Fouad et al.
Journal of Engineering and Applied Science (2024) 71:45
https://doi.org/10.1186/s44147-024-00378-x

Journal of Engineering and Applied Science

RESEARCH Open Access

The effectiveness of geothermal systems in cooling residential buildings: a case study of a residential building in Alexandria, Egypt

Heba Fouad[1,2*], Ayman H. Mahmoud[1] and Rania Rushdy Moussa[3]

*Correspondence:
heba.fouad@sha.edu.eg

[1] Architecture Department, Faculty of Engineering, Cairo University, Giza, Egypt
[2] Architecture Department, Faculty of Engineering, The Higher Institute of Engineering in El-Shorouk, Cairo, Egypt
[3] Architecture Department, Faculty of Engineering, The British University in Egypt, Cairo, Egypt

Abstract

The urbanization of cities, the corroding of green areas, and the increasing demand for electric energy lead to the formation of heat islands in cities and the appearance of the global climate change phenomenon.

Therefore, it was necessary to resort to the use of renewable energy sources, such as geothermal energy, to be used in different applications, as it can be used to cool buildings in cities during the summer.

This research deals with the benefits of using geothermal energy systems, their different types, and the possibility of their application in Egypt. Also discussing the effectiveness of the vertical closed geothermal system in residential buildings in Alexandria Governorate in Egypt to reach an answer to a question.

The effectiveness of the geothermal energy system in residential buildings is to reduce the problem of rising temperatures, energy consumption for cooling, and carbon emissions and thus reduce the problem of the formation of heat islands in cities and the appearance of the global climate change phenomenon and reaching a sustainable, environmentally friendly building that achieves thermal comfort for humans through the use of a simulation program called TRNSYS-17, through which the current situation of the building was compared and the addition of a vertical closed geothermal system was assumed, the extent of its effectiveness was compared in the whole building, and the cost of a vertical closed geothermal system and a traditional air conditioning system (HVAC) in a building was compared (case study).

Hence, the efficiency of the vertical closed geothermal system appeared to reduce electric energy consumption and carbon emissions in the whole building at Alexandria in Egypt, especially the ground floor, which reached thermal comfort for humans and worked to reduce electricity consumption and carbon emissions by up to 22.93% in the building as a whole.

Keywords: Geothermal energy, Vertical closed geothermal system, Hot arid climate, Sustainable development, Renewable energy, Human thermal comfort, Urban heat islands (UHI), Global warming, Climate change

Introduction

Most countries around the world are targeting “renewable sources” as a future governmental initiative, especially developed countries, to reduce energy consumption and carbon emissions to limit the increase in global temperatures caused by the intensity of human activity, the absence of vegetation, the abundance of impermeable surfaces in cities, and increased energy consumption for cooling and heating [1], which causes an increase in the effects of both urban heat islands in cities (UHI), global warming, and global climate change. Therefore, climate change and energy supply are considered the two biggest challenges facing the world today [2].

Since one of the main reasons for the increase in energy consumption in Middle Eastern countries is cooling buildings due to population growth, industrialization, and the hot climate, more than a third of the energy consumed in buildings is spent on cooling systems [3]. So, it was necessary to turn to renewable energy sources such as solar energy, wind energy, and geothermal energy to provide energy without depleting traditional energy sources and without any negative impact on the environment at the lowest costs.

Geothermal systems in buildings are especially characterized by their many long-term environmental and economic benefits compared to other renewable energy sources, so the use of geothermal energy systems to heat and cool buildings has been evaluated and applied in many countries, such as the USA, the UK, the Kingdom of Saudi Arabia, and India, without testing it widely in countries with tropical and subtropical climates, Middle Eastern countries, and Egypt.

Although these countries are facing many problems related to energy efficiency, there is an increasing demand for it, and there is an increase in carbon and heat gas emissions. For example, in Egypt, we notice an increase in the rate of electrical energy consumption to cool buildings, which is responsible for 26% of the total consumption of electrical energy in buildings and 62% of the total consumption of electricity in cities [4].

However, renewable energy sources have not been sufficiently exploited, and only a few researchers have been interested in exploiting it in cooling buildings in this country.

Also, the use of geothermal energy in heating commercial buildings was investigated, and the environmental and economic efficiency of it was studied, but no attention was paid to residential buildings, although it is considered the second most important human need and is considered one of the most energy-consuming and carbon-emitting sectors in cities [5]. They also contribute to forming the largest part of the city’s area. The amount of carbon emissions resulting from it is large compared to the rest of the sectors.

Hence, the research aims to study the effectiveness of applying thermal energy systems to cool residential buildings in Egypt, evaluate it environmentally and economically, and propose it as a practical solution. It contributes to solving environmental problems resulting from climate change, heat islands, and increasing energy consumption for cooling in residential buildings by evaluating the effectiveness of the vertical closed geothermal system and determining its impact on reducing electrical energy consumption, reducing carbon emissions, and achieving thermal comfort for humans to ensure its efficiency in reducing the island effect and thermal insulation in residential buildings in Egypt.

This is done by selecting an existing residential building in Egypt, analyzing its current situation using the simulation program TRNSYS-17 and comparing the current situation with the assumption of adding a vertical closed geothermal system to the building in order to determine which is more efficient in reducing electric energy consumption, reducing carbon emissions, and accessing the thermal comfort of the person in the building and to determine if this system is useful and economical for its use in Egypt or if it is necessary to resort to other better solutions. Then, it evaluates its role in reducing the negative effects of heat islands and climate change on the Egyptian residential environment.

Geothermal systems in buildings

There are many geothermal systems that can be applied to heat and cool buildings, which differ from each other in design, implementation method, drilling method, pipe thickness, etc., so they can be divided into two different categories: surface geothermal systems with open loops and surface geothermal systems with closed loops (vertical, horizontal, submerged in a pond or lake, with geothermal substrates) [6], which is considered the most common system because it is the easiest and cheapest ground loop to install [6]. There is a new system that was issued recently, and it is a combination of renewable energy and geothermal energy and is considered one of the most efficient systems [7], as shown in Table 1.

Benefits of using surface geothermal systems in buildings

According to previous studies, the use of geothermal systems in buildings provides many benefits at all environmental, economic, health, psychological, social, and esthetic levels that accrue to the user, the city, and thus the world as a whole [8]. It saves energy and reduces pollution. In Table 2, there is a brief explanation of those benefits and their impact on all levels [9].

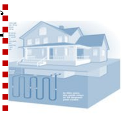
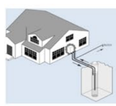
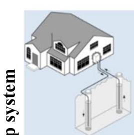
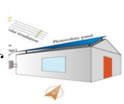
Therefore, the research will study the effectiveness of this system and its application in Egypt to benefit from these environmental, health, and economic benefits by identifying the potential of geothermal energy in Egypt and applying one of its systems there.

The potential of geothermal energy in Egypt

As a result of many studies and analyses that were carried out in Egypt by many researchers, the various geothermal energy resources in it were evaluated through the analysis based on geographic information systems for many places and the analysis of the geothermal characteristics of the Bahariya Oasis, the Western Desert, and the study of geothermal energy around the Red Sea. In addition, the Gulf of Suez uses magnetic methods [6].

Egypt appeared to have a relatively low estimated content of about 251 billion US dollars, consisting of 15 hot springs and 52 thermal wells located along the Gulf of Suez, the Red Sea, and the Western Desert, which differ from each other in surface temperatures ranging between 23 and 71 °C in hot springs and 35 and 50 °C in thermal wells, as shown in Fig. 1.

Table 1 Different types of geothermal systems

Type	Formation	Configuration	Description	Site Requirements	Advantages	Disadvantages
Closed loop system		**Horizontal**	Pipe network is in the ground, at a depth of about 1m-2m below the freezing line, depending .on local conditions	A large area of open land, preferably not shaded	Simple installation, lower construction cost and almost zero operating cost	Large open space required for installation
		**Vertical**	Vertical pipes are inserted into holes dug at a depth of 15m-120m	Suitable for most sites	It can be installed in a small space, with almost no operating cost	Higher cost (drilling); It requires the approval of the concerned authorities before implementation
		**Obscure**	A coiled tube or plate heat exchanger placed in water such as a river or lake.	Near to water bodies to support the system	Land space is limited, lowest cost of all closed loop systems	Possibly Requiring Supplier Approval for River/Lake Stream Works
Open loop system		**Groundwater (one well and drainage field)**	Access to the aquifer and lands suitable for receiving wastewater	Access to the aquifer and lands suitable for receiving wastewater	Thermally efficient, limited floor space required	high cost (drilling); taking and draining spent groundwater; Likely to require supplier approval
		**Groundwater (double well)**	A well is drilled to reach the groundwater, and then another well is drilled to drain the groundwater back into the same reservoir or groundwater	access to the aquifer	Thermally efficient, limited land area required, takes up unused water	high cost (drilling); likely to require supplier approval
		**Surface water**	Direct intake of surface water from a stream/river/lake. Wastewater is returned to the source	Near to bodies of water of sufficient size to support the system	Thermally efficient, limited land area, utilization of unconsumed water, less expensive if it is close to a water source than construction and more expensive when operating	The approval of the concerned authorities is required to take the water and drain it on the course of the river/lake
Hybrid system		**Closed system (Horizontal) + Solar energy systems**	A horizontal or vertical pipe network is dug into the ground, as well as a solar or wind system, etc., on the roof of the building	Suitable for most sites	Can be installed in a small space, thermally ,efficient	Higher cost (drilling); It requires the approval of the concerned authorities before implementation

Volumetric estimates through the HYDROTHERM model showed that the reservoir with a temperature of 170 °C and a depth of more than 1 km could generate 28.34 MW of electrical energy.

The entire Sinai over a period of 35 years [15] and temperature distributions of 90–180 °C were determined at a depth of 2–3 km with a preference for the use of open system or closed system submerged geothermal energy along the Gulf of Suez and the Red Sea [16].

This indicates the possibility of exploiting it for energy generation. For example, in the Bath of Pharaoh (Gulf of Suez), the deep temperature in it can be exploited in energy generation (over approximately 30 years of production) based on the results

Table 2 Benefits of using surface geothermal systems in buildings and their impact on all levels

Category	Benefit
Environmental [10]	- Reducing the use of conventional fossil fuels - Reducing global warming and gas emissions in cities, as it does not cause any emissions when installed and used
Economic [11]	- Reducing energy consumption by 20% to 50% compared to conventional energy - It has low maintenance costs that are almost nonexistent, as it provides low operation and maintenance costs. The system's life span reaches 50 years - It can be used to reduce the consumption of electrical energy for cooling and heating buildings by 25% to 50% compared to conventional heating or cooling systems - It can be used to heat water and swimming pools in buildings
Health and psychological [12]	- Contribute to creating a clean environment that helps improve human health and makes him live in a clean environment that protects him from diseases - Enables the user to reach thermal comfort continuously and with high efficiency - Provides calmness, which helps a person improve their psychological state and quality of life
Esthetic [13]	- It is possible to benefit from the entire site in various activities beautifully without any obstacles - Prevent the appearance of air conditioning devices in the building or on its roof
Social [14]	- Reducing unemployment rates and creating job opportunities for youth - Maintain good relations with neighbors and increase interdependence between them
Other (https://www.vpsupply.com/products/renewable-energy/geothermal)	- Investing untapped resources (the land under the building) - Renewable and always available: it is available permanently and continuously without interruption, because it is not affected by the surrounding climatic conditions compared to other renewable energies

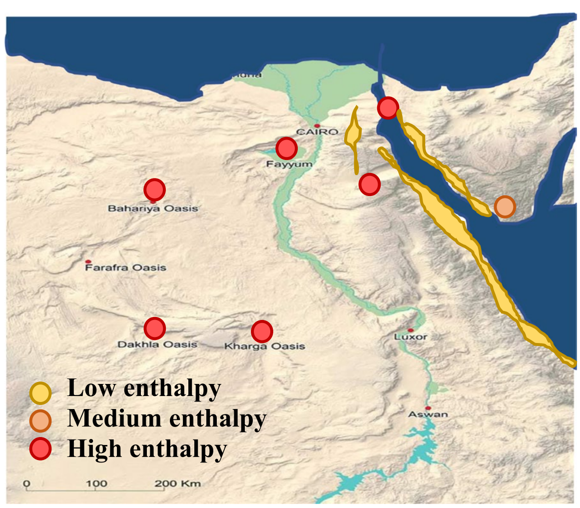


Fig. 1 Heat content classification of geothermal energy resources in Egypt. Source: A discussion on the potential use of shallow geothermal energy for cooling in Egypt, 2019

that indicate that the temperature in a thermal reservoir with a depth of 500 m is 130 °C; then, it can be classified, as shown in Fig. 1.

Hence, the geothermal energy resources in Egypt can be classified as shown in Table 3.

Table 3 Heat content classification of geothermal energy resources in Egypt

Heat content	Geothermal energy resources
Low enthalpy	The Oases of Kharga and Bahariya (Western Desert), Oyoun Musa and Ain Sukhna (Gulf of Suez), and the sulfur springs of Helwan, south of Cairo [17]
Medium enthalpy	Pharaoh's bath
High enthalpy	Along the rift in the Gulf of Suez and the Red Sea

A study of the possibility of exploiting geothermal energy in buildings in Egypt

Average ground temperatures in Egypt range from 15° to 25° at a depth ranging between 20 and 50 m, and they can be used either for direct cooling or to reduce the use of electric air conditioning units used in commercial and domestic buildings [18].

Recently, a new trend has appeared at the governmental and commercial levels to use geothermal energy to solve the growing problem of air conditioning in buildings in cities because of the following:

a. Reduces electricity consumption for air conditioners as it consumes approximately 100 MWh per 1 °C when the atmosphere temperature rises above 35 °C [19]
b. It limits the heat waves in the summer, especially the long ones, such as those in Alexandria, where millions of people need air conditioning, thus forming a large urban heat island in it [17]
c. Reduces pollution and improves air quality in the heat islands, where geothermal air conditioning can provide electricity better and more efficiently in Alexandria while reducing the burning of fossil fuels

Since Egypt is the most populated country in the Middle East and has relatively low reserves of oil and gas, it provides an opportunity to invest in renewable energy, especially in the production of geothermal energy, and since the majority of the country's energy is consumed by industries (47%) and buildings (20%).

Therefore, geothermal energy is an alternative energy option for Egypt. Moreover, there is a large land area (94% of desert land).

Some countries will explore geothermal energy resources as an alternative source of energy in the future, so we must think in an innovative way to develop an environmentally friendly building that reduces energy consumption, reduces heat islands, faces global warming and climate change, and limits the depletion of non-renewable energy sources by using geothermal energy in buildings. This is in order to reach a sustainable building that achieves thermal comfort for humans, through many data sets, studies, and analyses, as shown in Fig. 2.

These applications still require qualified people and technologies in the fields of geothermal energy investigation, design of power generation, cooling and heating systems in buildings, management of geothermal energy projects, monitoring systems that will be allocated to the Egyptian market, raising awareness in society, and decision-making about geothermal resources.

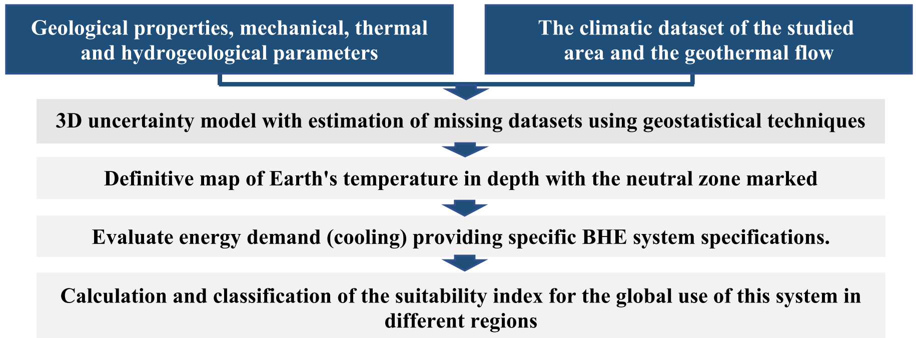


Fig. 2 Shows the data, studies and analyzes that must be considered to achieve the maximum benefit from geothermal energy systems to achieve thermal comfort in buildings

The population density in Egypt is concentrated on the banks of the Nile, especially in Cairo and the Delta, which makes these areas more energy-consuming and carbon-emitting.

Therefore, it is preferable to use a vertical closed geothermal system due to the lack of sufficient spaces to establish horizontal thermal energy systems and the lack of energy reservoirs in all regions. So, I will choose a vertical closed-loop geothermal system on the North Coast for application in this study.

Methods

The methodology is a simulation tool to study the effectiveness of applying thermal energy systems to cool residential buildings in Egypt, with the purpose of evaluating it environmentally and economically and determining its effect on reducing electrical energy consumption, reducing carbon emissions, and achieving human thermal comfort and, at the lowest cost, ensure its efficiency in reducing the island effect in Alexandria, Egypt.

The methodology used in this research was explained and clarified, and the stages that the research went through were identified, as shown in Table 4, and in it, the vertical closed geothermal system was chosen to be used in this study because it is considered the most effective and cheapest system among all geothermal systems, as shown in Fig. 3. It consists of a traditional distribution system inside the building,

Table 4 Stages of evaluating geothermal energy systems based on an applied case

The stages	Evaluating geothermal energy systems based on an applied case
The first stage (experimental stage)	At this stage, a choice is made about the study area that is the most populous and the most energy-consuming. The building's geometry is determined by the current situation, and the building is drawn on a SKETCH UP-2014 program
The second stage (monitoring stage)	Completely enter data information in the program TRNSYS-17 and analysis the case study situation and the thermal loads of the current in the building
The third stage (analysis stage)	Analyzing and studying the difference between the current situation of the building and adding a vertical closed geothermal system to each floor (difference in temperatures, electricity consumption, carbon emissions) and the difference in economic when purchasing and installing each system

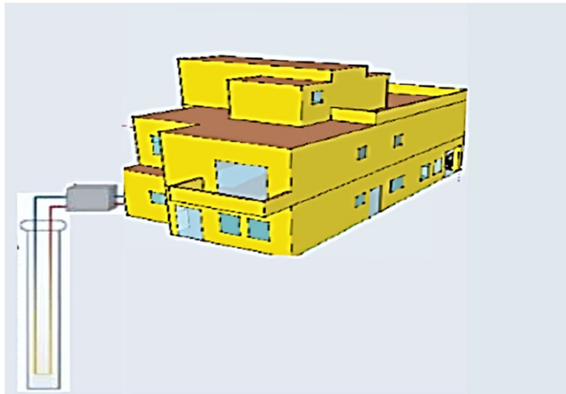


Fig. 3 The geothermal system add to building. Source: SKETCH UP-2014 program

a ground heat pump, and vertical closed ground loops, as shown in Fig. 4, and the TRNSYS-17 software as a simulation was chosen to be used in this study to measure the thermal loads and electricity consumption inside the case study.

The first stage (experimental stage)

In this study, the study area was selected, the building geometry of the current situation was determined, and the building (study case) was drawn on a program SKETCH UP-2014 program. What happened at this stage can be explained by the following points.

Choose a case study area

According to previous studies and analyses in terms of population [20] and energy consumption [21] for each governorate, as shown in Figs. 5 and 6, Alexandria, Egypt, was chosen as a study area because it is considered one of the most populous governorates in Egypt with population density and electricity consumption, and it has a relatively low percentage of green spaces and is more attractive to the population at the level of the rest of the governorates.

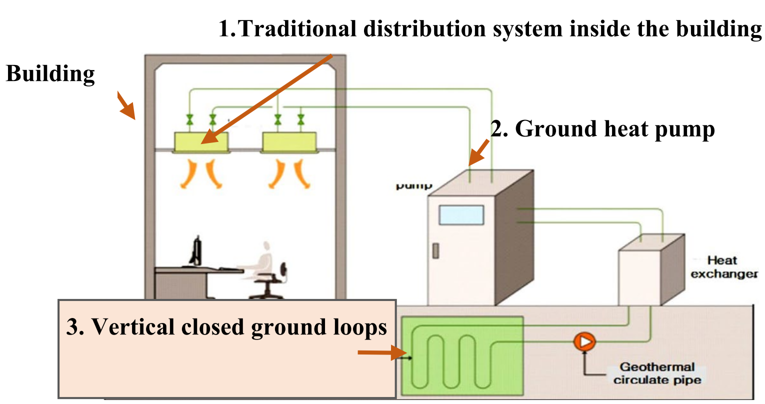


Fig. 4 The type of geothermal system chosen. Source: SKETCH UP-2014 program

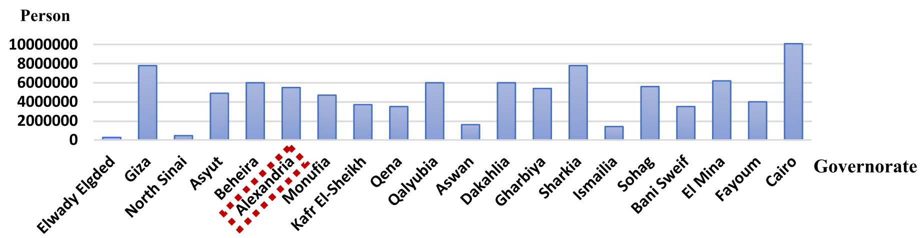


Fig. 5 Shows the population of each governorate of the Arab Republic of Egypt. Source: The Central Agency for Public Mobilization and Statistics in Egypt, 2023

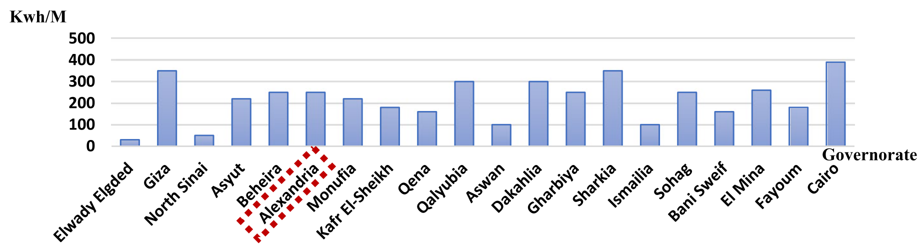


Fig. 6 Shows the consumption of electricity kilowatt-hours/mon Building geometry. Source: Ministry of Electricity and Energy website, calculate consumption in February 2021

Therefore, it is one of the most appropriate governorates to determine the impact of geothermal energy systems on the formation of heat islands in cities and human thermal comfort.

The building geometry of the current situation was determined

A traditional, two-story residential building located in the fifth settlement in Cairo, Egypt, was chosen randomly to be simulated in this research as shown in Fig. 7. The design of the building is shown in Fig. 8.

The building consists of a ground floor, a first floor, and a roof. It accommodates a large family consisting of six members and two workers, as shown in Fig. 6 and described in Table 5. This building, like most of the buildings located in Cairo, has an HVAC system used to cool the building during the hot seasons, which almost takes place between March and October.

Fig. 7 The case study design

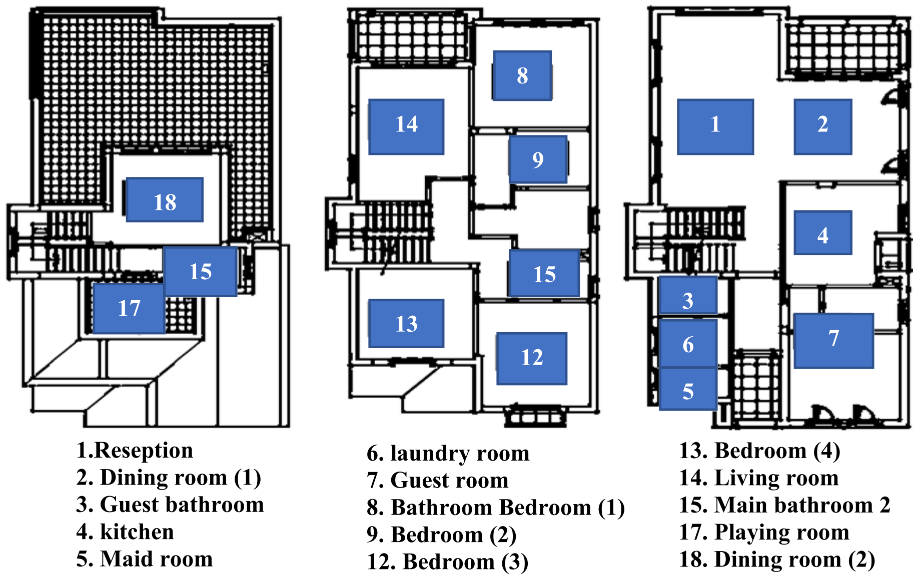


Fig. 8 The case study design and components

Table 5 Case study description

Case study	Description
Number of floors	2 floors and a roof
Number of users	6 persons + 2 occupants
Year of construction	2020
Type of building	Residential
Land area	250 m^2
Building area	144 m^2

The second stage (monitoring stage)

At this stage, data and information about the case study are collected, the modeling parameters for the current situation and the VCGS system are determined, and they are set in the program TRNSYS-17, to determine and analyze the current status of the building and when adding a geothermal system to each floor in terms of a thermal analysis of the current situation and its thermal loads.

Case study simulation

The TRNSYS-17 software was used as a simulation tool in this research to measure the cooling load inside the building before and after using the vertical closed geothermal system. A series of simulations were conducted to capture the effect of the vertical closed geothermal system on the building's heat, energy consumption, and carbon emissions reduction during the year, especially during the peak period.

A 3D model for the case study was built as a primary stage using the Sketch Up software, as shown in Fig. 9. This model was imported into the TRNSYS software for simulation.

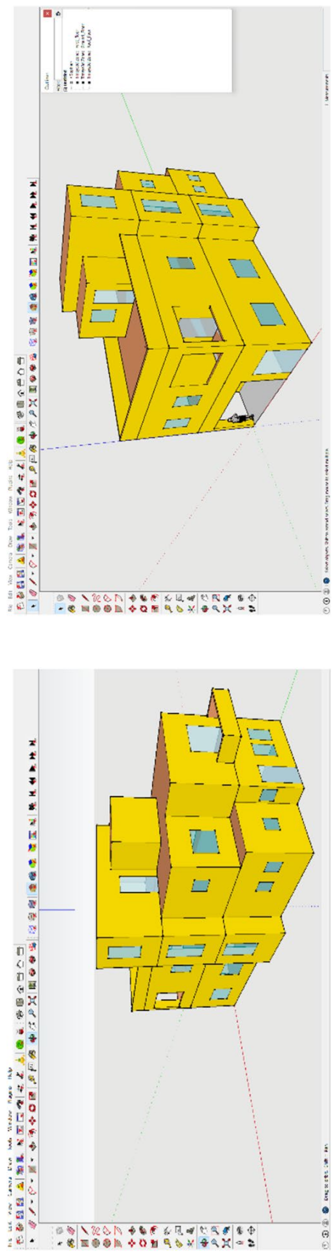


Fig. 9 The case study modeling on Sketch Up software

Modeling parameters

There were some parameters taken into consideration during the modeling process that affected the simulation results. All the modeling parameters were summarized and presented in Tables 6, 7 and 8.

There are many factors affecting the internal thermal loads of the building, such as users, indoor lighting, and the heat gain from operating equipment and devices; these factors contributed to the increases in the thermal loads inside the indoor spaces. According to the ASHRAE Guide [22], which is presented in Table 9, the thermal loads were calculated in terms of occupancy, lighting features, and electronic devices.

Taking into consideration the thermostat set point for the HVAC system, it is assumed to be 24 °C for optimal cooling, with an acceptable range of 23–26 °C.

Table 6 Modeling parameters in building envelop and layers

Ground floor layers	Floor layers	Surface layers	External wall layers
- Ceramic 50 × 50 × 1 cm - Cement mortar, 2 cm - 5 cm leveling sand - Fine concrete 10 cm - Moisture seal 2 cm - 15 cm ordinary concrete - Backfill	- Ceramic 50 × 50 × 1 cm - Cement mortar, 2 cm - 5 cm leveling sand - Reinforced concrete 15 cm - Internal mortar, 2 cm - 2 cm of paint	- Ceramic 50 × 50 × 1 cm - Cement mortar, 2 cm - 5 cm leveling sand - Concrete slopes of 7 cm - Moisture seal: 2 cm - Reinforced concrete 15 cm - Internal mortar: 2 cm - 2 cm of paint	- 1 cm of paint - External clamshell, 2 cm - A brick of 25 cm - External clamshell, 2 cm - 1 cm of paint

Table 7 Physiothermal properties of wall layers in the case of the study

Wall layers	Thickness (cm)	Thermal conductivity (W/m C°)	Density (kg/m^3)	Thermal resistance (m^2 C°/W)
External grout	2	0.88	2800	0.0227
Clay bricks	25	0.6	1800	0.416
Inner grout	2	0.88	2800	0.0227

Table 8 Physiothermal properties of windows

Glass type	VT	SHGC	*U*-value (m^2 C°/W)
Clear single glass 6 mm	**0.88**	**0.81**	**5.8**

Table 9 Internal earning transactions according to the ASHRAE Guide (2013) [22]

Internal earning transactions	Values
Heat gain due to space occupancy	130 W/1 person
Heat gain due to the internal lighting of the space	10.5 W/1 person
Heat gain due to equipment, devices, and computers	21.5 W/1 person

The parameters set for VCGS system

The piping of a vertical closed geothermal system has been excavated and designed, as shown in Table 10.

Calculation model

Temperatures and thermal loads in the current situation in the building were calculated using the TRNSYS-17 software, as shown in Figs. 10 and 11.

The third stage (analysis stage)

At this stage, study the results and analyze the difference between the current situation and when adding the vertical closed geothermal system in terms of temperature difference, electricity consumption, carbon emissions, and the cost of purchasing and

Table 10 The parameters set for VCGS system

Parameters	Values
Loop fluid type	Water
Fluid freezing point (°C)	0
Fluid specific heat (Cƒ) (kJ/kg°C)	4.184
Fluid density (ρƒ) (kg/m^3)	999.6
Fluid thermal conductivity (λƒ) (W/m°C)	0.6023
U tube loop pipe configuration	Double U
Pipe outer diameter (m)	0.0334
Pipe inter diameter (m)	0.0313
Pipe thermal conductivity (λρ) (W/m°C)	0.3913
Pipe flow type	Turbulent
Borehole radius (rb) (m)	0.10095
Grout thermal conductivity (λg) (W/m°C)	0.6926

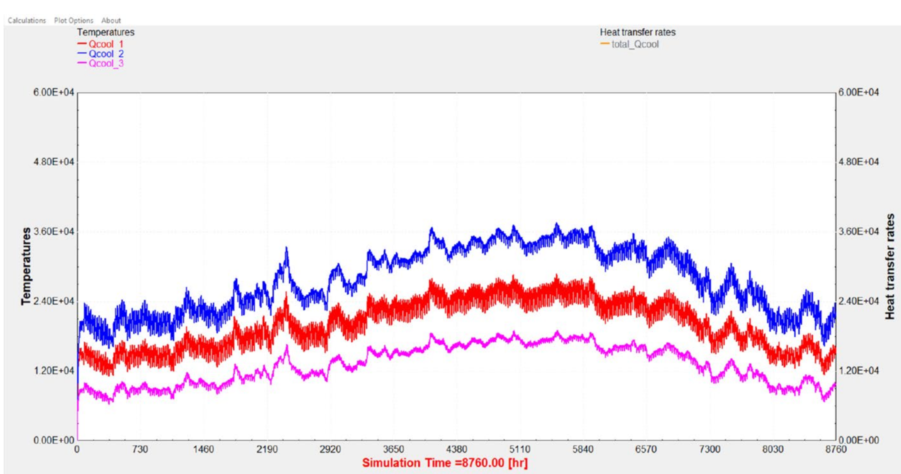


Fig. 10 Thermal loads in the current situation in the building

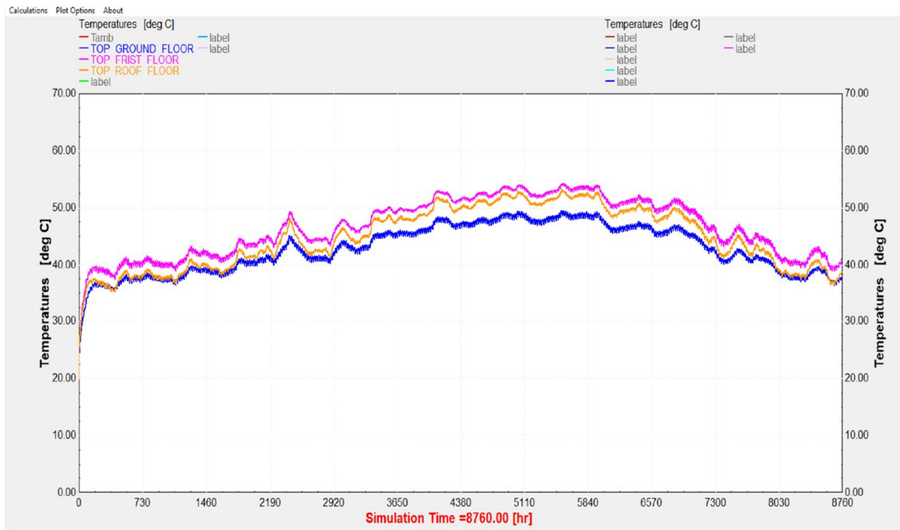


Fig. 11 Climatic analysis of the building

installing the closed geothermal system. This is to know the efficiency of the system and the possibility of implementation.

Results

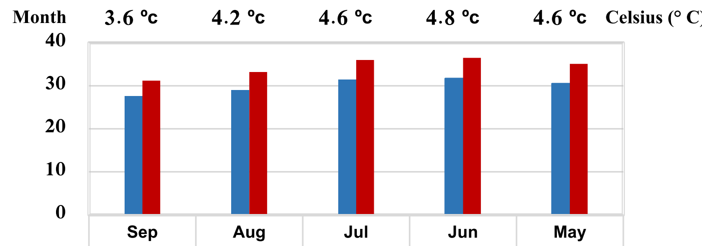
The results presented in this study were divided into four stages. It can be presented in the following ways:

A. The first stage presents the amount of heat loss after installing the vertical closed geothermal system in a residential building located in a hot, arid environment
B. The second stage measures the amount of energy loss from using the vertical closed geothermal system in Alexandria, Egypt
C. The third stage is to calculate the amount of carbon emission reduction from using the proposed system
D. Final stage: calculate the difference in economics when purchasing and installing each system

The first stage: the difference in temperatures between the current situation and after installing a vertical closed geothermal system

The research found that the temperature decreased by 36.5 °C in the current situation and became 31.7 °C when adding a vertical closed geothermal system during the peak period.

The temperature decreased by 3.6 °C in September, 4.2 °C in August, 4.6 °C in July, and 4.6 °C in May, as shown in Fig. 12.



	Sep	Aug	Jul	Jun	May
when adding a closed (vertical) geothermal system	27.6	29	31.4	31.7	30.5
the current situation	31.2	33.2	36	36.5	35.1

Fig. 12 The difference in temperatures before and after installing a vertical closed geothermal system in the building

The second stage: the difference of electrical energy consumption for cooling of floors between the current situation and when adding a vertical closed geothermal system

The research found that electrical energy consumption decreased by 7136.13 kwh in the current situation and became 5739.12 kwh when adding a vertical closed geothermal system during the peak period (summer), as shown in Fig. 13.

Then, we concluded that a vertical closed geothermal system helped reduce the electrical energy consumption for cooling by 22.93% during the peak period, as shown in Fig. 14.

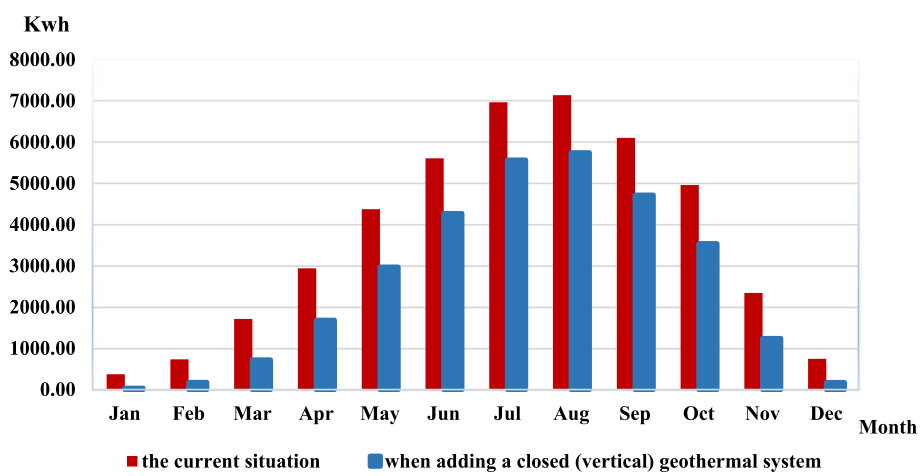


Fig. 13 The difference between the current situation and when adding a vertical closed geothermal system in terms of electrical energy consumption

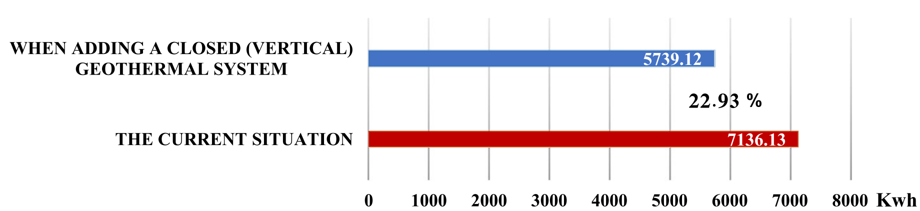


Fig. 14 The total percentage decrease in the electrical energy consumption for cooling the building during the peak period when a vertical closed geothermal system is added

The third stage is the difference between the current situation and adding a vertical closed geothermal system in terms of carbon emissions in floors

The research found that carbon emissions decreased by 5308.6 kg in the current situation and became 4269.3 kg when adding a vertical closed geothermal system during the peak period (summer), as shown in Fig. 15.

Then, we concluded that a vertical closed geothermal system helped reduce the carbon emissions for cooling by 22.93% during the peak period, as shown in Fig. 16.

Final stage: the difference between the cost of a vertical closed geothermal system and a traditional air conditioning system (HVAC) in a building (case study)

Costs of establishing the traditional HVAC system in the residential building were calculated. In this case study, a comparison was made between the cost of a vertical closed geothermal system, as shown in Table 11, and a traditional air conditioning system (HVAC), as shown in Table 12, in a building (case study).

By calculating the cost of establishing a vertical closed geothermal system, which amounted to 159,879.758 EGP, and comparing it with the cost of establishing a traditional air conditioning system (HVAC) in a building (case study), which amounted to 190,230 EGP, as shown in Table 11, it can be concluded that the cost of purchasing and

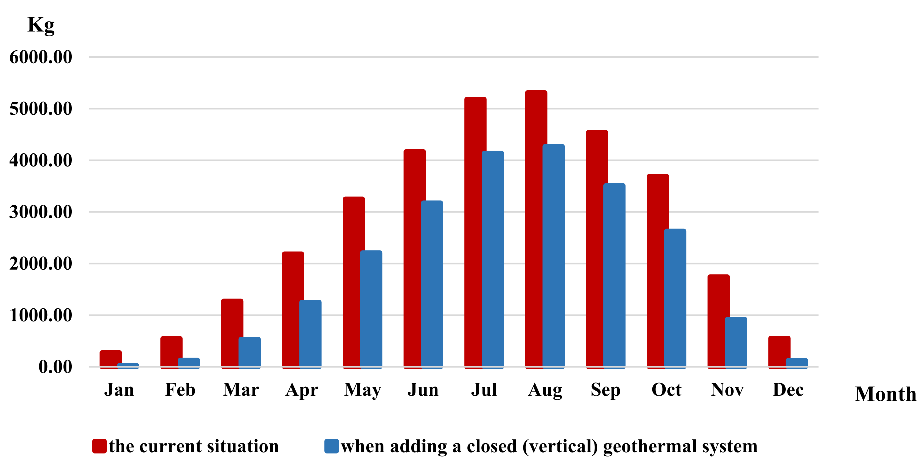


Fig. 15 The difference between the current situation and when adding a vertical closed geothermal system in terms of carbon emissions

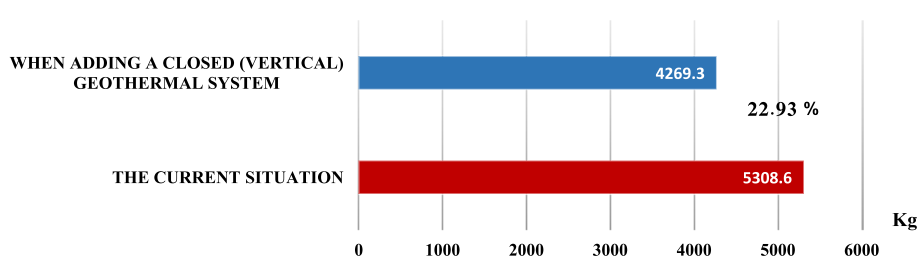


Fig. 16 Total building carbon emissions reduction during peak period when a closed vertical geothermal loop system is added

Table 11 The cost of establishing a vertical closed geothermal system in a building (case study)

Study	Required	Description	Used quantity		Total cost
Pre-operational cost	**Pipes buried underground**	- Number: 2 double U-rings - Diameter: 3 cm - Depth: 10 m - Type: Cupper tube	Required = 10 × 4 = 40 m		- Supplying and installing cost per a roll (20 m) = 1559.49 EGP [1] - 2 × 1559.49 = 3118.98 EGP - Underground pipe costs = 3118.98 EGP
	Pipes buried in the ceilings of the building	- 2 double U-shaped rings - Diameter: tube 3 cm - Type: high-density polyethylene (HDPE) pipe	**Ground floor**	The number of tubes = 32 × 2 = 64 tubes Pipe length = 8 m Required = 8 × 64 = 512 m	Costs of supplying and installing pipes in the ceiling of the ground floor = 25.6 × 1559.49 = 39,922.944 EGP Costs of supplying and installing pipes for the ceiling of the first floor = 25.6 × 1559.49 = 39,922.944 EGP Costs of supplying and installing pipes in the roof floor = 1 × 1559.49 = 1559.49 EGP The total costs of supplying and installing pipes to the roofs of the building = 39,922.944 + 39,922.944 + 1559.49 = 81,405.378 EGP
			First floor	The number of tubes = 32 × 2 = 64 tubes Pipe length = 8 m Required = 8 × 64 = 512 m	
			Roof floor	The number of tubes = 16 × 2 = 32 tubes Pipe length = 6 m Required = 6 × 32 = 192 m	
	Geothermal heat pump	Type: Macon	1		46,355.40
	Digging works	- Digging 2 wells to lay pipes in the shape of the letter (U); the radius of the well is 10 cm	25 m^2		The price of digging a square meter = 200 EGP Total excavation work = 25 × 200 = 5000 EGP
	The cost of backfilling		Required to backfill the used excavation work		4000 EGP
	The cost of installation work		Including (salaries of workers, engineers, and supervisors)		20,000 EGP
Total costs of establishing a closed vertical geothermal loop system in the residential building (case study) in Egyptian pounds					**159,879.758 EGP**

Table 12 Cost of establishing a traditional air conditioning system (HVAC) in a building (case study)

Floor	Fixed costs (purchase of air conditioning)	Installation costs	Total
Ground floor	23,880 × 3 = 71,640 EGP	850 × 3 = 2550 EGP	71,640 + 2550 = 74,190 EGP
First floor	23,880 × 3 = 71,640 EGP	850 × 3 = 2550 EGP	71,640 + 2550 = 74,190 EGP
Roof floor	20,275 × 2 = 40,550 EGP	650 × 2 = 1300 EGP	40,550 + 1300 = 41,850 EGP
The total cost of the conventional air conditioning system			**190,230 EGP**

implementing a vertical closed-loop geothermal system is relatively less expensive than the cost of a traditional cooling system.

The study costs were estimated according to the capacity of adaptations required on each floor of the building, as shown in Table 13, so that the total costs of purchase and installation are 190,230 EGP, by calculating the cost of establishing a vertical closed geothermal system, which amounted to 159,879.758 EGP, and comparing it with the cost of establishing a traditional air conditioning system (HVAC) in a building (case study), which amounted to 190,230 EGP.

Discussion

The process of construction and operation consumes a lot of energy, causing the depletion of fossil fuels and increasing the percentage of carbon emissions and greenhouse gasses. Consequently, the general characteristics of local climate change and heat islands are formed that cause the emergence of the phenomenon of global climate change, which negatively affects the environment and achieves thermal comfort for humans. Thus, there is a constant need for energy consumption to absorb the negative effects resulting from climate change and heat islands, so we must resort to using renewable energies such as solar energy, geothermal energy, and wind energy to reduce the burden on the state in terms of environmental pollution and achieve comfort in providing thermal energy for humans as well as rationalizing electricity consumption in buildings.

Geothermal systems can be divided into an open system in which the main cooling loop either adds or extracts heat, and the secondary loop transports natural water from another source to the heat exchanger to supply thermal energy. There must be sufficient distance between the supply pipes for the discharged water to regain efficiency thermally [25] and a closed system that can be horizontal, vertical, pond, or lake [26].

Geothermal cooling and heating are environmentally friendly and significantly reduce CO_2 emissions [27]. The integrated system can reduce CO_2 emissions by more than 7 kg per square meter. Therefore, the integrated system can make full use of shallow geothermal energy to build an energy-efficient HVAC system [28].

Replacing a conventional electric cooling system with a geothermal system achieves a 26% energy reduction in an apartment building in Memphis, Tennessee, by combining the microscopic properties of the earth [27].

The greatest focus by researchers on the subject of geothermal energy and its systems was on utilizing it in heating buildings, and there were a few researchers who were interested in using it in cooling buildings, so its benefits must remain applicable in other locations. If knowledge of geothermal systems spreads to the extent of solar panels, many will benefit on a small scale. There are hybrid systems used for heating and cooling that are more efficient than traditional geothermal systems, although geothermal energy does not suffer from any problems when operating compared to other renewable sources.

A study was conducted on the role of geothermal energy in heating commercial buildings and a study of its environmental and economic efficiency, but no attention was

Table 13 The calculation of the ability of adaptations required in each floor

The required air conditioning capacity for both the ground floor and the first floor	**The conditioning capacity required for the role of the roof floor**
The required air conditioning capacity = 300 × (height × width × length)/12,000	
- The area of the ground floor and the first floor = 140 m^2 - So the air conditioning capacity required for both the ground and first floors = 300 × (3 × 8 × 17)/12,000 = 1 0.2 HP - Hence, it requires 3 air condition 3 HP - The cost of the Sharp air conditioner, 3 HP, cool only, with the plasma feature = 23,880 EGP - The cost of installing a 3-HP air conditioner = 850 EGP [23]	- The roof floor area = 63.5 m^2 - So the air conditioning capacity required for the roof role = 300 × (3 × 6 × 10.5)/12,000 = 4.7 HP - Hence, it requires 2 adaptations of 2.25 HP - The cost of Sharp air conditioning 2.25 HP, cool only, with plasma feature = 20,275 EGP [24] - The cost of installing a 2.25 HP air conditioner = 650 EGP
The cost of operating the air conditioner per hour = the cost of kilowatts × the consumption of the air conditioner (kilowatt hours) **Cost per kilowatt in 2023 = 58 piasters × air conditioning consumption (kilowatt hour) 3500 = 203 per hour**	

given to residential buildings, even though it is considered the second most important human need and is considered one of the sectors that consume the most energy in cities at a rate of 74%, as it accounts for nearly half of electrical energy consumption. In Egypt [6], it is also the sector with the most carbon emissions in cities at 50% because it contributes to forming the largest part of the city's area [29], so the amount of carbon emissions resulting from it is large compared to the rest of the sectors that emit large amounts of carbon. Geothermal energy systems were also evaluated in the USA, Britain, Saudi Arabia, and India, but not Egypt.

Therefore, this research worked to study the effectiveness of geothermal energy systems in cooling residential buildings in Egypt, to complete the study on the role of geothermal energy and its systems in cooling residential buildings in Egypt, to evaluate its role environmentally and economically, and to propose it as a practical solution that contributes to containing environmental problems resulting from climate change and heat islands and increasing energy consumption for cooling in residential buildings.

As the research found that geothermal systems in buildings work to reduce temperatures, electrical energy consumption for cooling, and carbon emissions, which brings the user to thermal comfort inside the residential building at the lowest costs, then it can be proven that the closed vertical geothermal loop system is considered more efficient than traditional HVAC systems in terms of initial costs, and it also works to reduce the electrical energy used for cooling when operating and the temperature of the building.

Therefore, it is considered an effective and clean system that must be circulated in Egypt to benefit from its environmental and economic benefits.

So, if geothermal energy is exploited to cool residential buildings, we will take a step forward in reducing the burden on the state in terms of improving air quality, reducing greenhouse gas emissions, reducing energy demand globally, and knowing whether this system is beneficial for use in Egypt or not. Other, better solutions must be resorted to.

Conclusions

According to the above statements, we note the effect of a vertical closed geothermal system on reducing the temperature of the ground floor significantly, which led to reaching thermal comfort for humans in that floor, but in the first floor, because of the exposure of a large part of its surface to the sun and external heat, the percentage was lower, as well as the floor of the roof due to the exposure of all its surface to the sun and external heat, so the difference was small, but it is less than the traditional cooling system, and this resulted in a decrease in the amount of electrical energy consumption for cooling at a noticeable rate in the ground and first floors and thus led to a reduction in carbon emissions, which works to reduce the effect of heat island and thus reduce the effect of global warming and climate change.

Hence, the vertical closed geothermal system can be concluded as one of the effective solutions that works to reduce the effect of heat islands in residential buildings in Alex, Egypt, and contributes to reducing environmental problems (global warming and climate change).

The main objective of this research is to shed light on and raise awareness in Egyptian society and decision-making circles about the need to apply renewable energy systems, especially geothermal energy systems, to take advantage of Its environmental and economic benefits and exploit them in cooling by thinking in an innovative way by limiting consumption of fossil fuels and rising energy prices and consumption, rising temperatures, and carbon emissions, especially in the summer, in order to limit the formation of heat islands in cities and thus limit global climate change by applying geothermal energy systems in general and the vertical closed geothermal system in particular because they are safe, clean systems on the environment with installation and maintenance costs with a long life span.

Abbreviations

HVAC	Heating, ventilation, and air conditioning
VCGS	Vertical closed geothermal system
UHI	Urban heat islands
CC	Climate change
GW	Global warming
RE	Renewable energy
KWH/m	Kilowatt-hours/month

Acknowledgements
Not applicable.

Authors' contributions
All authors contributed to the study conception and design [Eng. Heba, Prof. Ayman, and Associate Prof. R.R.Moussa]. Data collection, simulation process, and analysis were performed by Eng. Heba. The first draft of the manuscript was written by Eng. Heba and Associate Prof. R.R.Moussa, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding
Not applicable.

Availability of data and materials
The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

Received: 16 August 2023 Accepted: 27 January 2024
Published online: 19 February 2024

References

1. Moussa RR, Mahmoud AH, Hatem TM (2020) A digital tool for integrating renewable energy devices within landscape elements: energy-scape online application. J Clean Prod 254:119932. https://doi.org/10.1016/j.jclepro.2019.119932
2. Moussa RR (2022) The potential of using anaerobic digesters in developing countries. Clean Eng Technol 9:100517. https://doi.org/10.1016/j.clet.2022.100517
3. Khalili M, Amindeldar S (2014) Traditional solutions in low energy buildings of hot-arid regions of Iran. Sustain Cities Soc 13:171–181. https://doi.org/10.1016/j.scs.2014.05.008
4. Egyptian electricity holding company annual report 2020/2021
5. Elbondira TA, Tokimatsu K, Asawa T, Ibrahim MG (2021) Impact of neighborhood spatial characteristics on the microclimate in a hot arid climate – a field based study. Sustain Cities Soc 75:103273. https://doi.org/10.1016/j.scs.2021.103273
6. Soltani M, Kashkooli FM, Dehghani-Sanij AR, Kazemi AR, Bordbar N, Farshchi MJ, Elmi M, Gharali K, Dusseault MB (2019) A comprehensive study of geothermal heating and cooling systems. Sustain Cities Soc 44:793–818. https://doi.org/10.1016/j.scs.2018.09.036. Elsevier Ltd

7. Moussa RR, Mahmoud AHA (2017) Energy-scape elements: an approach on integrating landscape elements with renewable energy devices. J Clean Prod 153:114–130. https://doi.org/10.1016/j.jclepro.2017.03.077
8. Al-Douri Y, Waheeb SA, Johan MR (2019) Exploiting of geothermal energy reserve and potential in Saudi Arabia: a case study at Ain Al Harrah. Energy Rep 5:632–638. https://doi.org/10.1016/j.egyr.2019.05.005
9. Shams MMEF, El-Aziz Amr HA, Moussa RR (2021) Comparative analysis on the effects of natural & artificial indoors lighting on the learning and interactive process. WSEAS Trans Power Syst 16:121–127. https://doi.org/10.37394/232016.2021.16.12
10. Yasukawa K, Uchida Y (2018) Space cooling by ground source heat pump in tropical Asia, 2018. www.intechopen.com
11. Dhepe N, Krishna R (2017) A review of the advancements in geothermal heating and cooling system. Glob J Enterp Inf Syst 9(1):105. https://doi.org/10.18311/gjeis/2017/15874
12. Roy D, Chakraborty T, Basu D, Bhattacharjee B (2020) Feasibility and performance of ground source heat pump systems for commercial applications in tropical and subtropical climates. Renew Energy 152:467–483. https://doi.org/10.1016/j.renene.2020.01.058
13. Sani AK, Singh RM, Amis T, Cavarretta I (2019) A review on the performance of geothermal energy pile foundation, its design process and applications. Renew Sustain Energy Rev 106:54–78. https://doi.org/10.1016/j.rser.2019.02.008. Elsevier Ltd
14. Cherati DY, Ghasemi-Fare O (2021) Practical approaches for implementation of energy piles in Iran based on the lessons learned from the developed countries experiences. Renew Sustain Energy Rev 140:110748. https://doi.org/10.1016/j.rser.2021.110748. Elsevier Ltd
15. Roy D, Chakraborty T, Basu D, Bhattacharjee B (2020) Feasibility and performance of ground source heat pump systems for commercial applications in tropical and subtropical climates. Renew Energy 152:467e483. Contents lists available at ScienceDirect, 2020
16. Olabi AG, Mahmoud M, Soudan B, Wilberforce T, Ramadan M (2020) Geothermal based hybrid energy systems, toward eco-friendly energy approaches. Renew Energy 147:2003e2012
17. El-Magd IA, Ismail A, Zanaty N (2016) Spatial variability of urban heat islands in Cairo City, Egypt using time series of Landsat satellite images. Int J Adv Remote Sens GIS 5(1):1618–38. https://doi.org/10.23953/cloud.ijarsg.48
18. Tinti F, Kasmaee S, Elkarmoty M, Bonduà S, Bortolotti V (2018) Suitability evaluation of specific shallow geothermal technologies using a GIS-based multi criteria decision analysis implementing the analytic hierarchic process. Energies 11(2):457. https://doi.org/10.3390/en11020457
19. Abdel Zaher M, Elbarbary S, El-Shahat A, Mesbah H, Embaby A (2018) Geothermal resources in Egypt integrated with GIS-based analysis. J Volcanol Geoth Res 365:1–12. https://doi.org/10.1016/j.jvolgeores.2018.09.013
20. (2023) The Central Agency for Public Mobilization and Statistics in Egypt. https://www.capmas.gov.eg/. Accessed May 2023
21. Ministry of Electricity and Energy website, calculate consumption in February 2021
22. ASHRAE Guide (2013) https://shop.iccsafe.org/2013-ashrae-handbook-of-fundamentals-pdf-download.html. Accessed 21 May 2023
23. Zhang S, Oclon P, Klemes JJ, Michorczyk P, Pielichowska K, Pielichowski K (2022) Renewable energy systems for building heating, cooling and electricity production with thermal energy storage. Renew Sustain Energy Rev 165:112560
24. Sharp air conditioning company (2023) https://sharpegy.com/sharp-conditioning/. Accessed 5 April 2023
25. Klaassen Curtis J (2014) Geothermal heat pump system. Lowa Energy Centre, Energy Resource Station
26. ASHRAE Handbook-1999. HVAC application. Energy related application. Chapter 31, Geothermal Energy. https://www.thenbs.com/PublicationIndex/documents/details?Pub=ASHRAE&DocID=256134. Accessed May 2023
27. Neves R, Cho H, Zhang J (2020) Techno-economic analysis of geothermal system in residential building in Memphis, Tennessee. J Build Eng 27:100993
28. Claesson J, Eskilson P (2015) PC design model for heat extraction boreholes. In: Conférence international sur le stockage de l'energie pour le chauffage et le refroidissement. p 41988
29. Mahbaz SB, Dehghani-Sanij AR, Dusseault MB, Nathwani JS (2020) Enhanced and integrated geothermal systems for sustainable development of Canada's northern communities. Sustain Energy Technol Assess 37:100565

Publisher's Note