Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Experimental and Theoretical Cooling Mode Energy Analysis of Geothermal Heat Pump System in Vardavard Substation Building in Iran

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Keywords: geothermal heat pump, COP, energy saving, energy modeling, hourly analysis, Vardavard substation, Iran

ABSTRACT

Although Iran is considered a high-potential country in terms of fossil fuel resources, it deals with the problem of rising electricity demand in some certain times of the year resulting in shortage of electricity supply. Therefore, electricity consumption reduction has become a prominent issue. Heat pumps utilizing vapor-compression cycle to provide cooling and heating is a big source of electricity consumption in peak demand hours. Geothermal heat pumps can decrease the consumption a great deal.

In this paper, the geothermal heat pump system in Vardavard Substation building is introduced. As the biggest GHP system yet installed in Iran, the paper presents analysis of the experimental data collected from the project site in cooling mode and developing results from a building energy modeling based on Energy Plus. The results indicate considerable energy saving in cooling mode electricity consumption compared to the previous air-to-air heat pump.

1. INTRODUCTION

Approximately 45% of energy consumption in Iran is attributed to buildings and more than half of this number is for cooling and heating facilities (Deputy Minister of Electricity and Energy, 2017). Therefore, energy consumption of cooling and heating utilities and improving the efficiency of equipment and related systems are of particular importance.

One of the ways to improve the efficiency of building mechanical installation systems is to use renewable energy resources. Using these resources make such systems more efficient while they also have other benefits such as reducing environmental pollutants, diversifying the required energy supply portfolio and thus increasing energy security in the building sector. Excessive dependence on fossil fuel resources is associated with many limitations. For instance, the pressure drop of natural gas pipeline in the cold season in many cases has made it impossible to supply the fuel needed for heating systems in the west and northwest of Iran. Similarly, many parts of the country with hot summer experienced electricity shortage in 2018 due to high electricity demand at certain hours ("TAVANIR," n.d.). Therefore, in terms of peak shaving at high energy demand and applying the principles of passive defense, the use of renewable resources locally is doubly important.

Geothermal heat pump systems by using the difference between the surface temperature and the depth of the earth by the ground heat exchanger greatly reduces the energy consumption of the compression cycle. The difference in surface temperature and depth of the earth can be found everywhere. So this method of cooling and heating can be applied everywhere. If it is possible to build a ground coil and have enough space to do so, it is a good option to improve the efficiency of compression systems.

According to the energy balance sheet for 2017 (which was published in 2019 and is the latest available version in Iran), at the end of 2017, there were a total of 22.2 million gas consumers in Iran, of which 1.1 million consumers were added in 2017. In that year, electricity consumption in the domestic sector was 32.7% of the total electricity sales of the Ministry of Energy. The per capita electricity consumption per household subscriber in 2017 was about 2968 kWh, which shows an increase of 3.9% compared to the previous year. This shows that in addition to increasing the number of household subscribers, electricity consumption and consequently per capita consumption of each household subscriber has also increased (Deputy Minister of Electricity and Energy, 2017). Therefore, as it can be seen, energy consumption in both gas and electricity sectors has been on the rise. Accordingly, as mentioned earlier, the government has decided to increase the country's electricity generation capacity by 25,000 MW during the Sixth Five-Year Development Plan (Government sixth five-year plan, n.d.). This number was 25,000 MW for the Fifth Development Plan, but less than a third of this amount was achieved during the years 2012 to 2016.

Considering the numbers discussed and taking a closer look at the energy balance, it is clear that the upward trend in energy consumption will be faster than the increase in energy production and the country will need energy imports in near future. In such a situation, however, the discussion of the proper and efficient use of energy will help to correct the consumption chart; an issue that is broad in scope and largely relates to energy economics, available facilities and equipment, and consumer culture. Unfortunately, the heavy subsidy in the field of electricity and the very low-cost figures for the consumer has turned the justification of the issue of energy saving and related projects a serious challenge. At the same time, due to the low costs paid by subscribers, people do not feel compelled to take the issue of energy efficiency seriously. The average price of electricity for the consumer in 2017 was approximately 680 IRR. This number, despite a limited increase during the years 2017 to 2020, due to the devaluation of the Iranian currency against dollar has in fact decreased in dollar terms and is one of lowest charging figure for energy in the world.

In such a situation, energy saving projects should start from within the energy trustees, namely the Ministry of Oil and Energy. In other words, the introduction of energy saving systems in areas such as cooling and heating, which comprise the most energy consumption, should be studied within the body of the Ministry and pilot projects should be implemented, and the technical-economic review of the output should be studied. It is also important to define the necessary financial incentives at the right time so that after the implementation of pilot projects, such projects can become economically justified among ordinary people and find their supporters.

On the other hand, it should be borne in mind that the issue of environmental pollutants and international obligations will be a serious issue for Iran in the medium term. And according to the Paris Agreement, Iran has voluntarily agreed to reduce greenhouse gas emissions in the country ("COP 21 Paris France Sustainable Innovation," n.d.). Clearly, as expected, failure to meet this demand in the medium term will be associated with international fine and many challenges. Right now, in the discussion of greenhouse gas emissions, the total number of domestic, commercial and public sectors as well as power plants is a significant number, most of which is related to the issue of cooling and heating of buildings. In other words, savings in heating and cooling will have a direct impact on power plants. In fact, electricity that is not produced reduces the operating hours of ongoing power plants. This prevents the construction of more power plants, and naturally, consequently, less fuel is consumed in power plants.

In such circumstances, the use of energy consumption reduction strategies in the field of cooling and heating supply can have a significant result in improving energy consumption and reducing greenhouse gases by observing the above-mentioned process and pattern.

Due to the fact that the country's power substation buildings currently use low-efficiency cooling and heating systems because of safety limitations inside the substation, these buildings are considered a good option for the implementation of installation systems with low energy consumption. Other advantages of the substations will be their acquisition by the Ministry of Energy and the facilitation of the implementation of the trial-and-error period and the conduct of pilot studies in this sector. Statistics show that there are a large number of substations with relatively small buildings and sufficient land in the area throughout the country. In order to have 24-hour staff, these buildings must be heated and cooled at the required time. Therefore, substation buildings are a good target for the development of a new system of providing cooling and heating with significant savings. Preliminary studies and pilot projects help to plan and implement similar projects in the country and in different packages for government and non-government buildings.

Also, there are plenty of examples by other countries as it is not a newly developed idea in countries like Germany and the United states. So, there is a lot of literature to refer to. Desideri et al. (Desideri, Sorbi, Arcioni, & Leonardi, 2011)in their paper showed that the cost of heating a boiler is more expensive than providing heating using a geothermal heat pump system. Due to the high cost of drilling, many experimental studies focus on systems with horizontal coils rather than vertical coils (Demir, Koyun, & Temir, 2009). As a result, the economic justification of the heat pump system in comparison with other cooling and heating systems, in the case of adding a horizontal ground coil is more seen in the articles. Of course, it should be borne in mind that the efficiency of vertical systems is higher and depending on the definition of the project and its local conditions, these systems can be economical. There are many studies and articles in terms of technology and many comparing systems with each other. Galgaro et al. (Galgaro, Emmi, Zarrella, & Carli, 2014) demonstrated that ground coil heat pump systems work much more efficiently than air condenser systems. Baccoli et al. (Baccoli, Mastino, & Rodriguez, 2015) also showed that geothermal heat pumps with vertical converters have higher energy efficiency compared to air-to-air heat pump systems.

This paper investigates the energy saving impact of implementation of a geothermal heat pump system to provide cooling in Vardavard substation building. Vardavard substation, as one of the largest distribution substations in Iran, from which a large percentage of Tehran's electricity is supplied, used to be cooled in summer using low-efficiency air-to-air heat pump system. Therefore, it was selected for studying the effect of using geothermal heat pump system in reducing energy consumption. The Geothermal heat pump in Vardavard, which is the biggest of its kind yet installed in Iran (Renewable Energy and Energy Efficiency Organization, n.d.), has been in operation for a while now and this paper only deals with the results from data logging and comparison with the previous system to calculate energy saving percentage.

2. MATERIALS AND METHODS

2.1. Pilot Project Introduction

Vardavard substation building is located at 51.4 degrees east longitude and 35.8 degrees north latitude, and the altitude in this area is about 1400 meters above sea level. Vardavard substation building is located in an area with a semi- dry climate, relatively hot summers and cold winters. Since the building is connected to the outside air from all four sides and the area is relatively windy in most months of the year, and due to the seams available to pass the tray of power hub cables into the building, the air infiltration factor in calculating the cooling load is of special importance. The figures 1 and 2 illustrate the building and the approximate distance of the ground heat exchanger to the building.

Fig1: Vardavard substation building

Fig.2: The location of ground heat exchangers and its approximate distance to the building

Summary information of geothermal heat pump system designed is as follows:

- Area of the building infrastructure (main hall only): 1020 square meters

- Building cooling load (based on HAP(Carrier) calculations): 300,000 Btu/hr

- Number and capacity of geothermal heat pump devices: 9 devices with nominal load 60,000 Btu/hr, (Note that heating load overweighs in this climate, therefore, total load of the geothermal heat pumps exceeds required load for cooling)

- System type: vertical closed-loop geothermal heat pump

- Number of wells: 16 wells each 160 meter deep with a diameter of 10 inches. Figure 3 illustrates ground heat exchanger layout with all the wells in parallel

- Type and size of pipes used in wells: polyethylene, 40 mm, single U

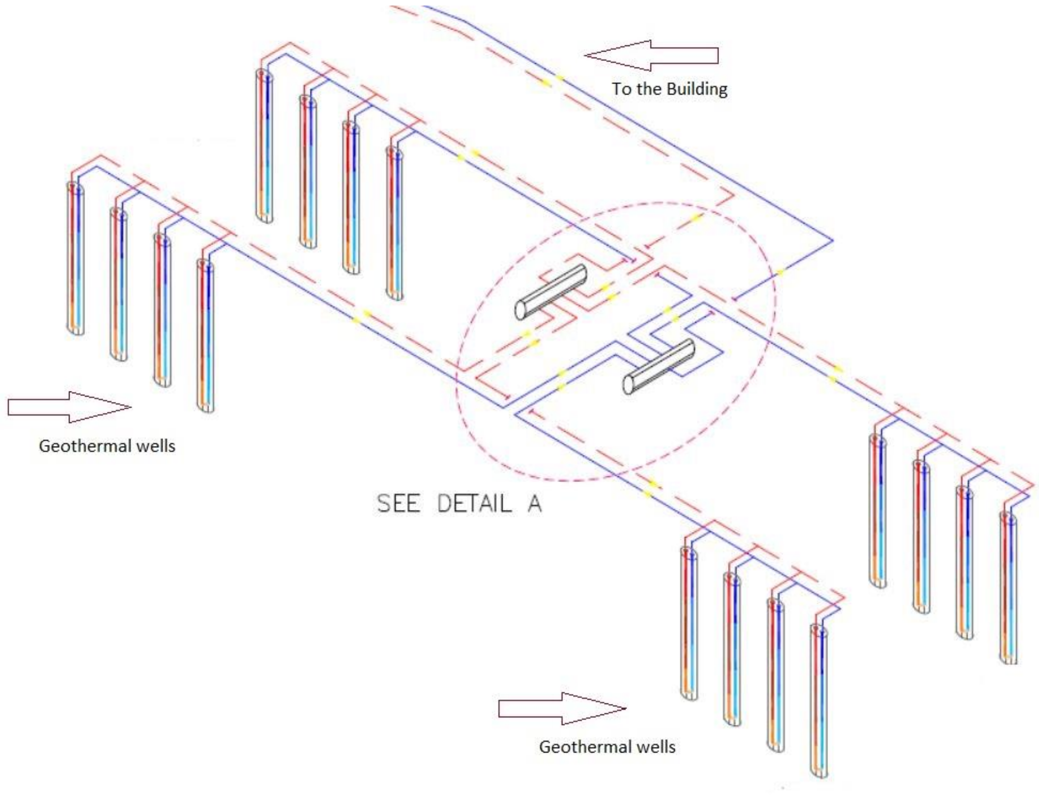


Fig3: schematic design of ground heat exchanger in Vardavard substation

Fig4: Collector room for ground heat exchanger defined in Fig3 with thermometers and barometers on every circuit

2.2. Methodology

First, climate analysis and collection of weather information is done using the relevant software and by referring to the data of the Meteorological Organization. The main application of this data is the possibility of preparing an energy plus climate file (epw) for use in hourly load analysis. The prepared climatic file is used as input to Design Builder software for energy analysis. The three-dimensional model of the building is defined and analyzed by defining the characteristics of heat transfer coefficient of walls, corridors, floors and ceilings in this software and comparing the performance of cooling systems in two modes of geothermal system and former installation system i.e. air-to-air heat pump

At the next step, the information taken from the geothermal heat pump devices installed in the project will be examined. This information includes temperature data including inlet and outlet air from heat pump devices and the temperature of inlet and outlet of fluid to the device. The power consumption of the device is also measured. Seasonal COP is calculated from the information obtained over a specified period of time. As all the geothermal devices capacities are the same in the project, analysis of the operation of each device is feasible through measuring the main pipeline thermodynamic parameters. In other words, by measuring the temperature of the fluid when entering and leaving the ground and collecting electricity consumption figure from the main panel, it is possible to calculate the seasonal performance coefficient. The value of seasonal performance coefficients obtained in the hot season is used for software modeling and extraction of energy consumption to provide cooling throughout the year. Also, system performance modeling is carried out with previous cooling supply equipment and the results are extracted. In the next step, the amount of reduction in energy consumption to provide cooling is evaluated and calculated by comparing the results and diagrams of the two models. Finally, the result is examined to analyze the possibility of developing similar projects, especially in the substations buildings.

2.3. Modeling

In order to analyze the load on an hourly basis and calculate the amount of energy consumption to provide cooling, Design Builder software with the ability to analyze energy and mechanical and electrical utilities as well as preparing an architectural form has been used.

Figure 5 shows the model prepared for the whole building. In the prepared model, the spaces are drawn separately defining where geothermal heat pump devices are utilized.

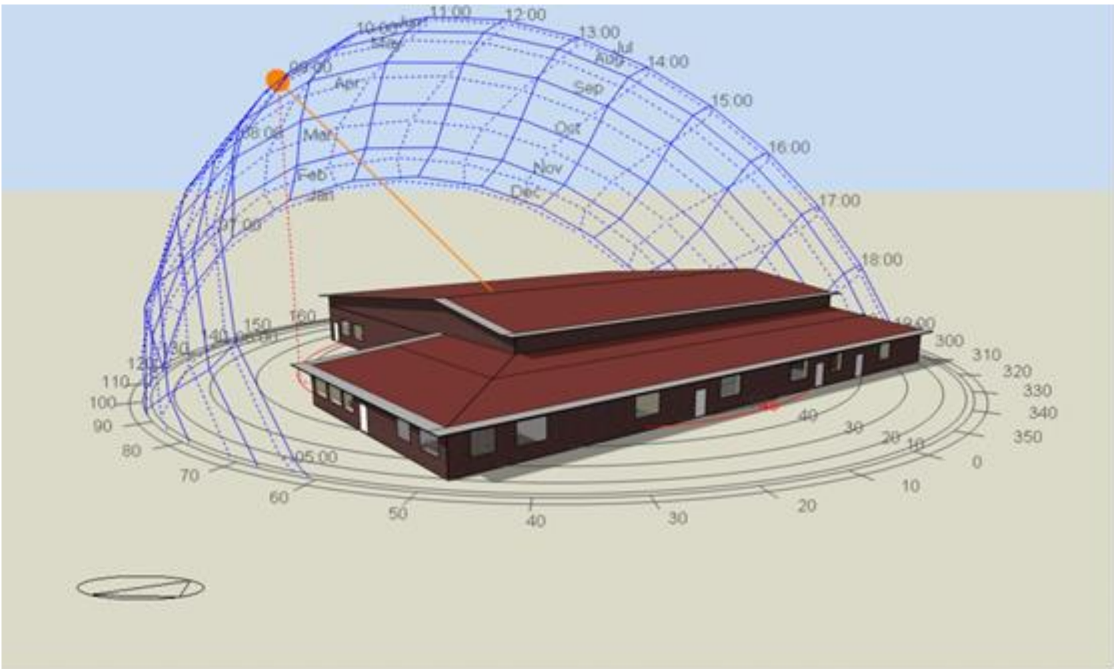


Fig5: 3D Modeling of Vardavard Substation building

Thermal properties of the walls, floor, roof and factors such as infiltration were fully taken into account. The weather file was created based on the average available data of the past 10 years from the nearest weather stations.

3. RESULTS AND DISCUSSION

The graph of data taken from the geothermal heat pump device for a period of about one month in the summer of 2020 is presented in the figure 6.

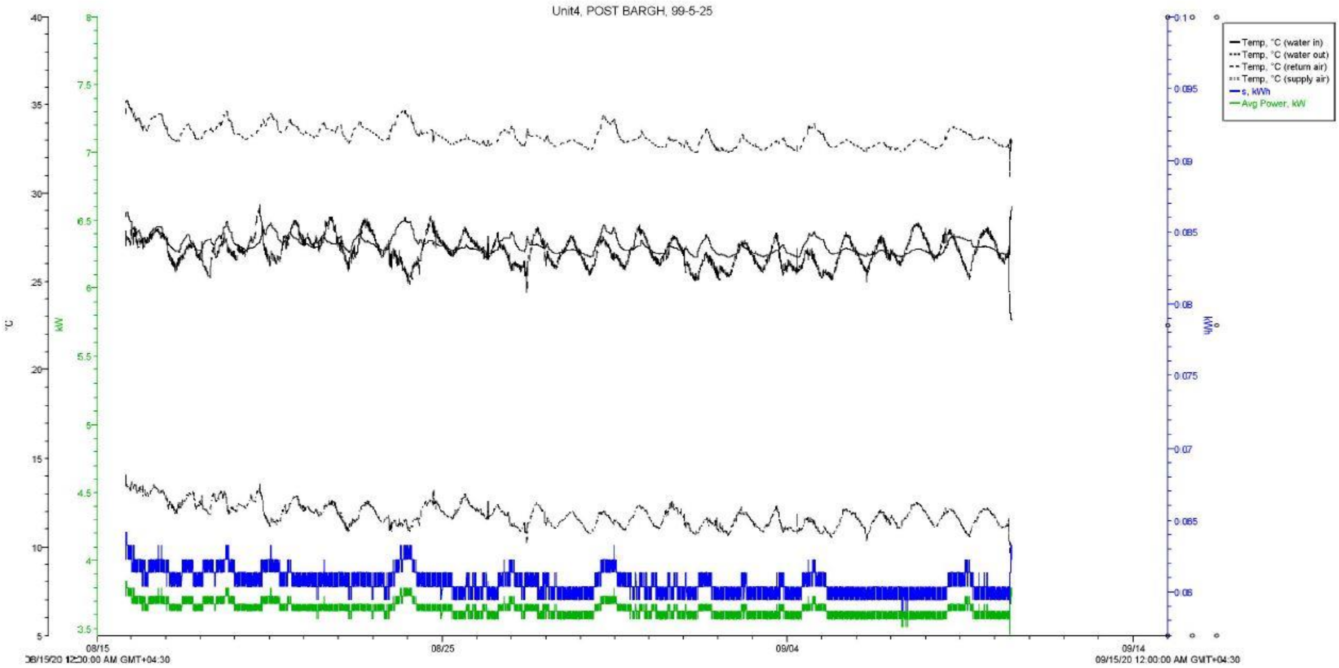


Fig6: Collected data in summer

According to the collected data, the average figures are as follows:

The average inlet air temperature to geothermal heat pump: 26.73 ºC

The average outlet air temperature from geothermal heat pump: 11.8 ºC

The average entering water temperature: 27.03 ºC

The average leaving water temperature: 33.19 ºC

The average power consumption: 3.64 kW

To calculate the heat absorbed by evaporator, the following formula (Oklahoma University, 2011) has been used by installing sensors on the air intake and suction point of the device.

$Q_{Eva} = 1.08 \times V \times (T_2 - T_1)$

Where:

“V” is the volume of air thrown into the environment in cfm (cubic feet per minute). According to the manufacturer's catalog, the value is 2000.

“T_2” is the average inlet air temperature to geothermal heat pump

“T_1” is the average outlet air temperature from geothermal heat pump

“Q_{Eva}” is the average heat in Btu/hr, absorbed by the evaporator from the building

Therefore:

Q_{Eva} = 58047 Btu/hr

Since W_{ave} = 3.64 kw

Therefore seasonal coefficient of performance (SCOP) is as follows(Kavanaugh, 2014):

$SCOP_{cooling} = Q_{Eva,\ ave} / (W_{ave} \times 3412) = 4.67$

So the seasonal COP of 4.67 is used in energy modeling to extract total energy consumption for cooling.

The previous air to air heat pump system seasonal COP is 2.1

The results for load calculation and energy modeling is as follows:

As it can be seen in Fig7, weak roof insulation and then infiltration effect are the most effective parameters increasing cooling load on the peak load day. Infiltration is due to the duct banks holes to the building for cable trays which as mentioned before was something inevitable.

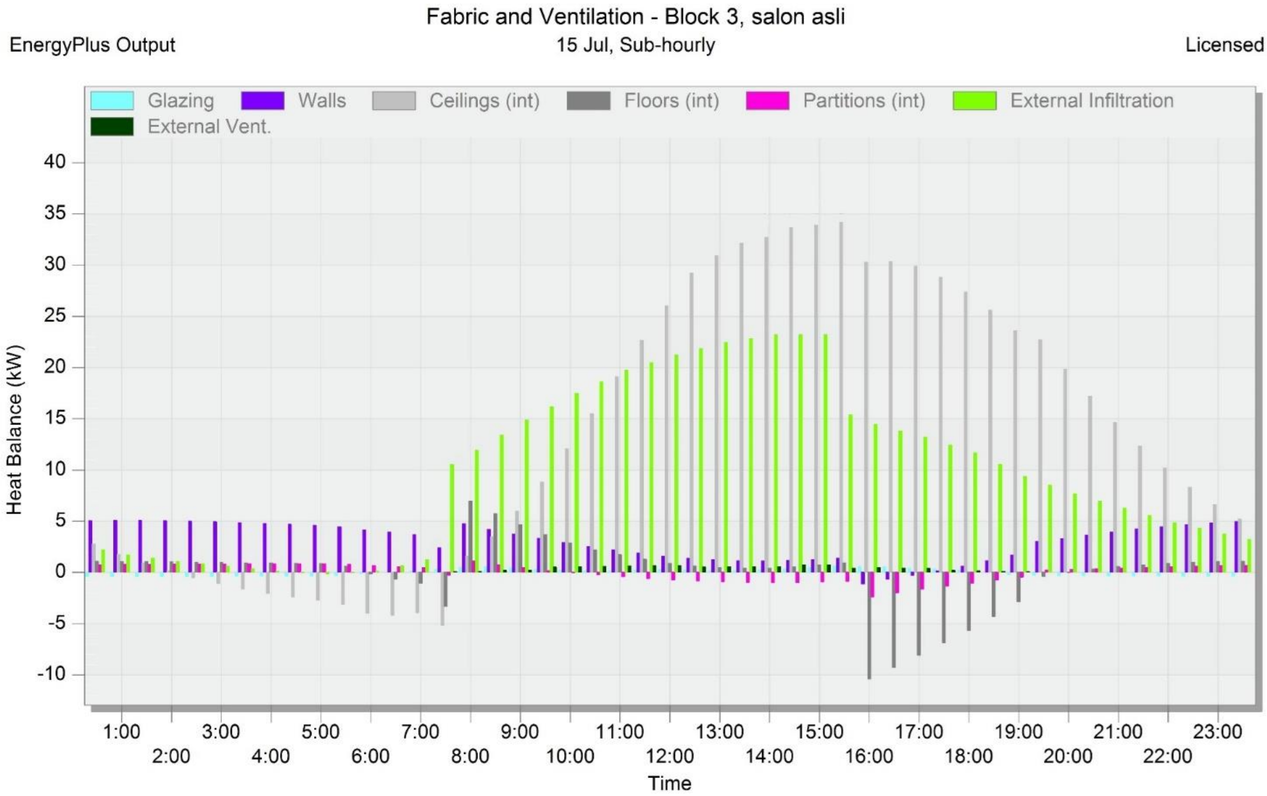


Fig7: Effective parameters on the cooling peak load

Energy modeling and the results for monthly cooling energy consumptions for two scenarios; one utilizing geothermal heat pump and the other, air to air heat pump are presented in the figures 8 to 11. Figure 8 displays daily electricity energy consumption for cooling with air-to-air heat pump while figure 9 illustrates daily electricity energy consumption for cooling with geothermal heat pump. Figure 10 presents comparison of monthly electricity energy consumption for both scenarios before and after geothermal heat pump system installation. As it can be seen, the electricity consumption with an air-t-air heat pump was almost 50 percent more.

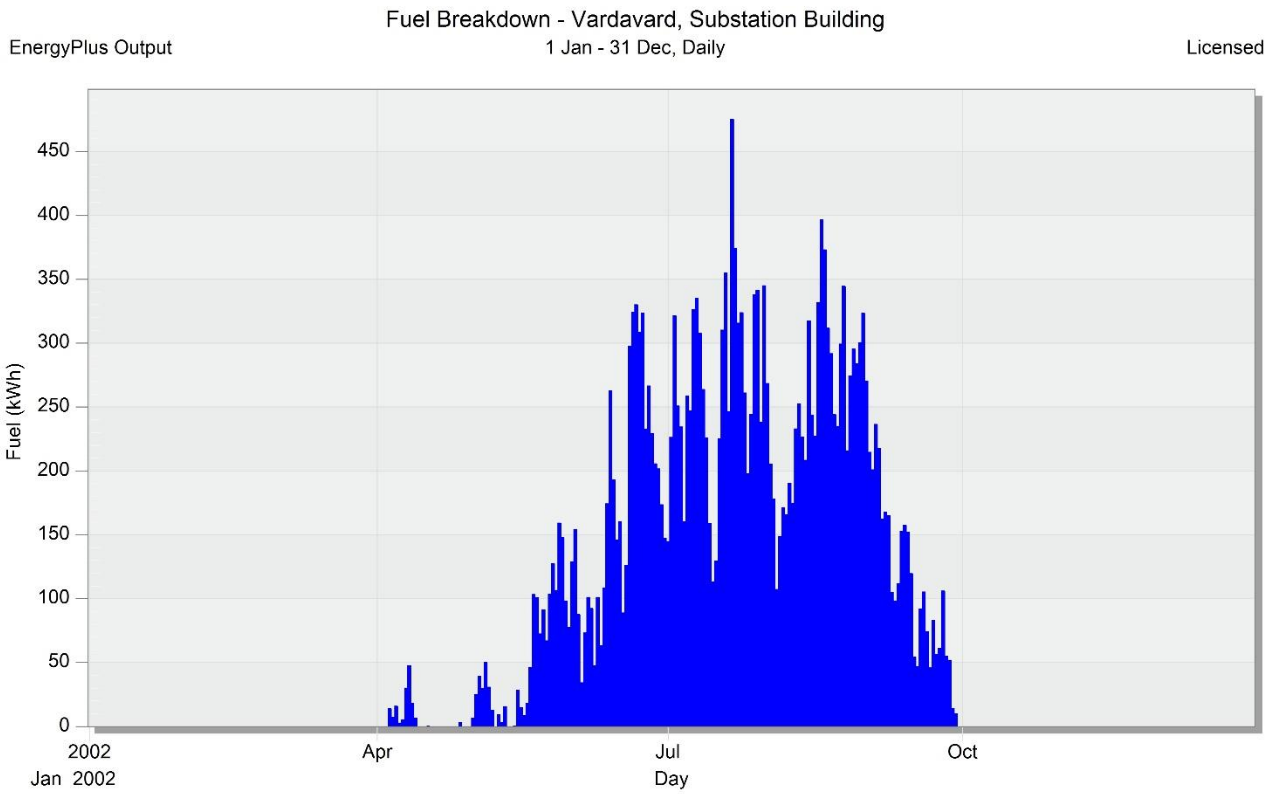


Fig8: Daily electricity energy consumption for cooling with air-to-air heat pump

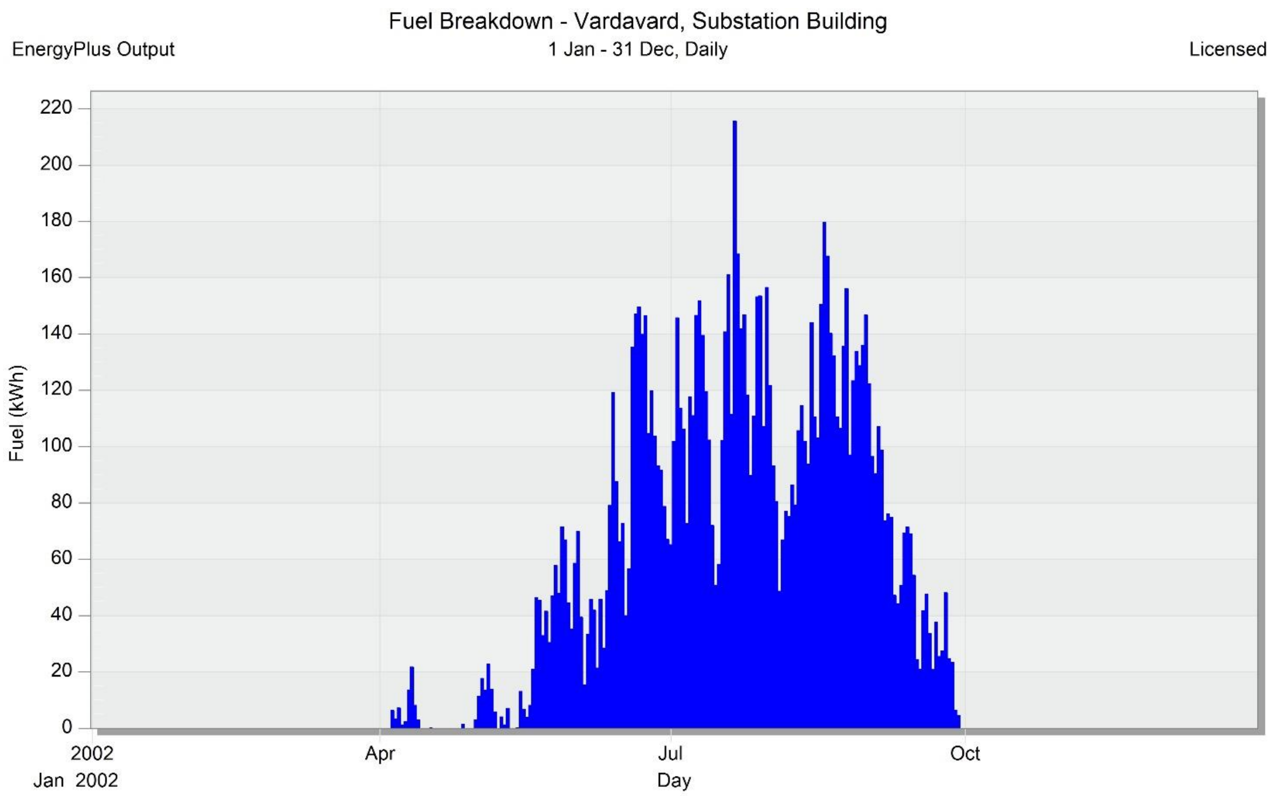
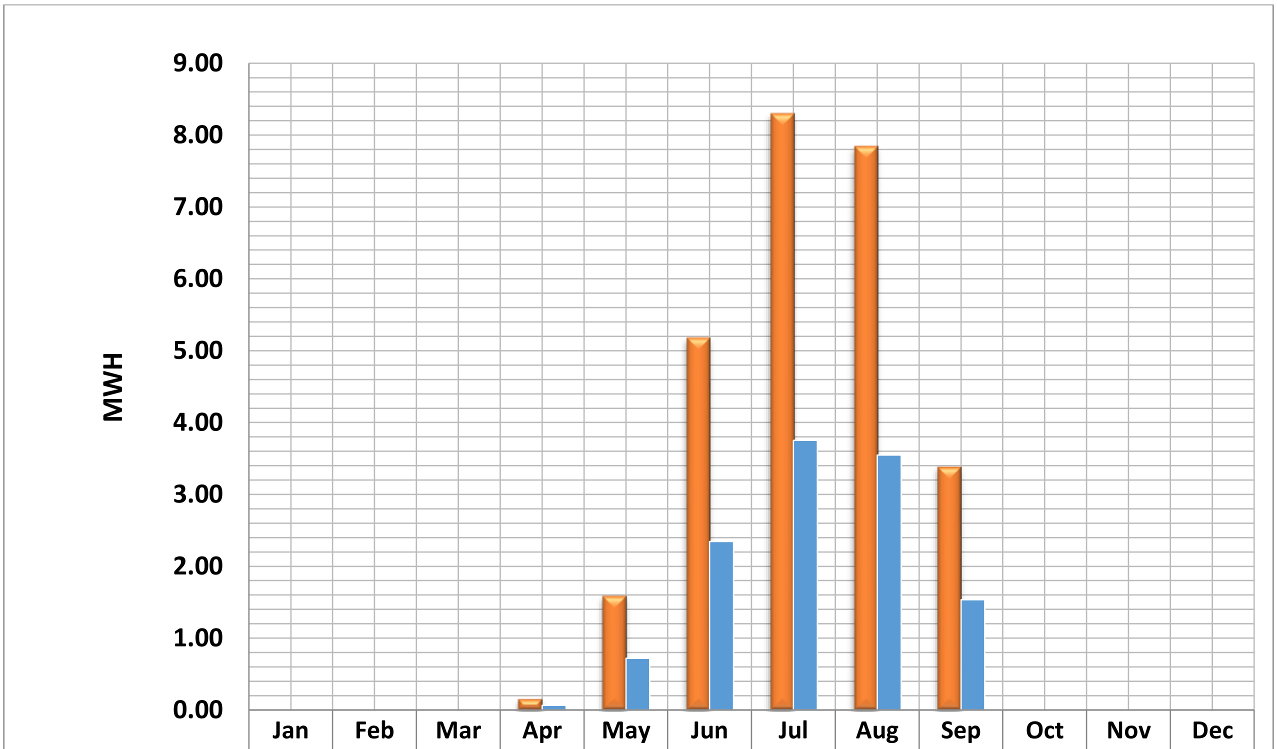


Fig9: Daily electricity energy consumption for cooling with geothermal heat pump



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
base case	0.00	0.00	0.00	0.15	1.59	5.18	8.30	7.84	3.39	0.00	0.00	0.00
proposed case	0.00	0.00	0.00	0.07	0.72	2.35	3.75	3.55	1.53	0.00	0.00	0.00

Fig10: Comparison of monthly electricity energy consumption for both scenarios

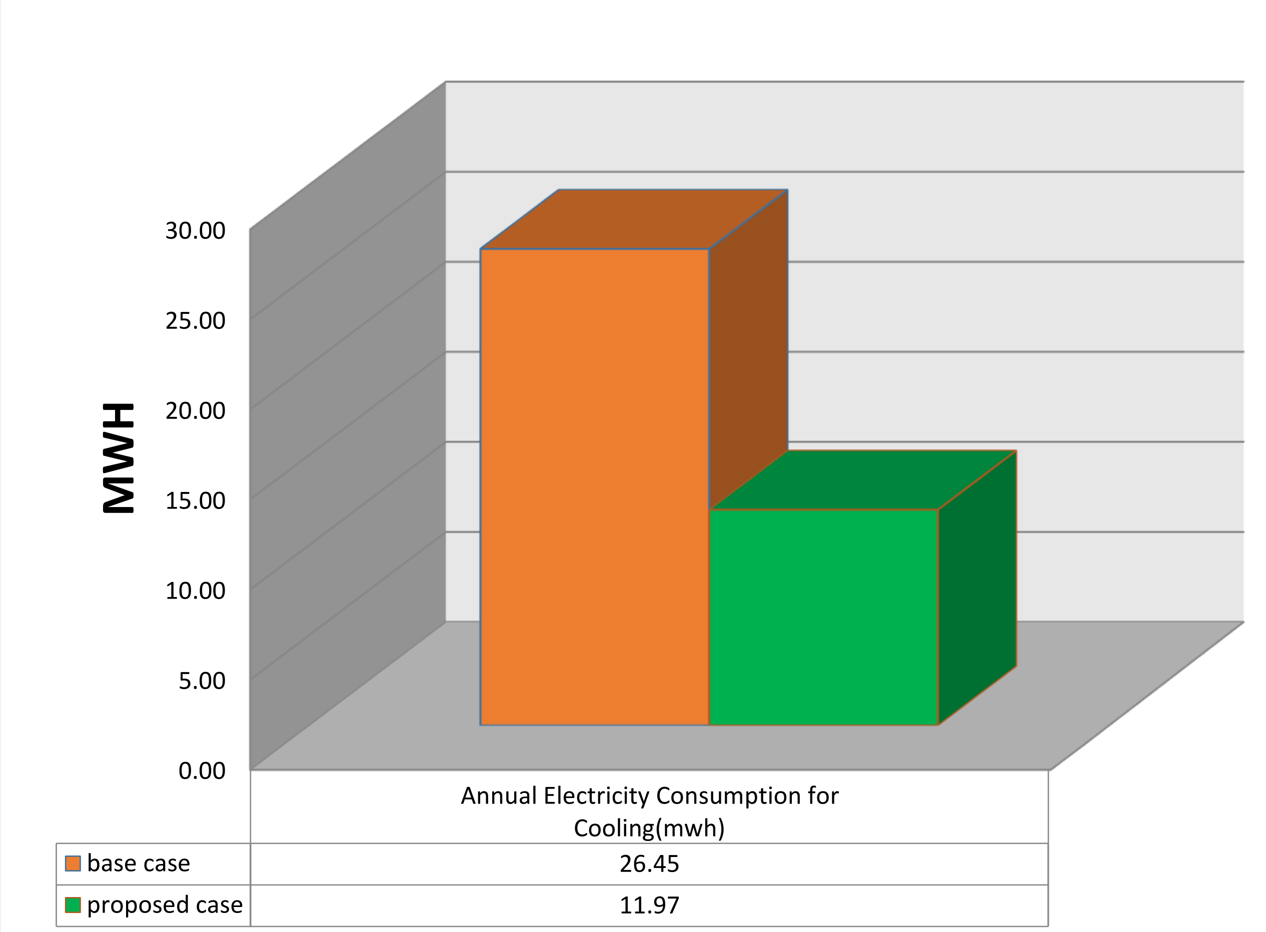


Fig11. Annual electricity energy consumption for cooling for both scenarios

As it can be seen in figure 11, geothermal heat pump utilization has led to a considerable energy consumption reduction of about 54 percent for cooling by reducing annual electricity consumption from 26.45Mwh to 11.97Mwh. Considering 7.98Mwh of electricity consumption for the circulation pump of ground heat exchanger, the annual net electricity consumption with geothermal heat pump system will be 19.95Mwh. Therefore, the saving will be about 24 percent which is still a considerable amount of energy consumption reduction.

4. CONCLUSION

Providing cooling through the application of geothermal heat pump could be a viable solution for electricity demand peak shaving in summer in Iran. Substation buildings can be the perfect candidate as they currently utilize low-efficient cooling devices. Vardavard substation building geothermal heat pump project proved significant energy saving through GHP systems. As the first semi-large scale geothermal heat pump project in Iran, an energy saving of about 24 percent was achieved in cooling mode in comparison with the previous air-to-air heat pump. Therefore, the same solution could be implemented for other substation buildings as they usually have plenty of land for ground heat exchanger installation. It is believed that in case of extensive utilization of such systems to provide building cooling load, the issue of high electricity demand in summer in some regions in Iran could be addressed and resolved. It is assumed that geothermal heat pumps could turn into a big market in the future in case more pilot projects are on the agenda by Ministry of Energy. The results of the studies for heating application of geothermal heat pump in Vardavard substation building and the recommended mechanism to provide incentives to the users of such systems will be published in the coming papers.

REFERENCES

Baccoli, R., Mastino, C., & Rodriguez, G. (2015). SC. *Applied Thermal Engineering*. https://doi.org/10.1016/j.applthermaleng.2015.03.046

COP 21 Paris France Sustainable Innovation. (n.d.).

Demir, H., Koyun, A., & Temir, G. (2009). Heat transfer of horizontal parallel pipe ground heat exchanger and experimental verification. *Applied Thermal Engineering*, *29*(2–3), 224–233. https://doi.org/10.1016/j.applthermaleng.2008.02.027

Deputy Minister of Electricity and Energy. (2017). *Energy balance sheet*.

Desideri, U., Sorbi, N., Arcioni, L., & Leonardi, D. (2011). Feasibility study and numerical simulation of a ground source heat pump plant , applied to a residential building. *Applied Thermal Engineering*, *31*(16), 3500–3511. https://doi.org/10.1016/j.applthermaleng.2011.07.003

Galgaro, A., Emmi, G., Zarrella, A., & Carli, M. De. (2014). Possible applications of ground coupled heat pumps in high geothermal gradient zones. *Energy & Buildings*, *79*, 12–22. https://doi.org/10.1016/j.enbuild.2014.04.040

Iran Government sixth five-year development plan.

Kavanaugh, S. (2014). *Geothermal Heating and Cooling*. Retrieved from http://library1.nida.ac.th/termpaper6/sd/2554/19755.pdf

Oklahoma University. (2011). *Ground Source Heat Pump Design and Installation Guide*.

Renewable Energy and Energy Efficiency Organization. (n.d.). *geothermal heat pump*.

TAVANIR. (n.d.). https://www.tavanir.org.ir/en/#