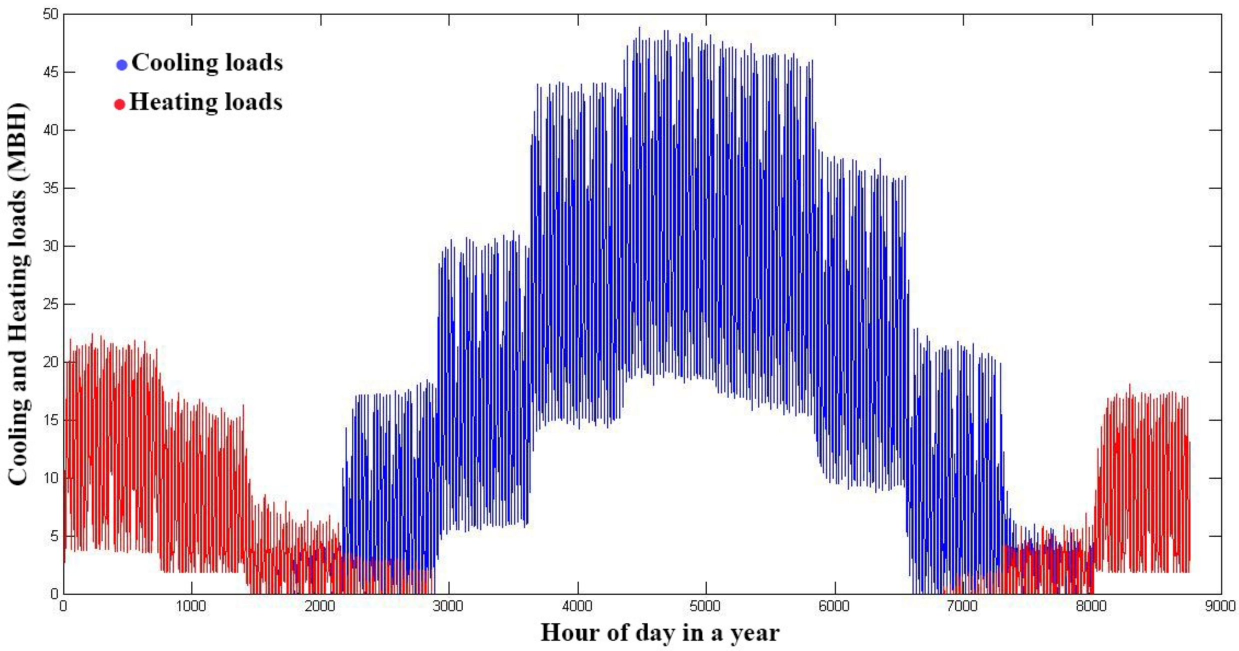

(c)

Figure 3. Simulated hourly loads for a) Bushehr b) Sarab c) Yazd

2.3. Heating and cooling cycles

Regarding the heating cycle, the ground hot water contributes to the refrigerant's boiling by using the evaporator and it turns into the low-temperature vapor. The vapor then leads to the compressor by the reversible valve. Afterward, the vapor compresses and headed to volume reduction, thus the temperature increases. Another reversible valve is for transferring the hot gas to the condenser. Then, the temperature reduces and finally, the pressure and temperature fall down in the throttling valve. Hence, the refrigerant enters the heat exchanger once again to begin the cycle (figure 4, a).

As regards the cooling cycle, it is going to operate an opposite cycle. The refrigerant releases heat to the water which flows into the ground. Then, it gets cold and leading to decrease the environment temperature in summer (figure 4, b).

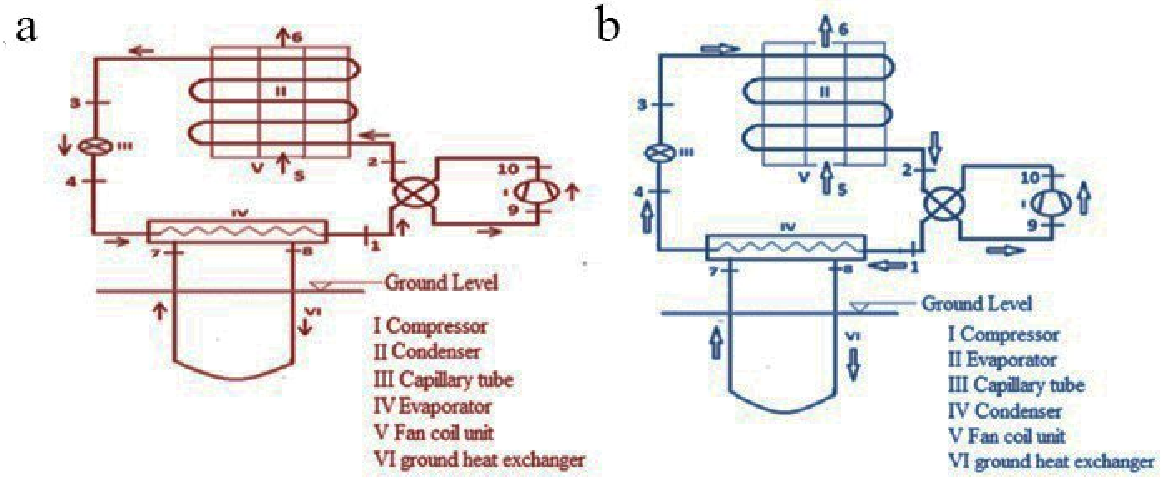

Figure 4. a) GSHP heating cycle b) GSHP cooling cycle [23]

3. EXERGY ANALYSIS

In order to find system efficiency and determine the best climate for installing GSHP, exergy analysis is conducted [24]. To be precise, exergy analysis is a relatively new method that assesses thermodynamic performance of different systems from the perspective of the second law of thermodynamics. The exergy methodology of this significance is due to the fact that economic approaches can be considered besides the thermodynamic and also the optimization will obtain. In recent years, a substantial increase in the use of the second law analysis and the design of energy systems occurred. This is mainly for this reason that the first law of thermodynamics focus on the system energy balance while the second law offers more appropriate aspect to evaluate the system performance. Furthermore, this type of analysis can identify the main source of irreversibility and entropy production cuts in various processes. According to Dincer and Rosen [25], exergy analysis is a method to use both mass and energy equations with second law approach.

In fact, exergy is the maximum attainable useful work which can be obtained from a system or a flow. This useful work is maximum if only the reversible process is assumed. Furthermore, exergy is neither a thermodynamic property nor the thermodynamic potential of the system. In this study, the control volume (C.V) is considered assuming a border as it is shown in figure 5. Regarding this assumption, the equipment settled in the border are negligible and water flow streams are the only flows (inlet/outlet) of the C.V.

Generally, the exergy balance is as the equation 1:

$$\underbrace{X_{in} - X_{out}}_{\substack{\text{Net exergy transfer} \\ \text{heat,work,mass}}} - \underbrace{X_{des}}_{\substack{\text{Exergy} \\ \text{destruction}}} = \underbrace{\Delta X}_{\substack{\text{Change} \\ \text{in exergy}}} \tag{1}$$

Where for an open system is:

$$X_{heat} - X_{work} + X_{mass,in} - X_{mass,out} - X_{destroyed} = (X_2 - X_1)_{CV} \tag{2}$$

Or

$$\sum Q_k \left(1 - \frac{T_0}{T_k}\right) - W - P_0(V_2 - V_1) + \sum m_{in}\psi_{in} - \sum m_{out}\psi_{out} - X_{des} = \Delta X \tag{3}$$

Assuming that the kinetic and potential energy are negligible:

$$\psi_2 = (h - h_0) - T_0(s - s_0) \quad (4)$$

Where W is the work rate, Q_k is the amount of heat transferred to the boundary calculated in the temperature of T_k, h is enthalpy, s is entropy, V represents system volume, Ψ is the exergy of flow, and the zero subscript represents the dead state for T_0 and P_0 condition.

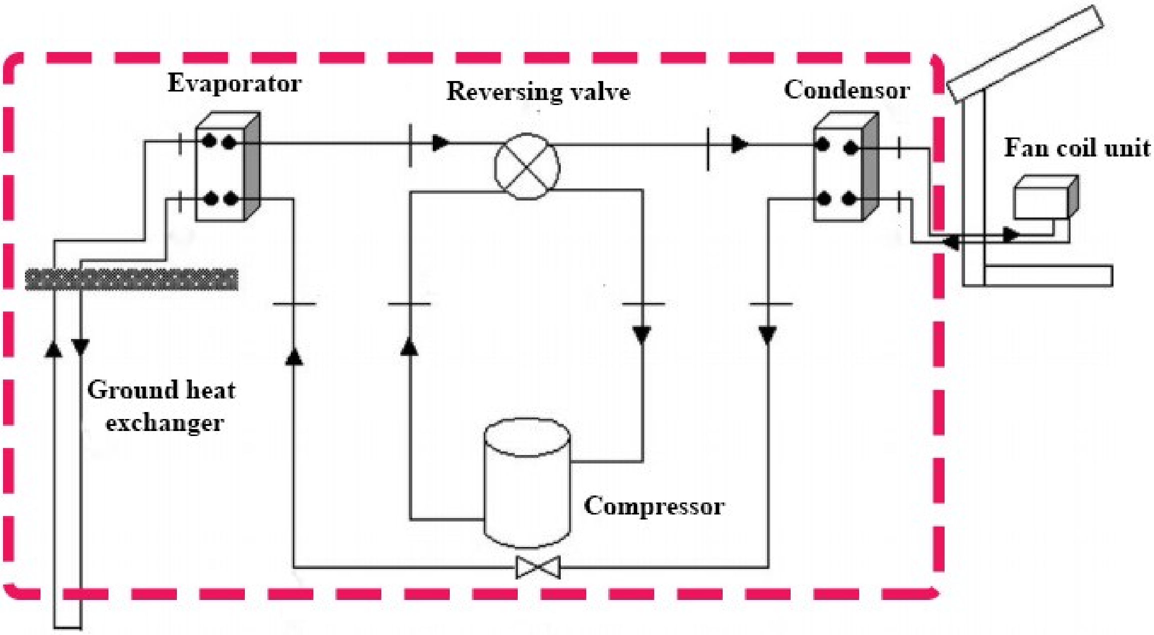

Figure 5. the assumed schematic of the system [26]

Another useful equation is the second low efficiency which is defined as the approximate measurement of reversible performance for a system. Thus, the amount of second law efficiency limited to a range of zero (completely exergy destruction) to 1 (no exergy destruction). Hence, the first step to obtain second law efficiency is to determine the exergy analysis or used work potential. In this regard, second law efficiency is calculated as the equation bellow:

$$\eta_{II} = \frac{\text{Exergy recovered}}{\text{Exergy expended}} = 1 - \frac{\text{Exergy destroyed}}{\text{Exergy expended}} \quad (5)$$

In this study, exergy analysis of a GSHP system installed in Sarab, Bushehr, and Yazd is calculated. To be exact, a control volume is considered as illustrated in figure 6.

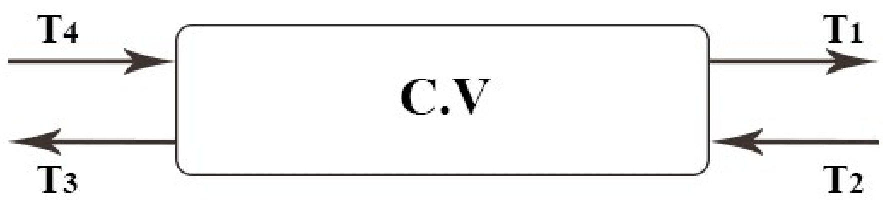

Figure 6. The assumed control volume

According to the assumptions, the temperature of water flows in the ground coil is the same as soil temperature. Further, the control volume in considered as an individual heat exchanger which the inlet water temperature is equal to the environment weather. Therefore, the second law efficiency is obtained using equation 6.

$$\eta_{II} = \frac{m_{cold}(\psi_4 - \psi_2)}{m_{hot}(\psi_3 - \psi_1)} \quad (6)$$

Accordingly, as it is shown in table 1, the efficiency for the coldest city is calculated due to the heating demand in January. On the other hand, for the warm city, it is calculated for the cooling purpose on August. Also, for the city with medium temperature, Yazd the efficiency is obtained during 1987 to [27]. The results for the three cities are shown for the mentioned month in table1.

Table 1. Second law efficiency results for the case study during 1987-2014

Year	η (Sarab)	η (Bushehr)	η (Yazd)
1987	0.4158	0.0217	0.206
1988	0.3329	0.0209	0.1689
1989	0.2635	0.0447	0.1682
1990	0.3415	0.0303	0.1602
1991	0.3783	0.0582	0.192
1992	1.0683	0.071	0.2009
1993	0.378	0.0507	0.1769
1994	0.3817	0.0627	0.191
1995	0.4576	0.0703	0.2125
1996	0.3877	0.0746	0.1739
1997	0.3913	0.0936	0.1941
1998	0.3166	0.0092	0.1673
1999	0.4115	0.0072	0.16
2000	0.3954	0.0484	0.1717
2001	0.3662	0.0258	0.1382
2002	0.3969	0.1773	0.1599
2003	0.3911	0.0227	0.1663
2004	0.467	0.0488	0.1736
2005	0.3147	0.0494	0.157
2006	0.3482	0.0374	0.1462
2007	0.3444	0.0199	0.158
2008	0.2904	0.0396	0.1175
2009	0.3753	0.0306	0.1543
2010	0.4502	-0.0229	0.1719
2011	0.3757	0.0392	0.157
2012	0.3906	0.0166	0.1812
2013	0.437	0.0416	0.1651
2014	0.3375	0.0083	0.1502

Results are shown and compared in figure 7. It is clear cut that second law efficiency has the maximum amount in the low-temperature city (Sarab). Seemingly, GSHP technology is highly influenced by climate regarding the thermodynamics analysis.

Afterward, the city with medium temperature has the acceptable efficiency while in the high-temperature city (Bushehr), it is comprised of low amounts.

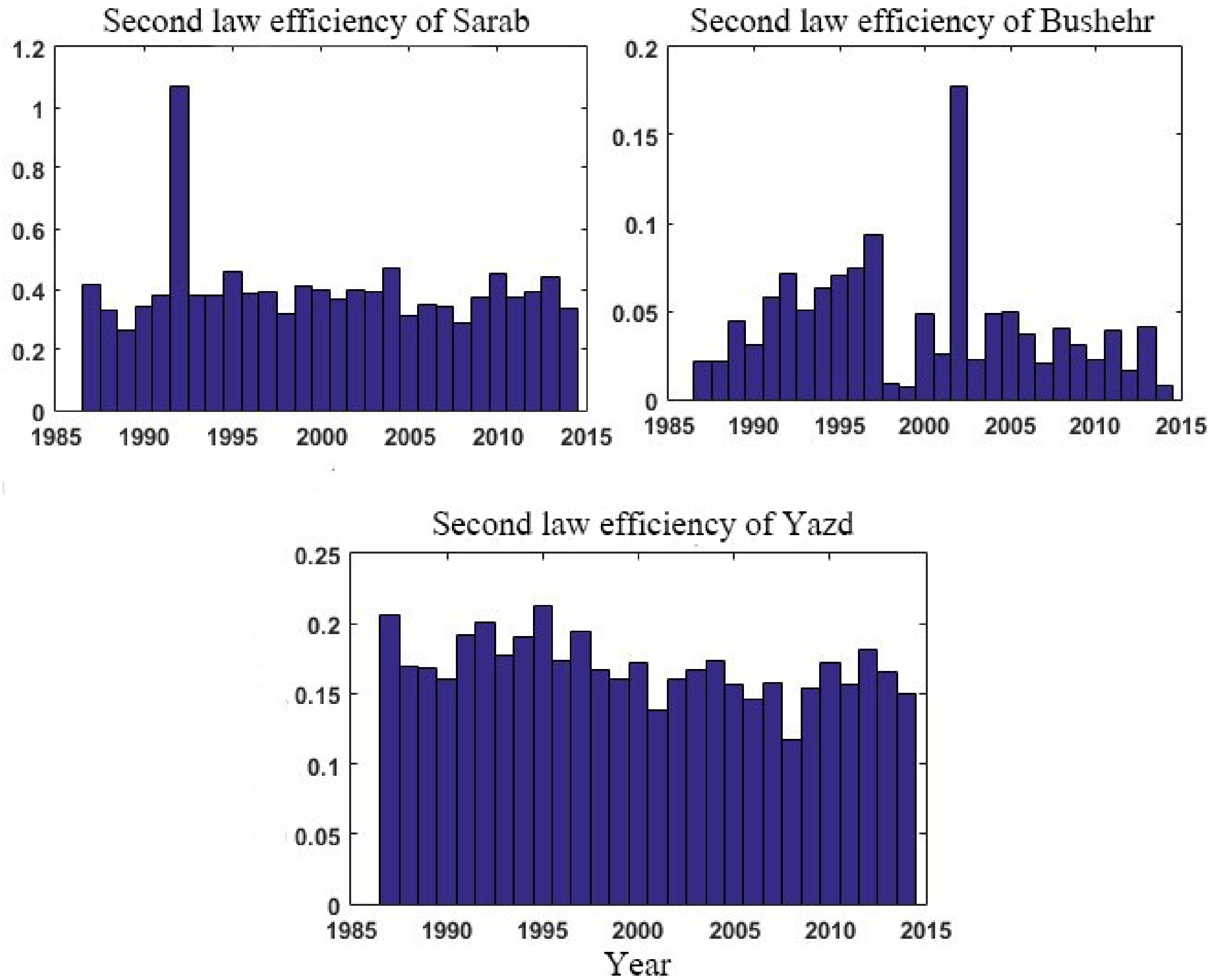

Figure 7. Second law efficiency for case studies

3.1. Soil temperature analysis

Soil temperature is one of the most important factors regarding the heat transfer between soil and underground water. To shed more light on this issue, soil temperature fluctuations decline after passing one-meter depth. Thus, it reaches to a very low amount after passing the average depth of 3-5 meters. Hence, soil temperature is measured in a constant temperature depth.

There exists an array of soil temperature measurements relating to both experimental and theoretical methods. Kasooda [28] presented a model in order to estimate soil temperature. In the equation bellow, soil temperature for different days of a year mainly depends on air temperature condition in annum, soil type and materials, and soil depth.

$$T = T_{mean} - T_{amp} \times \exp\left(-Z \times \sqrt{\frac{\pi}{365 \times \alpha}}\right) \times \cos\left(\frac{2\pi}{365} \times \left[t_{year} - t_{shift} - \frac{Z}{2} \times \sqrt{\frac{365}{\pi \times \alpha}}\right]\right) \quad (7)$$

Where T (°C) is the soil temperature in depth of Z in a special day of year (t_{year}), T_{mean} is the average soil temperature (°C) considered to be equal as the environment (average annual air temperature), T_{amp} represents the surface temperature range (°C) which is mostly affected by climate conditions and have the most significant impact on the system efficiency. T_{amp} is evaluated using the equation bellow:

$$T_{amp} = \frac{T_{s,max} - T_{s,min}}{2} \quad (8)$$

$T_{s,max}$ and T_{smin} are maximum and minimum surface temperature respectively in a year. According to equation 8, α is thermal diffusion of soil (m^2/day) and t_{shift} is a particular day with the lowest temperature.

It is clear cut that in order to estimate soil temperature of different depth, local weather data is needed in a year. In this investigation, a vertical coil is used in a depth of 40 m. According to system assumptions, exit water temperature is equal to soil temperature in depth. Considering equation 7, soil temperature is calculated in the t_{year} of 300 for the three mentioned cities during 1987 to 2014.

4. ECONOMIC ANALYSIS

The main indicator related to GSHP installation in different climates is economic analysis especially payback time calculation. Since financial analysis outweighs the technical results. In this regard, RETScreen software is applied in order to clarify the financial analysis. Therefore, heating and cooling loads from Hap Carrier 4.51 is calculated and used in the economic software. Considering the natural gas price is about 0.15 $/m^3, the electricity price is 0.014 $/Kwh, 30% debt required for 10 years, the inflation rate of 21% in Iran, and 50% of initial costs is supplied by Iran government in order to increase the share of [29], the payback time for the three case studies are resulted in table 2.

Table 2: Economic results of mentioned case studies

City	Climate condition	Payback time (year)
Sarab	Low temperature	3.5
Yazd	Medium temperature	7
Bushehr	High temperature	Not in range

It is clear cut that in low-temperature cities, the payback time in lowest. In other words, the GSHP technology results better in cold climate for the heating purpose. It is mainly for this reason that the natural gas is an important factor in heating where the economic analysis is hinged on the amount of natural gas reduction by replacing GSHP. Hence, this amount is calculated higher in low-temperature climate and appears in payback time parameter.

5. CONCLUSION

According to reports, energy consumption is rising gradually all over the world. It is taken for granted that this increase can be an important concern for energy resources. Therefore, renewable energies become a new source of energy to compensate the fossil fuels limitations. Geothermal energy especially heat pumps are kind of contributors to decrease the share of fossil energy and also the greenhouse gasses reduction. In Iran, most of the total energy consumption related to the residential sectors. As regards, this study outperformed evaluating the impact of climate on GSHP installation by using both economic and thermodynamic analysis. Hence, the exergy analysis assesses due to determine the second law efficiency. As a result, the coldest city has the highest efficiency which shows the impact of climate on GSHP installation. Regarding the economic analysis, the payback time is calculated for replacing GSHP in building as the heating/cooling demand using the RETScrean software. Consequently, the low-temperature city (Sarab) has the payback time of 3.5 years; however, the high-temperature city (Bushehr) is not economically acceptable. Moreover, the payback time for the medium temperature city (Yazd) is calculated as 7 years.

In conclusion, the best climate for installing the GSHP technology is the low-temperature regions for heating demand.

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