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Effects of Installing a Geothermal System in a Residential Building for Cooling Purposes in Lucknow, Uttar Pradesh, India

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Abstract: In the last century, urban expansion has doubled the electricity demands and has also contributed to the increase of Urban Heat Islands (UHI) subsequently triggering the phenomenon of global climate change. Electricity is mainly consumed in residential buildings all over the world, contributing to the rise in temperature and the UHI phenomenon in big cities. In this regard, this study has tried to investigate the effect of adding a geothermal or ground source heat pump (GSHP) system in a residential building for cooling purposes in a hot climate such as the summer season in Lucknow city of India. This study has used Design Builder to make a building model of a residential building and then used Energy Plus as a simulation tool for comparing the change in CO₂ emission and electricity or energy consumption for cooling, before and after the installation of GSHP in the residential building in a hot dry climate. The simulation has shown a significant impact on the residential building after the addition of a geothermal system. The temperature gets reduced by 9.3% in Zone 1, 10.75% in Zone 2, and 5.9% in Zone 3. In addition, CO₂ emission and electricity consumption of the entire building has reduced by 28.1%. The thermal comfort increased and the CO₂ emission was reduced which provided a solution for increasing the sustainability of the building in the form of GSHP which will also help in the subsequent reduction of UHI and climate change.

Keywords: Ground source heat pump, Geothermal energy, Energy Plus software, residential buildings, Energy consumption reduction.

I. INTRODUCTION

These days, cities are defined by a lack of greenery, a high population density, and a large amount of built-up territory, which raises temperatures, creates the Urban Heat Island (UHI) effect, increases energy demand, and causes problems with climate change [1]. Today, the entire world is facing two big challenges; energy supply and climate change [2]. The majority of emerging nations have significant energy needs when it comes to cooling residential buildings. Owing to increased industry and population, buildings now use more than one-third of their energy for cooling. Some studies suggest that if the temperature is increased by 2°C it will cause an increase of 1 to 9% in electricity consumption. The demand for fuels derived from non-renewable resources, such fossil fuels, will rise as a result of this increase in energy consumption, which will lead to an increase in the production of greenhouse gases [3].

Renewable sources of energy may be applied as an alternative, particularly in hot dry climates, which are of vital significance because of the negative impacts due to the release of atmospheric greenhouse gases, which will lead to ecological issues and a surge in demand for fossil fuel reserves [4]. Today the obstacle is not merely to enhance and retain the thermal features of buildings but also to decrease the electricity demand necessary for building cooling in hot and arid regions, especially during summertime [5].

Sustainable techniques like the use of geothermal energy can be an option for cooling buildings in hot and dry climatic regions and also reducing the environmental issues caused by the generation of energy these days [6] (Lashin 2015). This research looks into the possibilities of using a ground-source heat pump (GSHP) system for cooling residential buildings in dry and hot climatic regions and partial replacement of an

HVAC cooling system which will eventually reduce the emission of greenhouse gases. A simulation method was used in this research to measure the changes that occurred after installing a geothermal system for cooling residential buildings. The overall reduction in temperature, carbon emissions, and energy consumption will make it a sustainable building.

Geothermal Energy

The word geothermal can be broken down into two words 'geo' and 'thermal' which mean 'earth' and 'heat' respectively. The soil is observed to possess a stable temperature in the temperature range of about 16 to 29°C at a depth of about 6 to 10 m all year around and it can be used as a source for heating and cooling buildings, energy generation, or for direct underground heat. The GSHP system also called as geothermal system works basically on the stable earth temperature principle for cooling and heating purposes. This system uses ground loops to connect it to the earth and treat it as a sink or source for both cooling and heating purposes [8]. Geothermal energy systems also find their application in hot springs which can directly be used for cleaning and bathing purposes [9]. Although this system has a high initial construction and installation cost its benefits in the context of the environment and economy overpower it when compared to other sources in the renewable category [10]. There are many studies that show that using geothermal systems can cause a high reduction in energy use [11]. A high reduction in carbon emission can also be expected from the system which is beneficial for the environment [12] [11].

A study conducted on a residential building in Oregon, USA shows that a high reduction in cost is observed by the reduction in energy consumption. According to a Canadian residential complex's analysis, CO₂ emissions have decreased by 50% after using geothermal energy [11]. In a US residential complex, the addition of a GSHP system resulted in a 49% decrease in energy use. A 19.7% decrease in electricity consumption was noted in a residential building in Cairo, Egypt [13]. The reduction in CO₂ emission for a residential building in Alexandria, Egypt after the installation of a geothermal system was found to be 22.93% [14]. A reduction in energy consumption by 25 to 75% is observed by using a geothermal energy system making it a sustainable solution in northern and central Europe [15]. Middle Eastern countries like Egypt have not yet explored geothermal energy systems due to their high initial cost and lack of studies in the area [16]. It can also reduce the emission of carbon by 7 kg/m² but it has a high installation cost and requires skilled professionals who are fewer in number [17]. It can also benefit the environment by reducing fossil fuel use and thus subsequently reducing gas emissions and global warming [18]. Besides reducing energy consumption, it also has a very low maintenance cost [19]. Its contribution to reducing emissions and thus making the environment clean can improve human health by protecting it from various diseases [20].

Geothermal systems mainly differ in their design, method of installation, pipe thickness, and drilling method. Geothermal systems can be classified into two parts; open-loop systems (OLS) and closed-loop systems (CLS) [17]. The close loop

system with horizontal configuration can be easily installed but it requires a large area in the installation process [21]. The CLS system with vertical configuration is suitable for most of the sites and requires a small space for installation but this system is costly (drilling) [9]. The OLS system with groundwater (one well and double well) configuration is thermally efficient and requires limited floor space [21], [22]. Sometimes a hybrid system may also be used by combining a horizontally configured CLS system with a solar energy system and it has high thermal efficiency [23].

Geothermal Energy in the Indian Context

In India, the exploration of geothermal energy is still in its initial stage and very few studies have been conducted in this regard. Shahare and Harinarayana 2016 have analyzed the use of geothermal energy for space conditioning by using a heat exchanger and validating it by computational fluid dynamics (CFD) modeling. The advancements in the field of geothermal heating and cooling systems have been reviewed by Dhepe and Krishna 2017a. However, GSHP is garnering more interest for cooling purposes in many regions [25].

II. MATERIALS AND METHODS

The effectiveness of the geothermal system (GSHP) has been evaluated in this study by the use of a simulation tool to determine the reduction in carbon emission, and electrical energy consumption and also for achieving cooling comfort in a hot climate by using DesignBuilder software which is based on EnergyPlus as a simulation tool. A vertical close loop system (GSHP_{CV}) was used in this study because it is a cheap and effective system.

First of all, a study area was selected for which the climatic condition simulation had been done. After that, the geometry model of a building was made using DesignBuilder software. Various data and information about the building components and its environment were entered into the program and after that simulation process was performed; first for the current situation and then after adding a geothermal system. Analysis and study of the difference between both situations have been done in three contexts namely electricity consumption, carbon emission, and temperature difference.

Study area

Lucknow, the capital city of the most populated state of India, Uttar Pradesh, was chosen for the study because of the recent heatwave that occurred in the year 2024, at the time when this study was performed. The location of the study area is shown in **Figure 1**. The climatic condition of Lucknow was entered into the system for simulation.

Building model

A building model was made in the DesignBuilder with all its descriptions according to the local buildings built in Lucknow. It was made up of random geometry but its components and materials were selected based on the study

area. The model which was built in the Design Builder is shown in **Figure 2**. This building model can be divided into three zones. Zone 1 consists of the single-story part of the building which is located in the front part of the building. So, this zone has a ground floor and a roof. Zone 2 is situated just behind Zone 1 which consists of the ground floor part of the two-story building. Zone 3 consists of the first floor and roof part of the building. The information about the description entered into the system is shown in **Table 1**. The building accommodates a total of eight members and three workers. This building has an HVAC system for cooling like most of the buildings in the Lucknow region. This system is used for cooling mainly in hot seasons which usually span over from May to July.

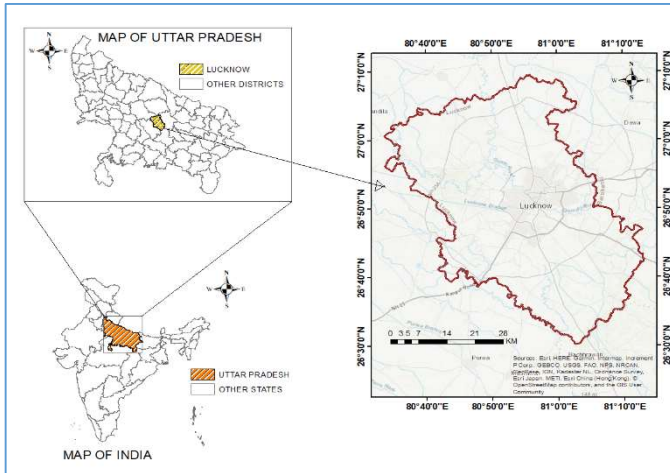


Figure 1. Location of the Study Area

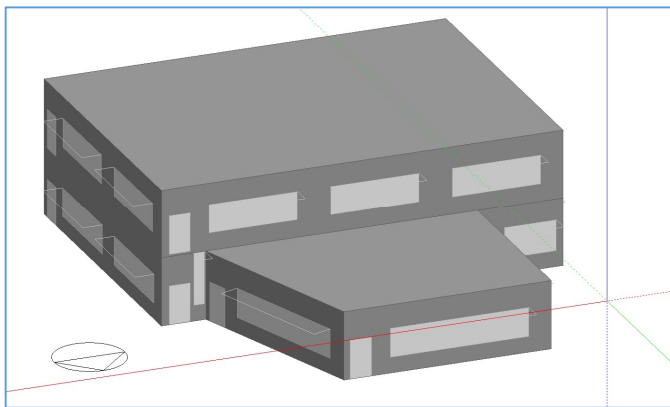


Figure 2. The Building Model Used for Simulation in the Design Builder

TABLE 1
Description of the Case Study Model

Elements	Description
Number of Zones	3
User description	0.0188 person/m ²
Year of construction	2023
Building type	Residential
Plan area of the building	690 m ²

Energy Plus software was used for the simulation purpose in this study to measure the changes occurring before and after adding GSHP into the building. Simulations were done in series to capture the change in CO₂ emission, energy consumption, and building temperature during the peak month of June. The model shown in **Figure 2** was evaluated in Energy Plus.

Parameters Used in Modeling

The results of the simulation process were affected by the modeling parameters taken into consideration. The summarization of these parameters was done and presented in **Table 2**, and **Table 3**. The calculation of the thermal loads in terms of lighting features, occupancy, and electronic devices was also done as per the American Society of Heating, Refrigerating, and Air-conditioning Engineers (ASHRAE) guide.

TABLE 2
Modeling Parameters Used in the Building.

Components	Description
External walls	Brick/block wall of 25 cm thickness (1 cm of paint)
Flat roof	Flat roof U – value = 0.25 w/m ² k (reinforced concrete of 15 cm thickness with 5 cm leveling sand and a moisture seal of 2 cm)
Internal partitions	Lightweight 2*25 mm gypsum plasterboard with 100 mm thickness
Ground floor (Zone 2)	Ordinary concrete of 15 cm thickness with 5 cm leveling sand and a moisture seal of 2 cm
Door	Wooden doors of 1.10 m width and 2.00 m height (both external and internal), frame width of 4 cm
Window	0.8 m width and 1.1 m height (sill height of 0.6 m, double glazing, 0.5 m overhang)

TABLE 3
GSHP System Description

Parameters	Values
Pipe radius	0.25 m
Pipe thickness	0.02 m
Pipe thermal conductivity	200 w/m-k
Pipe depth under-ground surface	3.50 m
Pipe length	15 m

Calculation Model

The calculation of temperature and electricity consumption was done using EnergyPlus software as shown in **Figure 3** and **Figure 4**. The electricity generation in Lucknow city is based on thermal power stations that use coal for their operation. As per the report of the CO₂ baseline database for the Indian power sector released by the central electricity authority of the government of India, 0.82 kg of CO₂ is emitted for every kWh of electricity generated [BD]. This information was used for the calculation of CO₂ emission for the building. If the energy consumption in the building is represented by (A) kWh then the CO₂ emission from the building will be

$$\text{CO}_2 \text{ emission in kg} = A * 0.82 \dots \dots \dots (1)$$

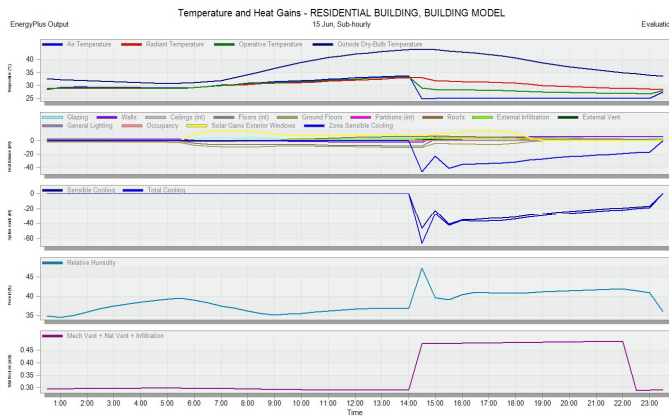


Figure 3. Temperature and Heat Gain Output of the Simulation

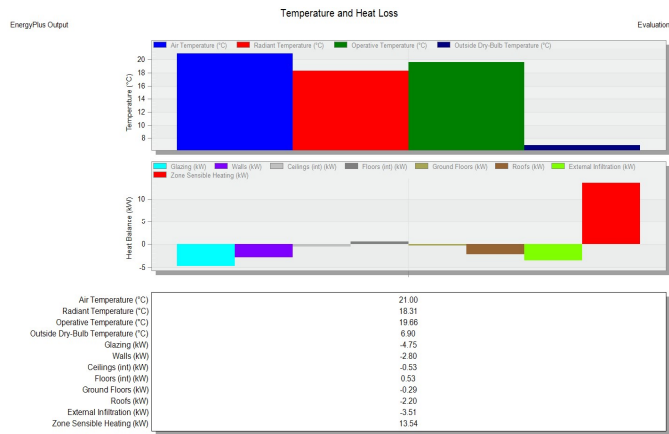


Figure 4. Temperature and Heat Loss Output of the Simulation

III. RESULTS AND DISCUSSION

The results of the study were divided into three parts. The first part presents the effect on temperature after the installation of GSHP in the residential building located in the hot and dry environment of the study area. The second part evaluates the difference in the consumption of electricity before and after the installation of GSHP. The third and final part measures the change in the amount of CO₂ emission before and after the addition of the GSHP system in the building.

Part 1: The temperature difference before and after the installation of GSHP

The temperature observed in Zone 1 of the building in the current situation was 32.34°C and it becomes 29.34°C after installing GSHP in the building. The temperature in Zone 2 was 31.99°C and 28.55°C before and after the addition of a geothermal system in the residential building respectively. The observed temperature in Zone 3 was 34.36°C in the current situation and 32.33°C after the installation of the GSHP system in the building. The change in temperature for each Zone is shown in **Figure 5**.

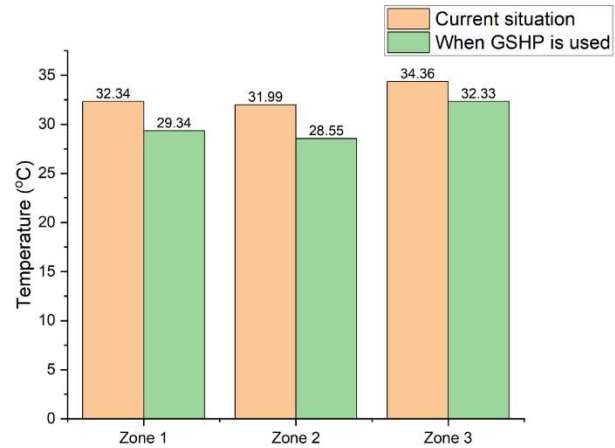


Figure 5. The Difference in Temperature before and after the Addition of the GSHP System in all Zones

The reduction in temperature may be attributed to the cooling effect of geothermal energy which maintains the temperature of the building in resonance with earth's temperature. The effect of the GSHP system can be observed in terms of the reduction in temperature on each floor. A temperature reduction of 9.3%, 10.75%, and 5.9% was observed in Zone 1, Zone 2, and Zone 3 respectively in the peak month of June.

Part 2: The reduction in electricity consumption in the residential building before and after the addition of a GSHP.

The result obtained for electricity consumption in Zone 1 in the current situation and after the addition of the GSHP system was 756.24 kWh and 560.34 kWh respectively. The reduction in energy consumption was observed to be 25.9% in Zone 1 of the building. The decrease in energy consumption was 105.81 kWh in Zone 2 after adding the GSHP system. This decrease in energy consumption is due to the effect of geothermal energy use incorporated in the study which reduces its dependence on conventional sources. Along similar lines, the energy consumption was reduced from 1021.2 kWh to 720.43 kWh in Zone 3 after installing GSHP in the residential building. The result obtained is shown as a graph in **Figure 6**.

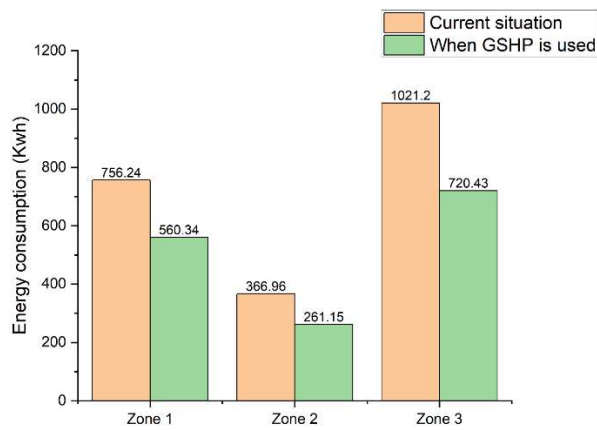


Figure 6: The change in energy consumption before and after the installation of the GSHP system

The reduction in energy use in terms of percentage for Zone 2 and Zone 3 of the building was 28.8% and 29.4% respectively. The overall reduction of energy consumption for electricity purposes for the entire residential building was found to be 602.48 kWh which was about 28.1% of the current electricity use as shown in Figure 7.

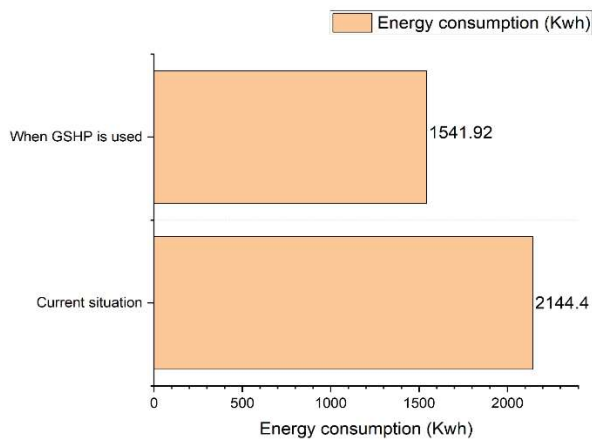


Figure 7. The overall energy consumption reduction in the building after adding GSHP in the building

Part 3: The CO₂ emission reduction after the installation of GSHP in the building

The energy consumption of the building was converted into CO₂ emission by the formula in equation (1) for each of the Zones in the building. The result obtained for Zone 1 was 619.92 kg and 454.47 kg before and after the addition of the GSHP system in the building. This shows that there was a reduction of 25.9% in Zone 1 of the building. The CO₂ emission observed in Zone 2 of the building was 300.94 kg for the current situation and it became 214.143 kg after the installation of the GSHP system in the building. So, a reduction of 28.8% was obtained after adding a geothermal system to the building. The CO₂ emission was reduced by 246.47 kg in Zone 3 which was 29.4% of the current situation. The reduction in carbon emission is proportional to the energy consumption as per equation 1, hence the reduction in energy consumption will also

trigger a change in CO₂ emission. The change in CO₂ emission is shown as a graph in Figure 8.

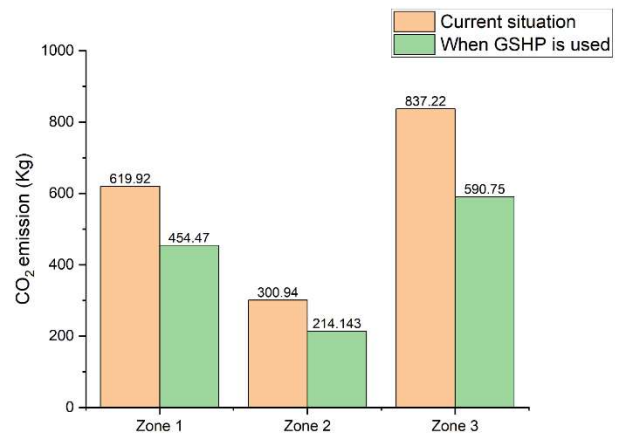


Figure 8. The change in CO₂ emission for each zone

The overall reduction in CO₂ emission was found to be 498.72 kg which is 28.4% of the current CO₂ emission in the building. The overall CO₂ emission is shown in Figure 9. The reduction in temperature, energy consumption, and CO₂ emission for each zone is shown in Figure 10, Figure 11, and Figure 12.

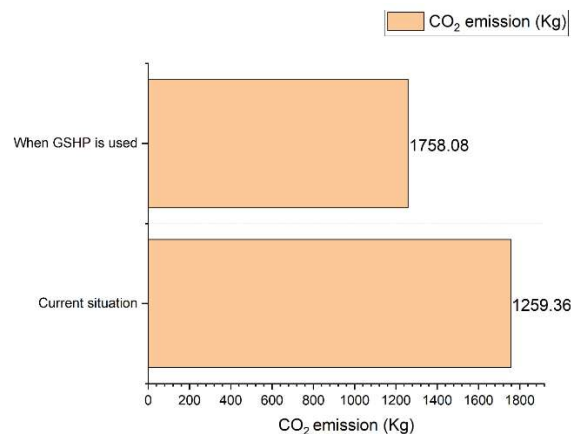


Figure 9. The decrease in CO₂ emission for the entire building

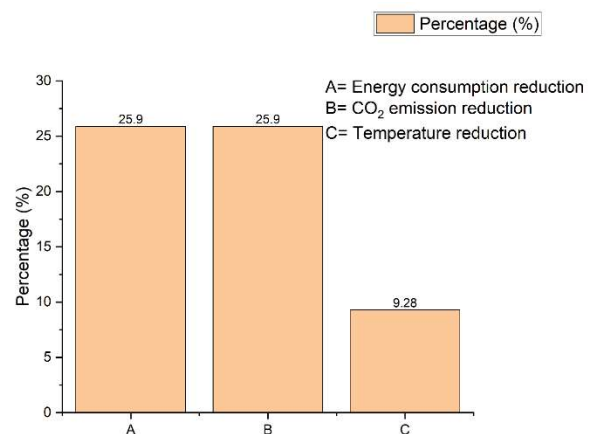


Figure 10. Reduction in temperature, energy consumption, and CO₂ emission for zone 1

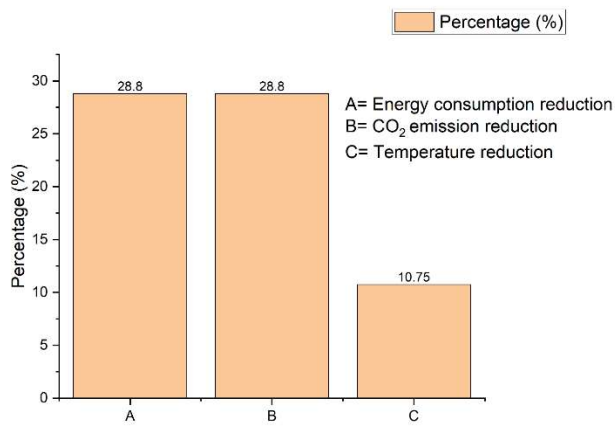


Figure 11. Reduction in temperature, energy consumption, and CO₂ emission for zone 2

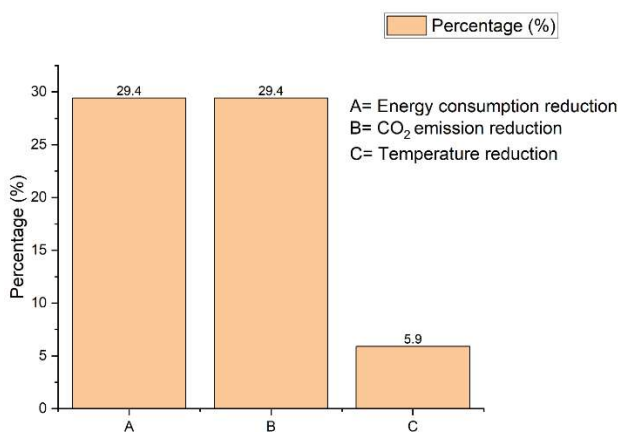


Figure 12. Reduction in temperature, energy consumption, and CO₂ emission for zone 3

The result of this study is found to be in agreement with other studies performed in this context. A study performed on a residential complex in Canada shows a reduction of 50% in CO₂ emission [11]. A reduction of 49% was observed in energy consumption after adding the GSHP system in a residential complex in the USA. The reduction observed in the electricity consumption in a residential building located in Cairo, Egypt was 19.7% [13]. The reduction in CO₂ emission for a residential building in Alexandria, Egypt after the installation of a geothermal system was found to be 22.93% [14].

III. CONCLUSION

As heatwaves are becoming common in many parts of the world a sustainable approach for cooling becomes very important for residential buildings. This study has shown and proven that the use of the GSHP system in a residential building helps in the reduction of temperature by 9.3% in Zone 1, 10.75% in Zone 2, and 5.9% in Zone 3. This study has also shown a reduction in CO₂ emission and energy consumption by 25.9% in Zone 1, 28.8% in Zone 2, and 29.4% in Zone 3. The overall reduction in CO₂ emission and energy consumption for the building was 28.1% after the use of the geothermal system. The results can be better if the spacing between pipes and depth of excavation can be designed properly

It can be concluded from this study that the addition of a GSHP system in the residential building not only helps in the reduction of temperature but also decreases CO₂ emission and the use of cooling energy. So, this decreases the negative effects of fossil fuels on the environment and also increase sustainability. This study can be a good tool for illustrating the benefits of the use of geothermal energy in the building and can also be instrumental in the endeavor toward sustainability in the use of energy for the buildings.

Acknowledgments

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