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ECONOMIC COMPARISON OF THE GEOTHERMAL HEAT PUMP SYSTEM AND CONVENTIONAL WATER HEATERS FOR HOT WATER SUPPLY IN APARTMENT BUILDINGS

[a*] Rehan Jamil, [b**] Abdulrahman K. S. Alhusayni

a, b: Department of Building Engineering, College of Architecture and Planning,
Imam Abdulrahman Bin Faisal University, Saudi Arabia
*rjamil@iau.edu.sa **abdulrahmankhalid97k@gmail.com

***Abstract*:** Saudi Arabia is in the process of dealing with energy availability, production, and consumption by foreseeing the possible issue of energy shortage in the country. Considering a huge demand for energy in the region the government has taken solid steps to address the issue and has formed various authorities to monitor, control, and manage energy consumption. The building industry is the highest consumer of energy where it is used for heating/air conditioning the indoor spaces, lighting, and running appliances and heating water during winters. This article presents an economic comparison of a conventional hot water heating system and another technique of Geothermal Heat Pump System (GHPS) which uses the heat energy of earth for heating water for domestic use. The effort has been made to assess the possible use of GHPS in apartment buildings in Saudi Arabia. Detailed design and analysis are conducted for both systems and a cost estimate is prepared. Life Cycle Costing is performed which includes the installation and operational costs of both the systems for a period of 5 years. The conventional system proves to be economical in terms of installation but in terms of energy consumption for the next 5 years, it becomes very expensive. Whereas the GHPS system shows almost one-third the total cost of the conventional hot water heating system showing a significant amount of energy consumption and financial benefit. The research shall prove to be beneficial for the construction and building industry in their efforts to reduce energy consumption by creating innovative designs and ideas.

Keywords: Hot water supply, geothermal energy, geothermal heat pump, economic comparison, Life Cycle Costing,

1 INTRODUCTION

Using sustainable means for the operation of a building during its lifetime has become as essential as the inhaling of oxygen to remain alive. Continuous use of fossil fuels has resulted in the depletion of the world's energy resources causing an escalation of fuel costs day by day. Buildings are the basic element in the world and have great importance in life where the person spends most of the time inside it. A building needs energy resources for the operation of mechanical, electrical, and plumbing services throughout its life. The energy consumption patterns show that buildings are the highest energy consumers with 41% of energy followed by transportation and industries with a consumption of around 30% of the share. For residential buildings, it has been found that around 73% of energy is used for heating and cooling of the inner spaces whereas almost 12% of the energy is consumed for heating the water for domestic use [1].

Due to having hot–arid climates, Saudi Arabia was named one of the 10 countries with the highest energy consumption per capita in 2014. According to a report published by the Saudi Energy Efficiency Centre (SEEC), the per capita energy consumption in the country is more than three times higher than the world average [2]. Moreover, according to an estimate, the electricity generation in the country consumes almost one-third of the daily oil production in KSA. Saudi Arabia introduced the SEEC and Saudi Green Building Council (SGBC) in 2010 to rationalize the production and consumption of energy to increase efficiency in the Kingdom [3, 15]. The center started collecting data from all sectors involved in the field of energy through surveys. In 2016, after the announcement of Saudi Vision 2030, this center started working more efficiently. Since then the major objective of the center is to find sustainable means of producing energy and to make the country independent of oil-based resources till the year 2030. Keeping in view the fast-paced reduction in the world's energy resources and the negative effect of burning fuel on the world's environment, various renewable energy resources are being discovered and explored at large. One of the renewable energy resources is geothermal energy.

The Earth's crust has an abundant storage of heat energy. This heat energy is environment friendly and has a lot fewer emissions as compared to burning fuel and fossils. Geothermal Heat Pump System (GHPS) is one of the methods by which this heat energy can be extracted and put to some use. A common GHPS comprises of following three components.

1. Heat pumps
2. Heat exchanger loop (horizontal or vertical)
3. Heat distribution unit

Heat pumps operate using electricity to drive compressors that provide the necessary work for the concentration and transport of thermal energy. Basic heat pumps operate on the vapor-compression refrigeration cycle. The working fluid within the heat pump is usually a refrigerant, with the selection dependent on the overall characteristics and requirements of the GHPS. The heat pumps move thermal energy between the heat exchanger loops buried below the earth and the heat distribution unit by controlling pressure and temperature through compression and expansion. In addition to few main components of the system such as, compressor, expansion, and reversing valves there are some minor components as well which include fans, piping, and controls that contribute to the whole operation [4]. The heat distribution system is then utilized to heat the water to the desired temperature of at least 45ºC.

There are two heat exchanger loop systems adopted for the extraction of geothermal energy; open-loop and closed-loop systems. The closed-loop system is used more commonly than the open-loop system for having more advantages. In the closed-loop system, the fluid is passed through the pipes buried under the ground and it has no direct contact with the earth. There are two major types of closed heat exchanger loop techniques; horizontal and vertical. The vertical loop consists of many vertical pairs of pipes connected at the bottom with a U-shaped connector. This assembly is bored into the ground at a depth of 50m to 150m depending upon the amount of heat being extracted with a spacing of 5-6m. One of the top ends of each pair of pipes is connected with the main supply pipe and the other is connected with the main return pipe of the GHPS as shown in Fig. 1a. This type of system is utilized when there is limited space as it requires a smaller area for installation. Also, it is considered for the areas where the impact of geothermal energy is found at larger depths. On the other hand, a horizontal loop system is laid at shallower depths but requires larger areas. The configuration of the pipes in the horizontal loop system is generally kept similar to the vertical loop system with an exception that the prior can either be laid in series or parallel configuration as shown in Fig. 1b and Fig. 1c respectively.

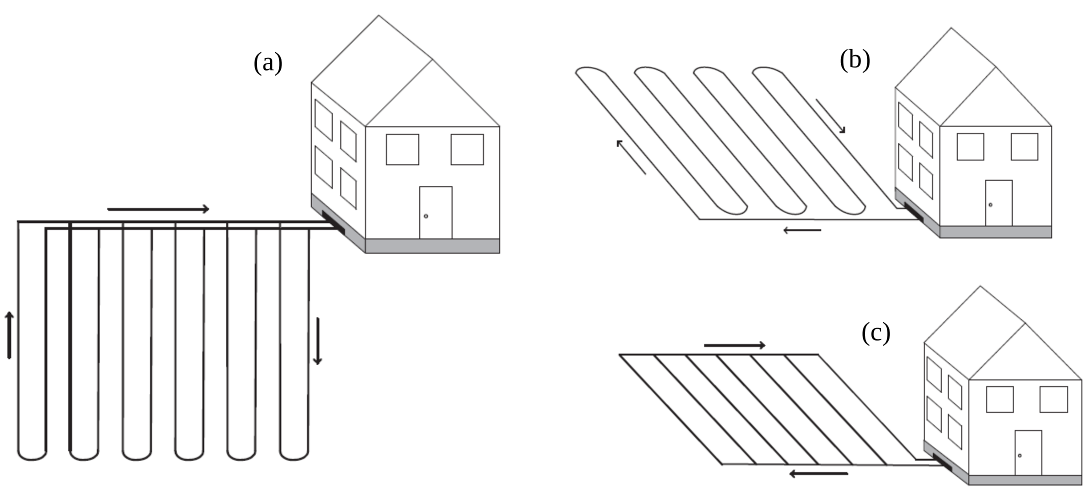

Figure 1: Heat exchanger loop system (a) Vertical, (b) Horizontal in series, (c) Horizontal in parallel [4]

The GHPS is being widely used in both residential and commercial buildings. Most common uses are found to be heating and air conditioning, however, few examples have been found for heating water as well. Kara and Yuksel [5] designed a geothermal heat pump in Turkey to supply hot water to flooring systems with a temperature of up to 45ºC. This method helped them in the conservation of electrical energy to heat water in boilers. Bloomquist [6] analyzed the GHPS for space heating by designing a hot water supply piping network for the whole community. In his research, he found the method quite efficient and concluded that the use of geothermal energy has a huge scope in future research works. Demirbas [7] has researched the prospects of geothermal energy and found that the reliance on geothermal energy shall increase gradually by the year 2040 around the globe. Mahmoudi et al. [8] used the geothermal energy to power the brackish water desalination unit in Algeria. He desalinated the brackish water to irrigate the farms and the greenhouse. He concluded that the system proves to be very efficient with 24h availability of power without producing any pollution and carbon emissions. In a few other articles, the utilization of geothermal energy has been explored for various purposes in Iceland and Turkey [9, 10]. A study has noticed that the installation and use of GHPS have been increasing at the rate of 10-30% in recent years [11].

To the best of authors' knowledge, no work has been performed and found in the literature for Saudi Arabia discussing the potential use of geothermal energy for heating domestic water. The purpose of this project is to analyze and discuss the possibility of utilizing geothermal energy for heating the water for domestic use. As the conservation of energy has been declared as one of the major tools in all of the green building certification authorities around the world including LEED, BREEAM, etc. [12], the article aims to conclude that the use of geothermal energy helps in saving energy in residential apartment buildings along with other financial benefits. The article shall help the stakeholders and provide them the guidelines for a sustainable building design.

2 EXPERIMENTAL PROCEDURES

2.1 Data Brief

The building selected for the case study is a multistorey residential apartment building located in Al Khobar, Saudi Arabia at 26º 15' 13" N and 50º 12' 29" E. The building comprises of 5 typical floors in addition to ground floor reserved for services and amenities. Each typical floor has a covered area of $375m^2$ and has 8 apartments on each floor. A single apartment has three rooms, a living, a kitchen, and three toilets. Fig. 2 shows the 3D model of the apartment building created in eQUEST. It is an application that helps engineers and researchers to prepare the building model and professionally perform energy-related simulations and analysis.

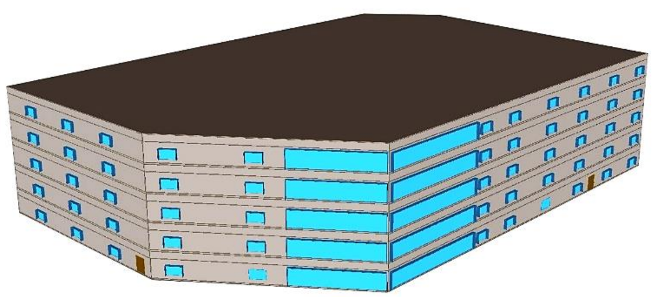

Figure 2: 3D Model of Apartment Building

The apartment building also has a vast area consisting of green lawns, playing area, and car parking within its site boundary. The water requirement of the building is being met by using freshwater obtained from the seawater desalination plant located on the eastern coast of Saudi Arabia in Al Khobar city.

2.2 Research methodology

The work methodology consisted of a stepwise procedure. Fig. 3 shows the workflow and details of each step. In the first step, the conventional hot water supply system was designed for the apartment building. In this system, it was considered that each toilet has a separate electric water heater and local hot water supply piping was provided within the toilet only. In the second step, the hot water system of the building was designed with the help of geothermal heat pumps. In this system, there was one pump taking supply from the main water storage reservoir at the ground floor and this pump let the water pass through various loops of pipes, having a thermally conducting material, buried under the ground. The water supplied by the first pump shall become hot by gaining the heat of the ground after passing through the loop network and shall be collected in a separate water tank. From this tank, the hot water was supplied to the whole building similar to a centralized heating system. The third step consisted of the hydraulic calculations for both systems.

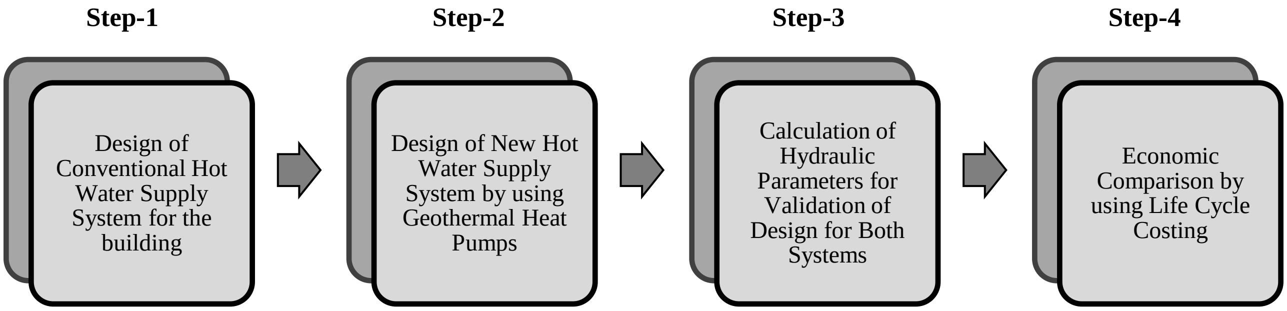

Figure 3: Methodology of Research Work

The EPANET 2.0 modeling tool was used for the analysis of hydraulic parameters of the designed layout. Slight modifications were done in the routing of pipes and their diameters to make the design correct and valid. The pipe frictional loss was calculated by using Hazen-Williams Eq. 1 as shown below [13, 16] whereas the pump power shall be calculated by using Eq. 2 which was used for GHPS.

$$h_L = \frac{10.67\ L\ Q^{1.85}}{C^{1.85}\ D^{4.87}} \qquad \text{.... Equation 1}$$

$$P = \frac{\Delta p\ Q\ \rho\ g}{1000\ \eta} \qquad \text{.... Equation 2}$$

Where h_L is the head loss in meters, L is the length of pipe under consideration (m), Q is the volume of flow of water in m^3/s, C is the Hazen-Williams roughness constant, D is the internal diameter of the pipe (m), P is the pump power obtained in kW, Δp is the total pressure required in meters, ρ is the density of water in kg/m^3, g is the acceleration due to gravity in m/s^2 and η is the pump efficiency. The final step consisted of the calculations of the cost of each system. The life cycle costing of both systems was done for a period of 5 years. The hydraulic and economic comparison along with results and discussion are presented in the next section.

3 RESULTS

3.1 Conventional Hot Water Supply System

The conventional hot water supply system for the apartment building was designed consisting of individual electric water heaters in each toilet. A general water heater having a capacity of 80 liters with an average power consumption of 1.2kW [14] was selected to be included in the design. A total of 125 water heaters were proposed to be installed in the building along with a CPVC (Chlorinated PolyVinyl Chloride) pipe system having diameters of 25mm and 20mm with respective thermal insulations.

3.2 Hot Water Supply by Geothermal Heat Pump System

In this step, an alternate proposal was prepared for the hot water supply system of the apartment building by using the technique of GHPS. The vertical heat exchanger loop system was adopted as there is less area available within the site boundary. 50mm diameter HDPE (High-Density PolyEthylene) pipes were proposed to be bored inside the earth up to a depth of 140m to extract heat from the earth. The heat exchanger loop system was designed as a recirculation system connected with the heat pumps. The heat distribution system was further connected to a network of CPVC pipes to supply hot water to the toilets of the apartment building as shown in Fig. 4a. After performing the hydraulic design of the whole system on EPANET 2.0, as shown in Fig. 4b, the total flow requirement of the apartment building was found to be 9.46lps (0.00946m^3/s) with a required pressure of 70m. These hydraulic requirements suggested a pumping system having a power rating of at least 10kW by using Eq. 2. To calculate the pump power, the efficiency of the pump motor was assumed to be the most common value of 65% found in hydraulic pumps for domestic water supply. The pump characteristics curves generated by the program are shown in Fig. 5.

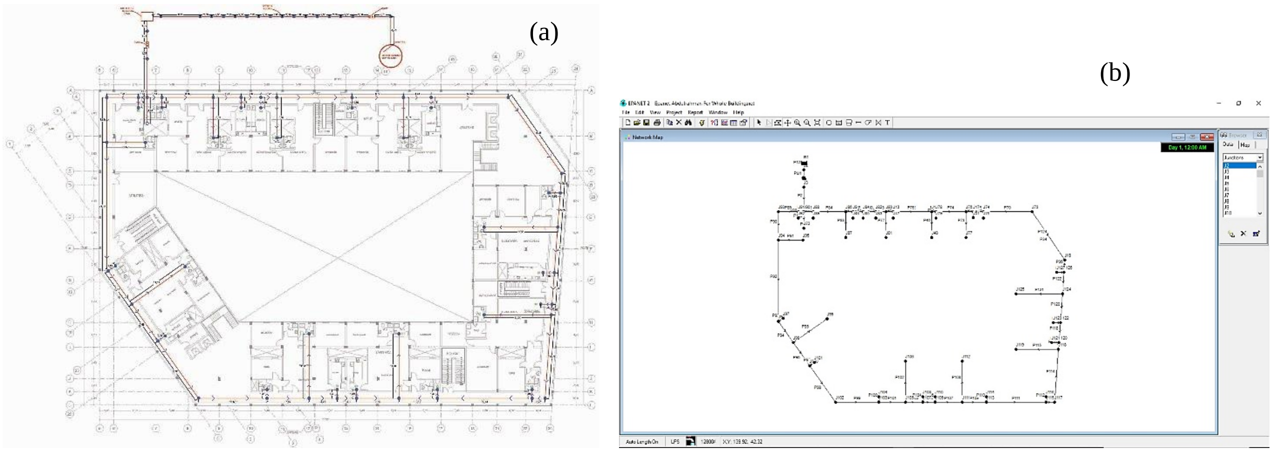

Figure 4: (a) Hot water supply layout of GHPS for a typical floor, (b) Hot water supply network model on EPANET 2.0

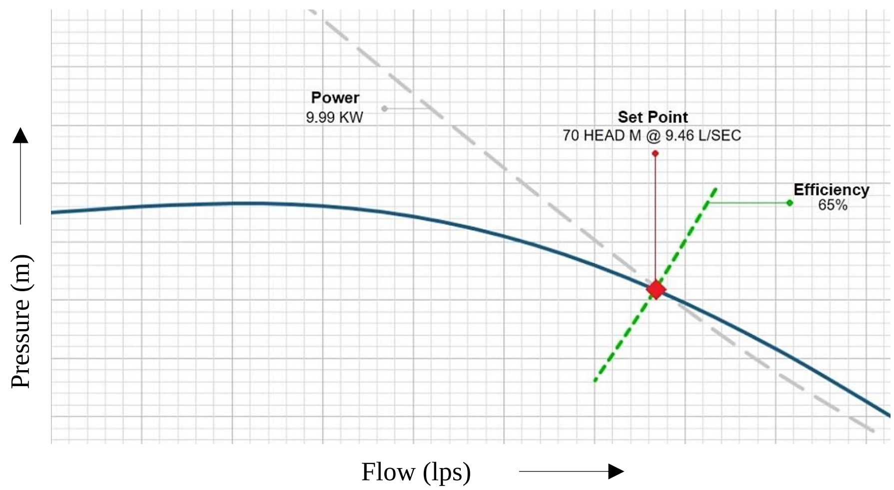

Figure 5: Characteristic curves of designed geothermal heat pump

3.3 Economic Comparison of Both Systems by Life Cycle Costing

After validation of the hydraulic design of both proposed systems, a detailed comparison was prepared for the economics involved in the execution of the design. Life Cycle Costing was performed which included the installation and operational costs of the systems for a period of 5 years. The cost of all materials involved in the design was obtained from the local markets of the Eastern Region of Saudi Arabia. A brief comparison is given in Table 1.

The other part of the LCC is the operational cost related to both systems. For a hot water system working in the Eastern Region of Saudi Arabia, it is assumed that the duration of working of such systems is almost 4 months because the winter season prevails from the mid of November till the mid of March, as shown in Fig. 7. For the case of a conventional hot water supply system, the water heaters are generally kept on for the whole season which makes around 2,880 hrs. of continuous working. Considering the required number of water heaters, the apartment building understudy would consume a huge amount of 432 MWh of energy each season.

Table 1: Bill of Quantities and Cost Estimate for Installation of Proposed Systems

Items / Materials	**Rate (SAR)**	**Conventional Hot Water System**	**Geothermal Heat Pump System**

		Quantity	Cost (SAR)	Quantity	Cost (SAR)
Electric water heater (Cap. 80 lit.)	550 Each	125 No.	68,750	-	-
Supply and installation of GHPS unit including pumps, compressor, electric control panels, valves, etc.	50,000 Each	-	-	1	50,000
Supply and installation of 50 mm dia. HDPE pipes as heat exchanger loops including boring and laying of pipes inside the earth	55/m	-	-	1,600 m	88,000
Supply and installation of 50 mm dia. CPVC pipes for hot water supply with thermal insulation	40/m	-	-	50 m	2,000
Supply and installation of 40 mm dia. CPVC pipes for hot water supply with thermal insulation	31/m	-	-	350 m	10,850
Supply and installation of 32 mm dia. CPVC pipes for hot water supply with thermal insulation	26/m	-	-	630 m	16,380
Supply and installation of 25 mm dia. CPVC pipes for hot water supply with thermal insulation	21/m	375 m	7,875	430 m	9,030
Supply and installation of 20 mm dia. CPVC pipes for hot water supply with thermal insulation	18/m	1,000 m	18,000	1,070 m	19,260
Supply and installation of 15 mm dia. CPVC pipes for hot water supply with thermal insulation	15/m	750 m	11,250	650 m	9,750
Total			**105,875**		**205,270**

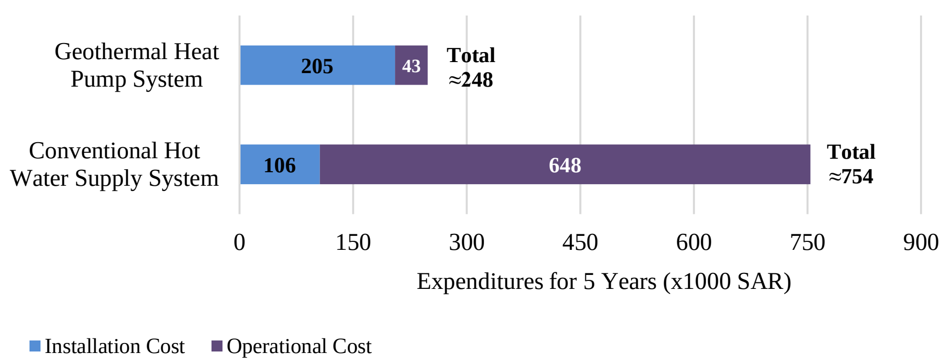

Figure 6: Economic Comparison of Conventional Hot Water Supply and GHP System for 5 years

On the other hand, the energy consumption of a GHPS is quite low, as it includes a hot water return loop system which reduces the load on the system by bringing back the unused water with sufficient retained heat instead of heating it again and again. Moreover, there is only one recirculating pump working for the system in addition to the compressor and heat distribution unit. The energy consumption for GHPS thus comes out to be 28.8 MWh for the whole season when the system is considered to be working for the same number of hours. The consumption tariffs as defined by the Government of Saudi Arabia are SAR 0.3/kWh. Hence for a period of 5 years, the cost of energy consumption for a conventional hot water supply system can be estimated to around SAR 648,000. Whereas this value for a GHPS comes out to be only SAR 43,200. Although the installation cost of GHPS is higher than the conventional hot water supply system, however, it proves to be very economical in a long run because of very low energy consumption, as proved by the LCC calculations. The comparison of installation and operational costs are shown in Fig. 6.

4 PRACTICALITY OF THE RESEARCH

The temperature of the internal surface of the Earth at a specific location remains almost equal to the annual average temperature of the surroundings above that surface, as proved by the phenomena of thermal inertia. It is also proved by the fact that during winter the internal surface of Earth feels warm and it feels cold during the summer season. As shown in Fig. 7, the annual average temperature of Dammam, a major city of the Eastern region of Saudi Arabia, is found to be 27.2 ºC [17]. It can be observed that the temperature of Earth's crust, which is the average annual temperature, remains higher from the mid of November till the mid of March. Hence during this duration of 4 months, there is a huge potential of extracting energy from the surface of the Earth in the Eastern region of Saudi Arabia by using GHPS for hot water supply.

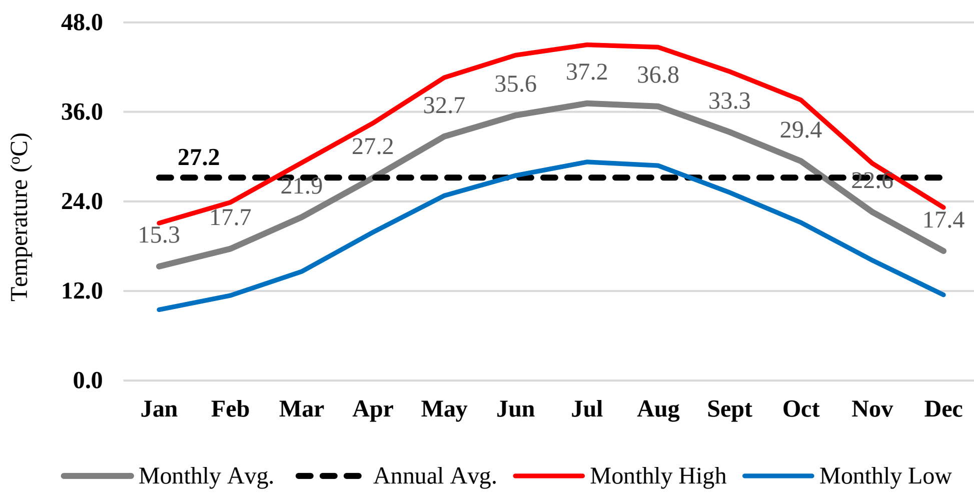

Figure 7: Temperature chart for Dammam based on the data collected from 1980 to 2016 [17]

As discussed in Section-1, most of the work related to GHPS, found in literature is done for space heating, floor heating, and water filtration techniques. However, the results obtained in this research are complimenting the results of the previous studies wherever water is involved as the heat absorbent. The methodology discussed in this research can widely be applied for apartments, hotels, and such building types where the consumption of hot water is comparatively higher.

5 CONCLUSION

An economic comparison was conducted for a conventional hot water heating system by using individual electric water heaters in each toilet against the technique of supplying hot water by using a geothermal heat pump system for an apartment building in Saudi Arabia. After the hydraulic design and analysis of both systems, a detailed cost estimate was prepared by obtaining the price of each material from the local markets in the Eastern region of Saudi Arabia. The installation cost for a GHPS was found to be almost doubled the cost of the installation of electric water heaters. However, the energy-related calculations for five winter seasons showed that the cost of energy consumption of electric water heaters was too high as compared to the energy consumed by a GHPS for the same period. The LCC technique was used to see the overall impact of the cost of both systems for a period of 5 years and it was found that the conventional hot water heating system cost around SAR 754,000 whereas, the same for GHPS was found to be three times less, valuing up to SAR 248,000. The GHPS system has shown a significant drop in energy consumption for an apartment building. Though the system is not much common yet however it must be adopted by the construction experts and designers to play their role in the Country's efforts of reducing the reliance on oil-based resources and achieving the goals of Saudi Vision 2030.

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