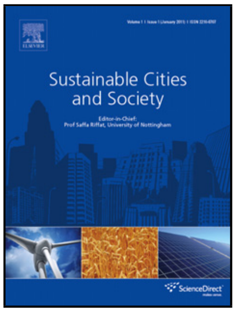

Title: A comprehensive study of geothermal heating and cooling systems

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PII: S2210-6707(18)30683-8
DOI: https://doi.org/10.1016/j.scs.2018.09.036
Reference: SCS 1274

To appear in:

Received date: 9-3-2018
Revised date: 28-9-2018
Accepted date: 28-9-2018

Please cite this article as: Soltani M, Kashkooli FM, Dehghani-Sanij AR, Kazemi AR, Bordbar N, Farshchi MJ, Elmi M, Gharali K, Dusseault MB, A comprehensive study of geothermal heating and cooling systems, *Sustainable Cities and Society* (2018), https://doi.org/10.1016/j.scs.2018.09.036

A comprehensive study of geothermal heating and cooling systems

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Highlight

- Comprehensive investigation of the geothermal heating and cooling systems
- Recognition and accommodation of several factors that can enhance the installation soundness of any geothermal heating or cooling system
- Overview of ground source heat pumps and ground heat exchangers in the geothermal heating and cooling systems

Abstract

Geothermal energy is one of the sources of renewable energy, which is local, reliable, resilient, environmentally-friendly, and sustainable. This kind of natural energy can be produced from the heat of the earth, and has different

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applications, such as heating and cooling of buildings, generating electricity, providing warm/cold water for agricultural products in greenhouses, and balneological use. Also, geothermal energy is not dependent on weather influences and can supply heat and electricity almost continuously throughout the year. This study provides a general overview of the geothermal heating and cooling systems. Topics addressed include: an introduction to energy and the environment as well as the relationship between them, a brief history of geothermal energy, a discussion on the district energy systems, a review of the geothermal heating and cooling systems, a brief survey of geothermal energy distribution systems, an overview of ground source heat pumps, and a discussion of ground heat exchangers. Recognition and accommodation of several factors addressed and discussed in the current review can enhance the installation soundness of any geothermal heating or cooling system.

Keywords: Geothermal, Greenhouse Gas (GHG) emissions, Heating and cooling systems, Ground source heat pump, Ground heat exchanger

Contents

1. Introduction

The development and consumption of fossil fuels have caused ecological problems. If human dependency on resources of fossil energy continues, it will likely raise the rate of global warming. In the future, global ecological problems will notably affect people’s patterns of using energy. Air pollution is a significant environmental issue in some of countries [1]. According to the world energy outlook in 2016, warning about air pollution and rules for environmental protection have increased. As shown in Fig. 1, the IEA's preliminary estimate of global energy-related carbon-dioxide (CO_2) emissions in 2015 displays that emissions stayed flat [2].

As illustrated in Fig. 1, there is a close relationship between energy demand, global economic growth and energy-related CO_2 emissions. However, in 2015, there was a clear decoupling of this previously close relationship and that is because of the successful results of climate debates [2]. Using renewable and clean energy resources is a suitable alternative to supersede fossil fuels consumption for environmental pollution reduction.

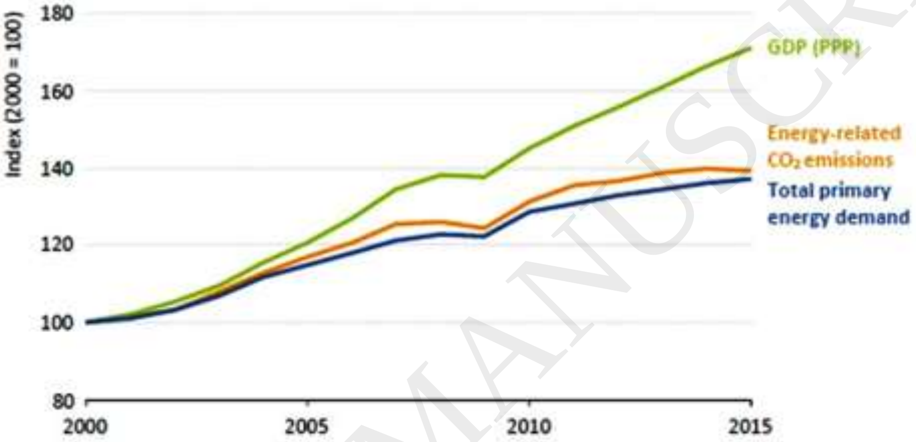


Fig. 1. Changes in energy demand, global economic output and energy-related CO_2 emissions [2]. Note that in this figure, GDP (PPP) refers to Gross Domestic Product on a purchasing power parity basis.

Heating and cooling utilizations considerably increase global energy requirements [3], and buildings have a significant impact on natural resource depletion [4-6]. Residential buildings are responsible for three-quarters of the whole energy consumption in the building sector; thus, it is important to enhance their energy efficiency and pay special attention to this [7]. Figure 2 indicates buildings' energy consumption percentage of total energy utilization in the different regions of the world. As illustrated in this figure, residential buildings are liable for an average of 20% of total consumption in developed countries, and for developing countries, this number is more than 35% [8]. As residential energy utilization is important for the present, it is prominent for the future as well [9]. Heating and cooling energy utilization in buildings (both commercial and residential buildings) through 2010-2020 in the different regions of the world and its projections between 2020 and 2050 are shown in Fig. 3. Additionally, Fig. 3

illustrates that residential buildings' energy consumption in the majority of regions is increasing, and in commercial buildings, energy utilization is increasing too, except in Oceania (Pacific OECD Countries) and South Asia [10, 11].

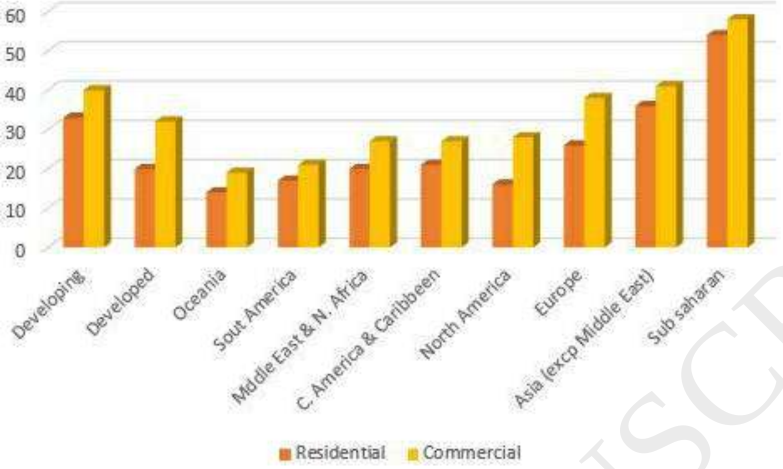


Fig. 2. Buildings' energy consumption percentage of total energy utilization in the different regions of the world [8]

Buildings are liable for one-third of greenhouse gas (GHG) emissions [12]. Fossil fuels such as natural gas, oil and coal have caused GHG emissions' growth and also cause climate change, global warming and ozone layer depletion, which have destructive impacts on the environment and human life throughout the world [4, 13-15]. In the last four decades, annual CO_2 emissions growth is more than 100%, and in 2011, it exceeded 32 billion tons [4, 16]. Also, it is predicted that CO_2 emissions will increase to 36 billion tons in 2020 [4, 17]. Residential buildings were responsible for nearly 6% of direct CO_2 emissions in 2011 [14, 18], and because of electricity utilization they were responsible for 11% of indirect CO_2 emissions, as well as being the fourth most CO_2-emitting in the world [16].

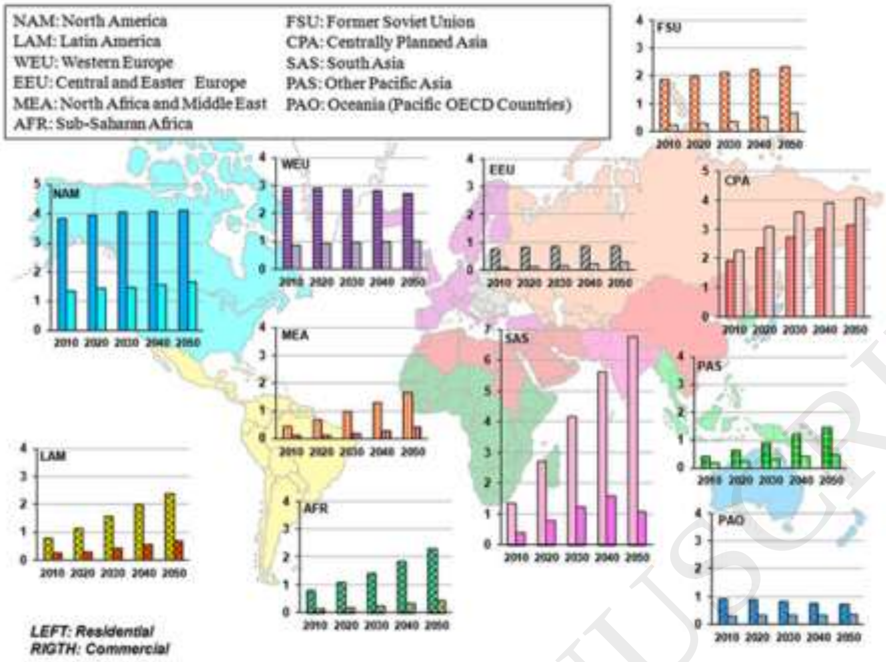


Fig. 3. Heating and cooling energy utilization in the buildings in the different regions of the world from 2010 to 2050. Note that energies are in PWh. Predictions are based on a frozen efficiency scenario [10, 11]

Renewable energy systems can be a good replacement for fossil fuel systems to provide more sustainable heating and cooling systems in both commercial and residential buildings [3]. 14% of the total world energy requirement is provided by renewable energy sources [19, 20]. Renewable energy sources include hydropower, geothermal, wind, solar, and marine energies, which are clean and unlimited energy resources [21, 22]. Principal renewable energy sources and their utilization forms are represented in Table 1.

Table 1. Principal renewable energy sources and their utilization forms [23]

Energy source	**Energy usage forms**
Geothermal	Power generation, urban heating, hot dry rock, and hydrothermal
Modern biomass	Power and heat generation, gasification, pyrolysis, and digestion
Solar	Solar dryers, solar home system, and solar cookers
Direct solar	Thermal power generation, photovoltaic, and water heaters
Hydropower	Power generation
Wind	Wind generators, power generation, water pumps, and windmills
Tidal	Tidal stream and barrage
Wave	Numerous designs

As illustrated in Fig. 4, for the USA in 2005, renewable energies account for approximately 8.88% of energy generation and this percent increased to 13.24% in 2014. Additionally, it is predicted that it will rise to 18% in 2040

[24-26]. The use of geothermal energy directly for district heating has increased remarkably [27], such that the use of geothermal district heating systems has increased by 10% over the past 30 years [28].

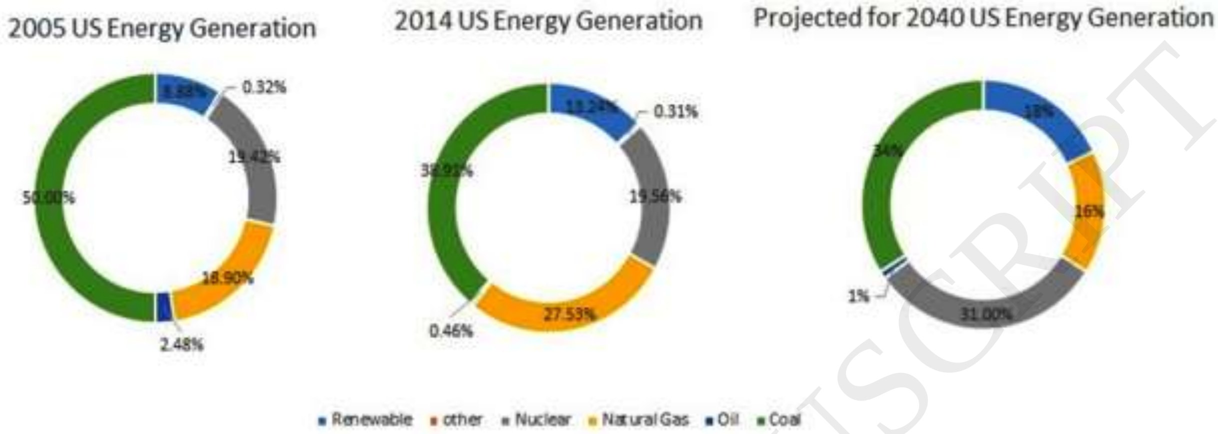


Fig. 4. Renewable energies participation in energy generation in the USA in 2005 and 2014 and its prediction for 2040 [24-26]

Werner [29] reported that district heating and cooling systems have powerful potentials to be viable heating and cooling supply options in the future. Solar water heaters can produce hot water using collectors; moreover, passive solar energy and solar thermal enable space heating and cooling. Industrial waste, urban solid waste, solid biomass such as animal and agricultural produce residues, wood processing and forestry residues, and wood chips, as well as biofuels, are used for heating and cooling. Depending on the location, geothermal energy produces heat by conduction or in hot steam or hot water form [3]. Generally, comparison of renewable energy sources has several aspects, economic, energetic, social, environmental, and so on. Table 2 summarizes the advantages and disadvantages related to different renewable energy sources employed for district heating and cooling systems. Additionally, typical sizes, operation and maintenance costs, efficiency and other criteria for different renewable energy heating and cooling systems are demonstrated in Table 3.

Table 2. Summary of renewable energy sources

Source	Description	Advantages	Disadvantages
Geothermal or ground source heat pumps [1, 3, 30, 31]	Built in locations above large geothermal sources, typically those with naturally occurring hot springs, geysers or aquifers	- Abundant and clean, Provides year around low cost heating and cooling using district energy technology - Weatherproof	- Expensive start-up and maintenance because of corrosion - Risk of hydrogen sulfide emissions - Subsidence, landscape change and polluting waterways - Long construction time - Hard to assess resource - Hard to modularize
Biomass [3, 30, 32]	Often using wood or energy crop based material to provide heat	- Abundant with a wide variety of feedstocks and conversion technologies, Indigenous fuel production and conversion technology in developing countries	- May release GHGs (e.g. methane) during biofuel production - Landscape change and deterioration of soil productivity
Solar [3, 30, 33]	Using sunlight and solar collectors to provide high temperature water for heating and cooling purposes	- Abundant supply, - Less environmental damage compared to other renewable options - Passive and active systems with the option to also provide cooling during warmer seasons using absorption chillers	- Storage and backup issues - Not a constant supply-intermittent and fluctuating nature

Table 3. Technical and economical comparison of different renewable energy heating and cooling systems [3, 34, 35]

		O&M Cost*		**Feedstock**			
Resource	**Technology**	**Fixed (per kW)**	**Variable (per GJ)**	**Cost (US$/GJ)**	**Conversion Efficiency (%)**	**Capacity Factor (%)**	**Lifetime (years)**
Biomass	Domestic heating	13–43		10–20	86–95	13–29	10–20
	MSW (CHP)	15–130		0–3	20–40	80–91	10-20
	Steam turbine (CHP)	1.5–2.5		3.7–6.2	10–40	63–74	10-20
	Anaerobic digestion (CHP)	37–140		2.5–3.7	20–30	68–91	15-25
Solar	Domestic hot water	1.5–10		N/A	20-80	4.1-13	10-15
Geothermal	Building heating		8.3-11	N/A	N/A	25-30	20
	District heating		8.3-11	N/A	N/A	25-30	25
	Greenhouse heating		5.6-8.3	N/A	N/A	50	20
	Ponds		8.3-11	N/A	N/A	60	20
	Heat pumps		7.8-8.9	N/A	N/A	25-30	20

*O&M: operation and maintenance

As shown in Tables 2 and 3, low-cost heating and cooling can result from geothermal energy heating and cooling systems. They have more than other systems' lifetimes and can be used throughout the year unlike some sources such as solar. As a general result, when heating and cooling functions are practical and environmentally friendly, the technical and cost performances of geothermal and biomass are approximately the same and solar is lower performance [3].

To the authors' best knowledge and due to the literature survey, despite all efforts available, there is no comprehensive review of geothermal energy usage in heating and cooling systems. Therefore, the main goal of this paper is to examine different aspects related to these systems. In section 1, an introduction to energy and the environment as well as the relation between them, with emphasis on the role of cooling and heating of buildings regarding energy consumption and environmental pollution are presented. In section 2, a history of geothermal energy with various applications is briefly surveyed. The district energy systems for the heating of spaces are discussed in section 3. Geothermal heating and cooling systems are described in section 4. The different types of distribution systems of geothermal energy are explained in section 5. Geothermal heat pump systems are discussed in section 6. Ground heat exchangers are studied in section 7. Finally, A summary of this review and also future contexts and challenges are presented in section 8.

2. Geothermal energy

Heat is a form of energy and the heat that is stored within the earth that causes geological phenomena on a terrestrial scale is called geothermal energy [36]. In layman's terms, geothermal energy is referred to that part of earth's heat that can be humanly exploited [36]. Geothermal energy has been used in different forms. Taking advantage of hot springs and pools for bathing and health treatments or simply for heating and cooking are examples of this kind of energy [37]. Our early ancestors believed hot springs to be spiritual, religious and mythical. Erupted natural springs have symbolized life and power in religions and cultures. Hot springs have been believed to be divine messengers notifying humankind of the vast energies stored beneath our feet [37].

Some applications of geothermal energy use the earth's temperatures near the surface (shallow geothermal), while others require drilling miles into the earth (deep geothermal). There are three main types of geothermal energy systems: direct use and district heating systems, electricity generation power plants and geothermal heat pumps. Fig. 5 illustrates a ground source heat pump for a district heating system, which consists of three major components. The first part is a U-shaped ground heat exchanger with a length of 50 m and a nominal diameter of 1.25 inches. A solution of water and antifreeze is usually used as the working fluid. The second part is a refrigeration cycle and the third part is the fan coil which relays the heated water to users [38]. Figure 6 shows the components of a district cooling system. It works just like the district heating system but has an absorption cooling cycle of LiBr, which is coupled to produce chilled water to distribute among users [39]. In the following sections, the history of geothermal energy applications is briefly explained.

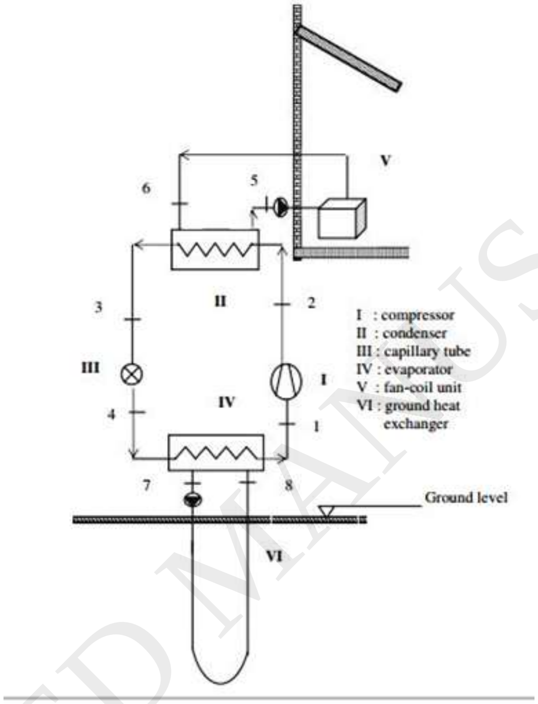


Fig. 5. Schematic of a ground source heat pump for district heating [38]

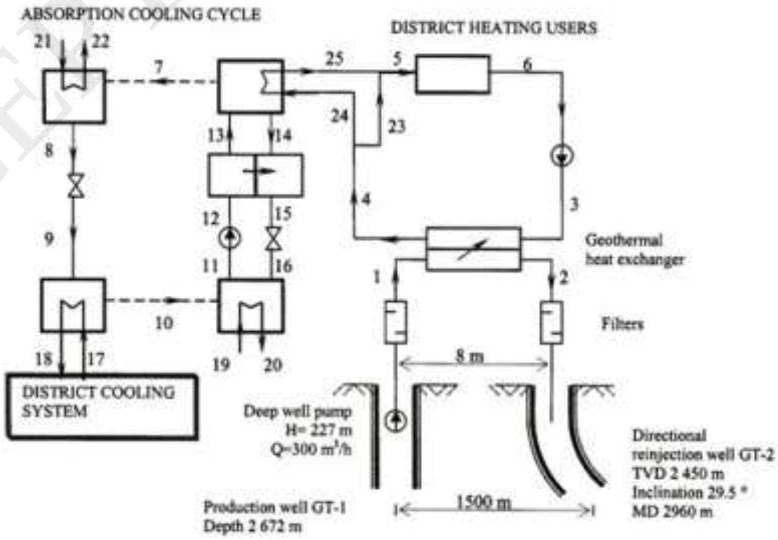


Fig. 6. Schematic of a district cooling cycle [39]

2.1. Primary utilization of geothermal energy

Discoveries verify that indigenous American employed hot springs thousands of years ago [37]. Hot springs of South Dakota incited Sioux and Cheyenne tribes to fight in the United States. The therapeutic power of hot springs was not veiled to humans. For instance, indigenous people had bathtubs in the rocks at the springs. They also used to drink water from hot springs to treat gastric health issues [37]. Much later white immigrants began to commercially exploit hot springs for hydrotherapy treatment.

Employment of geothermal energy for cooking has been proved to be widespread among Romans, Japanese, Turks and Icelanders, according to discovered documents. Furthermore, approximately two thousand years ago, there were bathing and medical treatment centers near Beijing in China. Romans widely developed hot springs in Europe for different purposes. A most significant activity of Romans was bathing. They took heed of wellness. They also held their social gatherings and business affairs in baths [37]. Chinese people published instructions on farming and treatment employing hot springs from the 4th to the 6th century, according to reports. For instance, Chinese farmers could take hot water to their rice crops in March and this practice allowed for three harvests per year [37].

Geothermal energy was also encountered in the mining industry [37]. In 1530, Agricola found that in mines beneath the ground, temperature rises with depth. Later, in 1740s, De Gensanne measured the temperature of a mine near Belfort in France using a thermometer [36]. For the first time, in 1791, Alexander von Humboldt [37] introduced a relation between temperature increase and depth, which was a basic parameter in geothermal energy exploitation. He measured a 3.8˚C per 100 m increase in depth in Freiberg, Saxony. In 1839, a high temperature of 38.7˚C was recorded in at the depth of 342 m in Neuffen, Southern Germany, which indicates a 9˚C increase in temperature every 100 m. This was the first geothermal temperature irregularity discovered [37].

2.2. Contemporary applications of geothermal energy

Early in the 19th century, wide advances of thermodynamics helped to employ thermal water for energy conversion from hot steam to mechanical energy and then to electrical energy with the assistance of turbines and generators [37]. Power from geothermal energy was established in Larderello, Tuscany, Northern Italy [40]. Those who first produced power for geothermal sources clearly from the region, according to Tiwari et al. [41]. Hot springs near Larderello were utilized to produce boron and other matter dissolved in water until the early 19th century. Francesco Larderel, who founded the boron industry, established a geothermal energy convertor in 1827 [40]. He built the first low-pressure steam boiler working with the heat of geothermal water by covering the surface of a pond with brick (Fig. 7). In this way, evaporation of boron-rich water and the production of boron was enabled by the pond’s heat and also powered pumps and related machines [40]. Much firewood was saved and desertification of the area came to an end.

In the early years of the 20th century, Piero Ginori Conti took control of the Larderello chemical industry and experimented with the conversion of geothermal energy to electricity [40]. He made the first geothermal electricity generator in 1904 in Larderello when he powered five light bulbs with a piston engine that was coupled with a 10 kW dynamo (Fig. 8) [41]. The engine was run by pure steam. Wet steam from a well in Larderello produced the required steam via heat exchangers to run the engine. It employed an indirect cycle in which geothermal fluid heated a secondary fluid to run the engine [40].

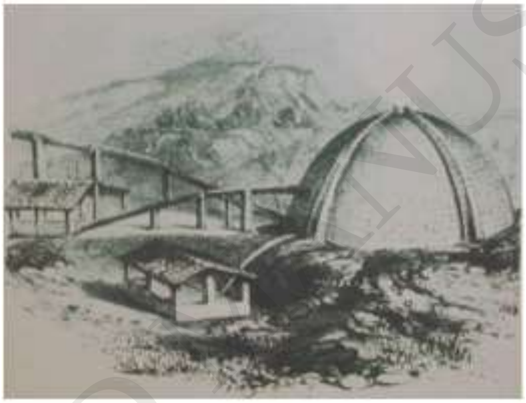


Fig. 7. Covered lagoon (“lagone coperto”), Larderello, Italy, 1904 [42]

Fig. 8. Piero Ginori Conti and the 10 kW experimental power plant, Larderello, Italy, 1904 [42]

It was only 9 years later, in 1913, that the first commercial geothermal power plant, called Larderello 1, was designed and produced by Tosi Electromechanical Company. The turbine for this electrical power plant was run by saturated steam. The steam was heated by geothermal fluids from two wells with a temperature of 200-250˚C via a heat exchanger. The power plant was capable of producing 250 kW (Fig. 9) [40].

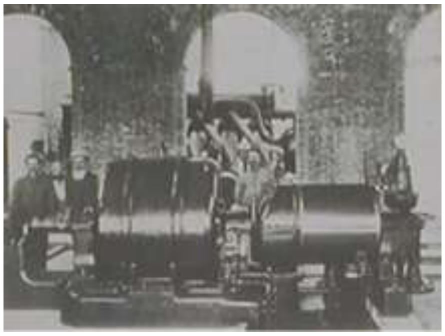


Fig. 9. First commercial geothermal power plant, 250 kW, Larderello, Italy, 1913 [42]

Two years later, the net power production hit 15 MW using the same technology with saturated steam. After 1931, new technology was taken advantage of and using deep drillholes, superheated steam of 200˚C was produced, eliminating any corrosion caused by saturated steam [37]. It was only by 1939 that gross power production of the field rose to 66 MW [37]. Because of its strategic importance, supplying required electricity to power Italy's railways, it was unfortunate that the field was leveled during WWII (Fig. 10) but it was rebuilt later [40]. Currently, the field is capable of producing 545 MW, which is 1.6% of the net power produced in Italy in 2010 (Fig. 11) [37].

Fig. 10. Geothermal plant at Larderello, destroyed in WWII, 1944 [42]

Fig. 11. Larderelo Power Plant [43]

The history of the USA exploiting geothermal energy goes back to 1890, in Boise, Idaho with a thorough district heating system, which was also duplicated at Klamath Falls at Oregon 10 years later [37, 44]. In 1926, a geothermal well in Klamath Falls was used to heat houses in an environmentally friendly way; only four years later, private houses in Klamath Falls began to make good use of geothermal wells for heating [37, 44].

For the first time, in 1920, it was in Reykjavik, Iceland that geothermal water was exploited to heat houses [37]. Reykjavik itself means steaming bay, a name coined by Vikings for its visible steaming springs. It was in early 1850 that hot water pools became accessible by drilling and were used to heat buildings; then it was time to use it for public places and district heating [37]. The torch-bearer in harnessing geothermal energy is Iceland absolutely. The country meets 53 percent of its power needs by geothermal power plants, which is approximately 79,700 TJ [37]. Almost all of the country's power is supplied by geothermal and hydroelectric energy. Figure 12 shows that by employing geothermal district heating in Iceland, CO_2 production in this country has decreased dramatically. It is obvious that over time, the CO_2 production has dropped significantly.

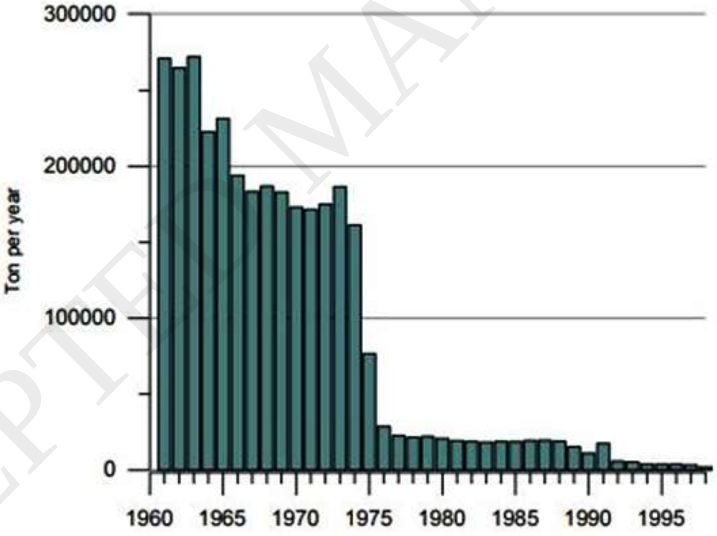


Fig. 12. CO_2 production in Iceland, replacing fossil fuels by geothermal district heating [45]

Elsewhere in the world, New Zealand installed its first geothermal plant in 1958 in Wairakei, the volcanic region of the country [42]. The New Zealand government was more eager to develop geothermal energy after two years of drought that limited hydrogenation and resulted in power shortages in 1947. They also longed to restrict their dependence on imported fuels. Therefore, they sent their engineers to Larderello in 1948. However, New Zealand engineers faced developing a technology which was applicable to the wet steam of their homeland rather than the dry steam of Larderello, which meant separating high-temperature water from steam. Nevertheless, they started drilling in 1949 and utilized 20 MW by 1952. As of 2004, New Zealand produced over 450 MW of electricity in the Wairaki [42].

Mexico established a research plant in 1959 in Pathe [36]. Northern California started development of the Geysers in 1960. The Geysers is capable of producing 750 MW of power and consists of 21 power plants. The net power produced is sufficient to run San Francisco [37]. It should be noted that geothermal energy can be unprofitable in certain conditions. Its profitability highly depends on demand, supply and cost of other energies. Yet, laws and regulations to protect the environment could make it economically feasible [37]. To clarify, in 1980, Germany drilled wells to exploit geothermal energy after the oil prices hit an unprecedented high, but the project was put on hold when the prices fell during the economic crisis. For similar economic reasons, projects in Greece and Argentina were closed [37]. Investments in geothermal energy highly depend on costs of fossil fuels and the regulations that make it economical. The distribution of geothermal energy use in the world is shown in Fig. 13. This figure shows that space heating has the highest percentage of geothermal energy application in the world. However, heat pumps have the greatest percentage of geothermal energy application in the US (Fig. 14).

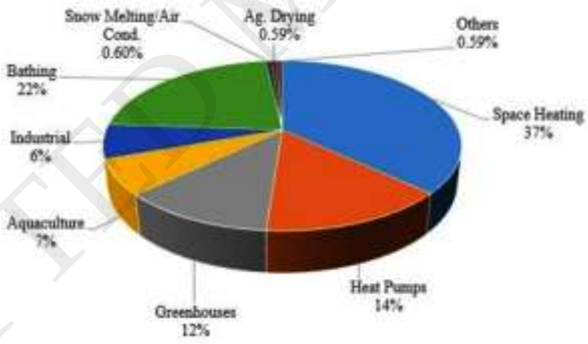


Fig. 13. Distribution of geothermal energy use in the world [44]

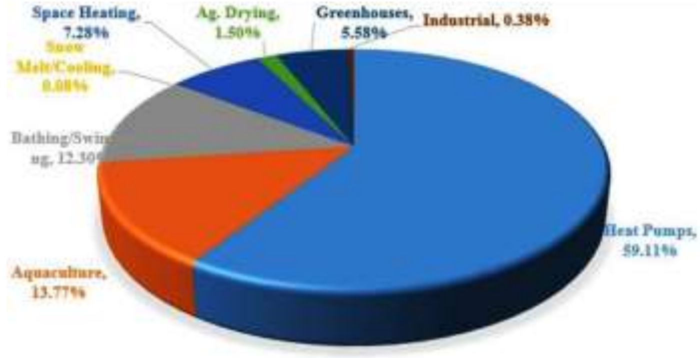


Fig. 14. Distribution of geothermal energy use in the US [44]

Table 4 illustrates the total geothermal power installed in various countries and an estimation of energy generated by these power plants in 2004. This amount of installed geothermal energy increased to 10,715 MW in 2010 [46], an increase in electricity production that shows a promising future for geothermal power plants everywhere. It was also forecasted that in 2015, there would be more than 18,000 MW of production of geothermal power plants worldwide [46].

Table 4. Total geothermal power installed worldwide in 2004 [42]

Country	Installed MW	Est. Energy Produced (GWh/a)
Argentina	1	not operating
Australia	<1	3
Austria	<1	5
China	32	100
Costa Rica	162	1,170
El Salvador	105	550
Ethiopia	7	30
France (Guadalupe)	4	21
Germany	<1	2
Greece	2	not operating
Guatemala	29	180
Iceland	200	1,433
Indonesia	807	6,085
Italy	790	5,300
Japan	535	3,470
Kenya	127	1,100
Mexico	953	6,282
New Zealand	453	3,600
Nicaragua	78	308
Papua New Guinea	30	100
Philippines	1,931	8,630
Portugal (Azores)	8	42
Russia	100	275
Taiwan	3	15
Thailand	<1	2
Turkey	21	90
United States	2,395	16,000
TOTAL	**8,771**	**54,793**

3. District heating

3.1. Introduction to district energy systems

Methods to supply energy required to heat or cool spaces such as apartments and public and industrial places in a city fall into two groups; first, to do it in the old-fashioned way from inside a building separate from other spaces; second, to do it from outside for the whole city. In comparison, much energy can be saved by second method, called the district energy system [47]. For instance, in Canada, 77% of GHG emissions are due to residential space heating and cooling. A local energy system, which is centralized and is capable of providing hot and cold fluids to neighbourhoods, can be an answer to energy challenges. Besides, by distributing hot water and cold and hot air, the emission of GHG could be controlled significantly [48]. This solution can be utilized in many countries. By utilizing such centralized systems and employing renewable energies, a simpler, less expensive and more environmentally friendly method can heat and cool spaces [48].

3.2. History of district energy systems

Innovations utilizing these systems date back to the 14th century, when some buildings in a village in Chaude-Aigues, France were connected to a geothermal source in 1334 [49]. Not looking to the remote past, the system was commercially introduced in the 1870s and 1880s in cities like New York and Lockport [50]. It was in the 1920s that in Germany district energy systems were applied for the first time in Europe [47]. In their wake, Soviet and China followed and applied the system in the 1930s and 1950s [47]. At present, there are over 80,000 systems across the world in metropolises like New York, Seoul, Beijing, Moscow, Hamburg, St. Petersburg, Paris, Bucharest, Stockholm, Copenhagen and Milan [51].

There have been different heat carriers through the time that are discussed in [52]. Water succeeded steam as a heat carrier and carbon dioxide is represented as the next successor in the future by [53]. At first and until the 1930s, high temperature steam was largely used as a transportation fluid using concrete ducts and tubes [47]. The drawback, however, was the jeopardy of explosion and high energy loss. These systems were used in apartments where the probability of explosion was low [47]. Steam’s successor was hot water with high pressure, which used shell and tube heat exchangers and concrete tubes with huge valves. These systems helped to save more energy but were not sufficient to meet energy demand [47]. Then, in the 1970s, it was time to use high pressure water with lower temperatures, which is called “Scandinavian district heating technology” [47]. This system employed underground tubes and is the one that is widely used all over the world [53].

As of now, Europe is the leader in using district energy systems and some of its countries are shifting toward sustainable systems [47]. For instance, Sweden changed its fuel from oil to coal to run district energy systems in the wake of the oil crisis in the 1970s and until now they have tried to gradually shift to biomass to fulfill their needs. Biomass had 53% of the share by 2014 [47]. The relative usage vastness of district heating systems and development of technology have set the stage to establish a district cooling system to cover not only heat demand but also cooling demand by the district system. These systems, however, are recently introduced, so are not as common as a district heating system [47].

Since the two major oil crisis in the 1970s that led to very high oil prices, interest in district heating systems increased, as reflected in [54-58]. Up to 2005, there was more interest in using renewable energy to run district heating systems [59, 60]. From experiences in Europe, there have been reviews and assessments of district heating which evaluate the early experiences in different countries like Germany, France and others that are reported in [61-65]; researchers in the Europe published a survey in 1971 for the first time [66]. It was in 1968 that the World Power Conference released the first thorough overview of district heating [65]. Today, information on every aspect of the district heating system is available and is provided by International Energy Agency (IEA) [67]. However, as was discussed, there is little information on district cooling systems [68].

3.3. District heating versus space heating

The world has many small cities and towns with low temperatures that are close to geothermal sources that can be connected to Geothermal District Heating systems (GDH). There are 271 similar cases and 70 % of them have a population of less than 5000 [47]. In such cases, they do not have numerous large buildings that make it economical to use GDH systems. Eventually, there will be more customers constructing small buildings connected to GDH systems. In these cases, they may have an additional system that provides hot water. Costs for this additional system in small-sized buildings make it unreasonable to connect to GDH [47].

In buildings of less than 930 m^2, connecting to GDH could be economical only if they have a high consumption of energy and if fuel (like electrical resistance) has a hefty price. In these circumstances, geothermal heating can offer 30-40% saving on fuel costs [47]. Unfortunately, it will not be economical at all compared to natural gas; in most cases, the economy of connecting small buildings to GDH cannot be a motive and some protective laws and regulations should be in force or environmental regulations must be developed [47]. Rafferty [47] found a design which managed to gain optimal results, including a short payback time. Some cases, though require some additional equipment such as a heat exchanger or pump would be less economical and would have a longer payback time [47].

4. Geothermal heating and cooling systems

There are many advantages to geothermal energy potentials that must not be taken for granted [69]. In general, exploiting geothermal energy falls into two categories, which are:

- Heating in cold seasons: since the temperature in the ground is higher than the atmosphere's temperature, sometimes it is sufficient for heating or only preheating. Moreover, applying and taking advantage of heat pumps highly increases heat removal from the ground [69].
- Cooling in hot seasons: underground temperature is cooler than temperature above the ground and the difference enables good use of it for cooling or precooling. Again, heat pumps used in reverse mode (cooling mode) can enhance the efficiency and the temperature provided for cooling can be lowered [69].

Geothermal-based heating and cooling systems consist of three major components, which are: heat pump, a heat exchanger installed underground, and a common air distribution system as air ducts [69]. The cost of the whole system depends on the heat exchanger cost, which varies by its size. Calculations and economic analysis are required to determine and design the right heat exchanger based on daily and average annual loads. Additionally, efficiency of heat exchangers can be vulnerable to some issues, such as an underground water stream and the possibility of freezing, thermal properties of different soils, and distribution of ground temperature. However, ground heat exchangers (GHEs) can be optimized environmentally and economically [69]. Figure 15 shows that when geothermal energy is employed in a HVAC system, there is a potential of reducing the energy bill by half.

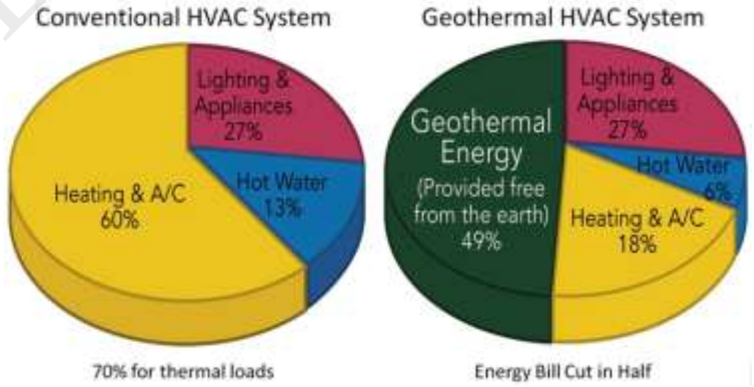


Fig. 15. Geothermal versus conventional HVAC system [70]

4.1. Ground-source heat pump (GSHP)

All heat pumps work between a high and low temperature. The low temperature medium is called a heat source (T_L) and the high temperature medium is called a heat sink (T_H). A ground-source heat pump or geothermal heat pump has the ground as its heat source or sink [69]. Here, GHE plays a role exchanging heat between the ground and the heat pump. Moreover, a heating or cooling coil is tasked with exchanging heat between the heat pump and a space. Sinks and sources of heat pumps are different in heating and cooling seasons [69]. When cooling (inserting heat into the ground), heat is exchanged from a cooling coil (low-temperature medium) to a refrigerant flowing in the GHE (high-temperature medium). However, in heating seasons (heat removal from the ground), heat is exchanged with a refrigerant flowing in the GHE (low-temperature medium) to a heating coil (high-temperature medium) [69].

4.2. Comparison of air-source and ground-source heat pumps

Comparing these systems, an air-source heat pump delivers outdoor air, which itself has a high temperature, to exchange heat, but a ground-source heat pump uses a ground temperature that has a lower temperature than outdoors, so the efficiency that depends on temperature difference is higher [69]. Most importantly, installation of GSHP from 1996 to 2008 in Canada increased significantly (Fig. 16). Consequently, Greenhouse Gas (GHG) emissions have decreased and the price of energy is highly reduced [69]. Table 5 illustrates a comparison between ground- and air-source heat pumps.

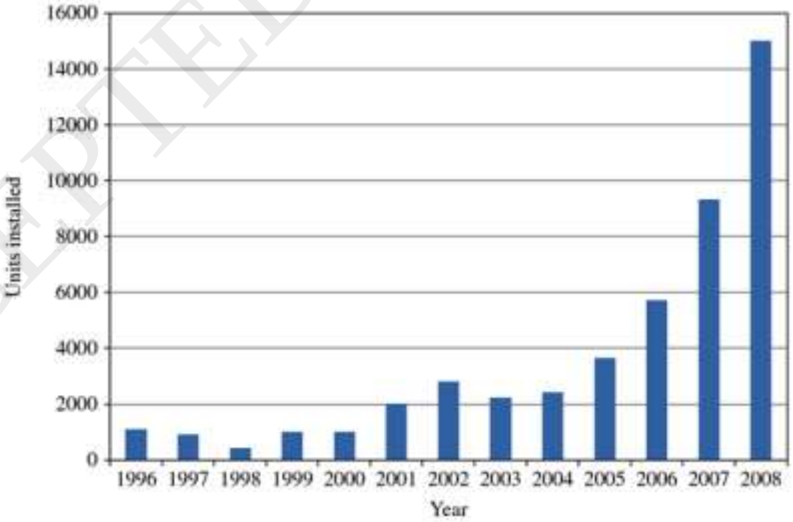


Fig. 16. Ground-source heat pump installation growth from 1996 to 2008 in Canada [69]

Table 5. Comparison of ground- and air-source heat pumps.

Quantity of symbol • indicates characteristic strength [71]

Characteristic	Air-source heat pump	Ground-source heat pump	
		Vertical	Horizontal
Efficiency	••	•••	••
Design criteria			
Feasibility	••	•	•
Construction difficulty	••	•••	••
Life cycle cost			
Installation	•	•••	••
Operation	••	•	•
Maintenance	••	•	•
Total	••	•	•
Environmental			
CO_2 emissions	••	•	•
Land disturbance	None	••	•
Water contamination	None	None	None
Durability	•	••	••
Practical issues			
Operating restrictions	••	•	•
Aesthetics	•	••	••
Quietness	•	•••	•••
Vandalism	•	None	None
Safety	••	••	••

Two different types of GSHPs can be used, whether using single or more reciprocating compressors [69]. For the lower to middle efficiency range of GSHPs, one compressor is sufficient, but in the high efficiencies, units are designed with two-speed compressors with same heat exchanger [72]. Single-stage heat pumps can provide heat at 55˚C, but buildings which require heat delivery of higher that 60˚C must be supplied by two-stage heat pumps [69]. The main challenge of using two-stage heat pumps is to employ the right refrigerant capable of working within the geothermal source and the second-stage condenser, where high temperature heat is transferred to the heating system [69]. The solution could be using different refrigerants in two single-stage heat pumps that are connected by a heat exchanger [73]. Table 6 shows the distribution of different heat exchanger types based on the number of installations in some provinces in Canada.

Table 6. Distribution of different heat exchanger types based on number of installations in some Canadian provinces [69].

Province	**Open-loop (% of provincial systems)**	**Closed-loop (% of provincial systems)**		**Pond/lake (% of provincial systems)**
		Vertical	**Horizontal**	
Ontario	12	15	67	6
Quebec	6	85	8	1
British Columbia	15	31	52	2
Alberta	7	72	19	2

4.3. Geothermal heating and cooling systems across the world

Another possible energy source for a District Energy (DE) system is the ground source heat pump, which typically has a coefficient of performance (COP) of about 4. A ground source heat pump transfers heat into the ground in summer and extracts heat from the ground in the winter [69].

The degree of adoption of geothermal energy depends on policy and other technology issues [74]. Geothermal energy is another important cold source for the cooling system [75, 76], which mainly refers to energy from the aquifer or groundwater. This estimated to conserve about 90–95% energy for District Cooling System (DCS) [77]. One of the largest groundwater reservoirs in Norway is used to serve the Gardermoen Airport as a complementary heat sink and source for DCHS [78]. During the cooling period, the chilled water is pre-cooled by the groundwater with a cooling capacity of 3 MW. It is then post-cooled by a combined heat pump/refrigeration plant with a cooling capacity of 6 MW [69].

5. Geothermal energy distribution systems

There are some different ways to distribute energy, which is gathered by geothermal heat pump from the ground that is the source of the energy. Energy can be distributed in the form of either hot water or hot steam. Some widely used forms of distribution fall into four groups [79]. These groups are: (a) ducted systems, (b) in-floor systems, (c) all-in-one systems, and (d) domestic hot water pre-heating.

5.1. Ducted systems

In this type of energy distribution system, which is also called a forced air system, ducts are installed through the residence and can be used for both heating and cooling (Fig. 17). This type of distribution is most favorable because the infrastructure does exist and was used for traditional energy sources like air heat pumps and oil furnaces [79].

Fig. 17. Ducted air systems [80]

5.2. In-floor systems

To heat a space from beneath and by putting pipes in floor is becoming a popular option for homebuilders. Warm fluid is circulated inside the pipes and the pipes radiate heat to heat the space. Because of its high efficiency, this is becoming a good choice for new buildings and for commercial purposes [79]. The only drawback is that in-floor setup of the pipes cannot be used for cooling processes since it could bring the floor to the dew point, which makes it wet and slick [79]. To prevent this occurrence, fan coils are installed to provide air conditioning. Chilled water is produced by reversing the process of the heat pump and is pumped through the coils [79]. Figures 18 and 19 represent horizontal and vertical settings of these systems.

Fig. 18. Geothermal in-floor systems, horizontal [81]

Fig. 19. Geothermal in-floor systems, vertical [82]

5.3. All-in-one systems

All-in-one systems are coupled system of in-floor and ducted systems. In this way, the demand is fully met and the advantages of both systems apply [79].

5.4. Domestic hot water pre-heating

This option is used to pre-heat domestic water, called desuperheating; there is sometimes a heat exchanger connected as an extra part or a part of a heat pump that has the role to preheat the water so that energy can be saved and some costs reduced [79]. Figure 20 illustrates a ground source heat pump fitted with a desuperheater to transfer the waste heat from the refrigeration cycle of the GSHP to a storage tank. The whole system has the potential of saving up to 70% of hot water costs [83].

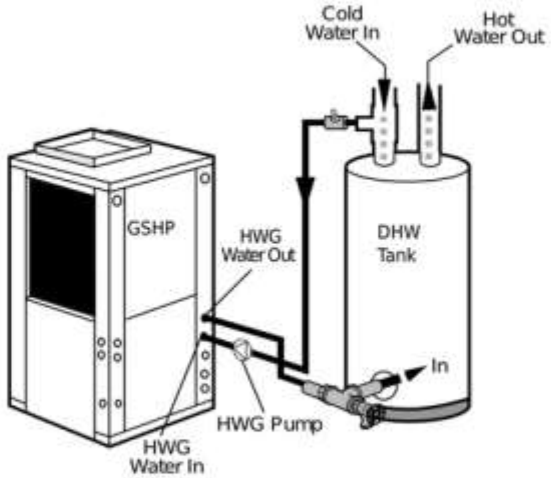


Fig. 20. Water to air GSHP with a desuperheater [83]

6. Heat pumps

Heat pumps have been widely used since the 1800s, when they were recognized for the first time [84, 85]. Electricity is the most common type of drive energy for heat pumps and enables them to utilize ambient air as a heat source or sink. The vapor-compression refrigeration cycle is the operational principal of heat pumps, and generally, a refrigerant is used as the working fluid [84, 86, 87]. The working principle of heat pumps is on the basis of the Reverse Carnot cycle, in which thermal energy is a product of electrical energy [88]. Consequently, thermal energy is transferred from an environment with a lower temperature to a medium with higher temperature [84, 85]. There are heat exchangers in both mediums, and a compressor is used to circulate the refrigerant between these heat exchangers. In the coils of a cold medium, the refrigerant absorbs the heat at a low pressure and therefore it evaporates. Then, the compressor pressurizes this vapor; it moves through the other heat exchanger to be condensed and releases the absorbed heat from the cold medium to a sink with higher temperature [89-91].

GSHPs are more efficient than the other types of heat pumps that can be found in the market, such as the widely used Air Source Heat Pumps (ASHP). This advantage is due to the heat source and sink of the thermal energy, which are the ground and the environmental air, for GSHP and ASHP, respectively. The ground behaves like a roughly constant temperature medium, which is colder than the air in hot seasons and warmer than it in cold seasons [92, 93]. For example, the annual change in temperature of the ground in Ottawa, Canada, with increasing depth, is shown in Fig. 21. As illustrated in this figure, ground temperature is roughly unchanging at nearly the average air temperature on a yearly basis [94, 95].

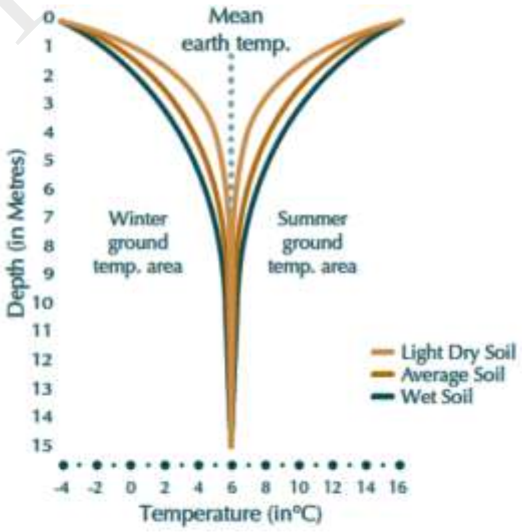


Fig. 21. Temperature changes with depth in Ottawa, Canada [89]

Thermal energy is moved between the conditioned space and the ground in a GSHP, controlling temperature and pressure by expansion and compression [89, 90, 96]. There are five important constituents in every GSHP [84, 96-98]: two heat exchangers (in cold and warm mediums), expansion valve, compressor, and reversing valve, indicated in Fig. 22.

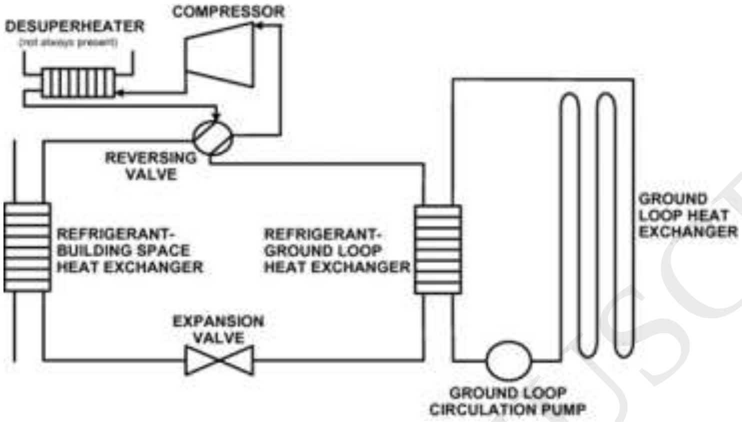


Fig. 22. General layout of a GSHP with a desuperheater [74]

When a GSHP is used for heating, it operates as follows:

1. The evaporator extracts thermal energy from the ground.
2. Cold refrigerant in a liquid-vapor phase (which is mostly liquid) enters the evaporator. Extracted thermal energy from the ground connection transfers to the cold refrigerant and therefore the refrigerant evaporates and becomes a low-pressure vapor.
3. The compressor receives vaporized refrigerant and consequently, increases its pressure and temperature (when the vapor leaves the compressor, its temperature is more than the temperature of the ambient air).
4. After leaving the compressor, high temperature vapor goes into the condenser. Due to its being higher the temperature them the building’s environment, the heat transfers from the condenser to the building. Because of this heat transfer, the hot refrigerant condenses into a high-temperature and high-pressure liquid.
5. High-temperature liquid travels through an expansion valve which results in reduction of pressure and temperature. The cold refrigerant enters the evaporator to start the cycle again.

During the cooling period, the direction of the fluid’s flow reverses, and consequently the direction of heat transfer. This means that heat is extracted from the conditioned space and is rejected into the ground. A desuperheater is another additional element that can be found in some systems. This heat exchanger transfers thermal energy from hot vapor to a water tank to reduce or even eliminate the required energy for heating water [84, 99].

6.1. Different types of ground source heat pumps (GSHPs)

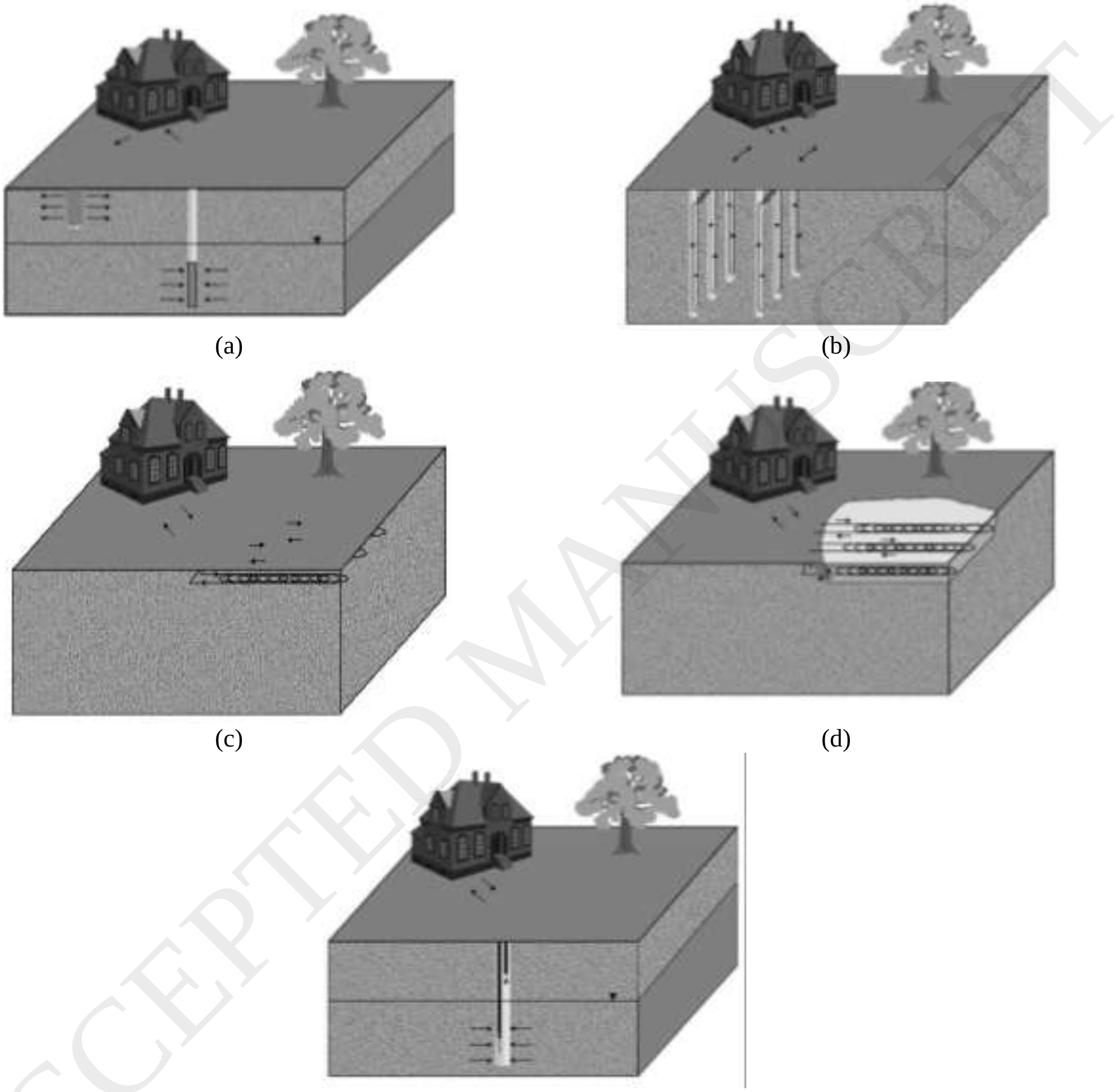
The geological characteristics, including the temperature below the ground's surface, the hydrological and the thermal properties of the location where the GSHP is going to be used, are decisive factors in the relative cost and design of the system. There are two kinds of geometries available for the circuits of heat exchangers that are buried in the ground [100]: horizontal and vertical. The GSHPs can be categorized according to the technologies that are used into four following main types.

6.1.1. Ground-water heat pump systems (GWHP)

GWHPs, also called open-loop systems, are the first type of ground source heat pump. Their first installation was in the late 1940s [101]. These are in the group of vertical systems that include wells and pumps to provide subsurface water for direct application or to a heat pump. The utilized groundwater is then released to a recipient. The most decisive factors in designing pertain to the availability of groundwater and its chemical characteristics. The advantages of GWHPs are their low cost and that they do not need a wide ground area to function. The drawbacks of these systems are related to the lack of groundwater, its poor quality, retraction of groundwater and its re-injection [100]. Figure 23(a) illustrates a schematic illustration of a GWHP.

6.1.2. Ground-coupled heat pump systems (GCHP)

GCHPs are also called closed-loop systems [102]. To overtake the problems connected with groundwater availability and quality, this type of GSHP was developed during the 1970s. The required pumping energy is less than for the previous type (GWHP), due to less elevation [103]. In these systems, the heat exchangers' pipes are made from high-density polyethylene, which and are buried in horizontal ditches or vertical boreholes. These pipes are used to extract heat from the ground or reject it there. Antifreeze solution or water are commonly used fluids in this application. In vertical GCHP systems, 30.5 to 120 m in depth and 76 to 127 mm in diameter boreholes can be used as the ground heat exchangers, and these boreholes are backfilled with a material to protect groundwater from contamination [104]. One of the challenging steps in the design of vertical GCHP systems is proper sizing of the depth of boreholes[104, 105]. In horizontal GCHP systems, the length of parallel pipes is 121.9 to 192.9 m per ton of cooling and heating load, in 0.91 to 1.83 m deep ditches. The diameter of these pipes is 19 to 38 mm. Since the temperature of the soil is not stable in the upper layer of soil (with a higher temperature than soil below 10 m in late summer due to solar irradiation and lower temperature caused by heat losses at the end of the winter), a disadvantage of horizontal systems is that the COP is variable in the heating mode [100]. Figure 23(b) illustrates a typical schematic of vertical and horizontal GCHP systems, respectively.



(a) (b) (c) (d) (e)

Fig. 23. A schematic illustration of different classes of ground-source heat pumps: (a) GWHP systems, (b) vertical GCHP systems, (c) horizontal GCHP systems, (d) SWHP systems, and (e) SCW systems [106]

6.1.3. Surface-water heat pump systems (SWHP)

Any body of water, which is in direct contact with the atmosphere, is defined as surface water, including lakes, ponds, rivers, and oceans [107]. SWHPs are in two main configurations:

1. The open-loop system: In this type, surface-water is extracted from the intake area, and subsequently the utilized water is discharged to another area as a receptor [100]. This system can be employed for almost any use, including commercial, residential and institutional buildings, for both heating and cooling applications [107].
2. The closed-loop system: This type of circulation system, which is used for extraction and rejection of thermal energy, is located within an open channel, such as a lake or a pond, at an optimized distance from the pond's surface. For each ton of the cooling or heating load, from 30.5 m up to 91.4 m long pipes are needed. These pipes are 19 to 38 mm in diameter [100]. Like an open-loop system, this system can be used for more or less any application. One merit of closed-loop systems is that they do not need any screening or filtering of the water body, although they do need a heat exchanger submerged in the water [107].

When designing SWHP systems, having the maximum and minimum temperatures of the water body over the year, statistically, would be ideal. Unfortunately, it is very rare for such statistically derived data to be found. Moreover, water body temperature profiles for this usage are dependent on its bathymetric profile and weather conditions. In other words, for two lakes of identical area and different depth, the temperature of the one which is much deeper might be stratified throughout the year, while the other one might be entirely unstratified. Accordingly, extrapolation cannot result in authentic data [107]. Rather, meteorological data can be used for simulation models of temperature profile. In cases where there are no statistically measured data for the temperature of the lake, the best method is to use simulation data [107].

6.1.4. Standing column well systems (SCW)

SCWs use groundwater pulled from wells and their configuration is a semi-open loop. The vertical well, which is filled with groundwater up to the water table level, is used as a ground heat exchanger (Fig. 23(e)). Even though most of the time they function by recirculation of water between the heat pump and the well, during peak periods of cooling or heating load, to make up the flow they can “bleed” some water from the system. This occurs where groundwater flows into the column from the surrounding structure to cool the surrounding rocks and column in cooling periods (when heat is rejected into the earth) and vice versa during heating periods [108]. Generally, the vertical borehole that allows the fluid to be in contact with the rocks is about 15 cm in diameter and is hundreds of meters in depth. One of the drawbacks of this technology is its installation cost [100]. Tables 7 and 8 include different types of heat pumps and their advantages and drawbacks, to ease their comparison.

Table 7. Different categories of GSHPs [100]

Main categories	Description	Sub categories	Heat source	Working depth
GWHP	Ground-water heat pump (open-loop systems)	-	Ground	6-100 m
GCHP	Ground-coupled heat pump (closed-loop systems)	Horizontal	Soil	1.5 m
		Vertical	Soil	6-120 m
SWHP	Surface water heat pump	Open-loop	Surface water	0-5 m
		Closed-loop	Surface water	0-5 m
SCW	Standing column well systems	-	Groundwater	Up to 450 m

Table 8. Advantages and disadvantages of different categories of GSHPs

Categories	Advantages	Disadvantages
GWHP	- low installation cost [100] - simplicity of construction [100] - small amount of ground area [100]	- limited availability of groundwater [100] - poor chemical quality of water [100] - groundwater withdrawal and re-injection [100]
GCHP	- independent of groundwater availability and quality [100] - low pumping energy [103]	- difficulty of designing appropriate sizing the depth of borehole (in vertical GCHP) [105, 109] - variable COP during heating season (in horizontal GCHP) due to soil temperature variations [100]
SWHP: open-loop	- flexible (extraction rate is adjustable due to demand) [110] - adaptable (installation is possible at most surface water sites) [110]	- lake mixing interfering effects (by changing natural currents) [110] - contamination of surface water - temperature effects [110] - physical blockage [110] - susceptibility to damage [110]
SWHP: closed-loop	- quite low installation cost due to reduced excavation costs [88] - maintenance cost is low [88] - works at lower temperatures (due to working with refrigerant fluid) [88]	- contamination of surface water [88, 110] - temperature effects (threatening aquatic life) [110] - physical blockage [110] - susceptibility to damage [88, 110] - variation of water temperature with weather temperature [88]
SCW	- shorter boreholes [108] - more stable temperature of water [108]	- significant installation costs [100]

6.2. Hybrid ground coupled heat pump systems (HGCHP)

GSHP systems have been widely used in the last two decades and are gaining popularity for different usages such as residential, commercial and institutional buildings. When the difference between annual rejected heat to the ground and extracted heat from the ground is considerable, the average temperature of the loop fluid would rise or fall, according to the dominant direction of heat transferred [111]. Figure 24 represents this decrease in average ground temperature because of the dominant heating period in Urbino, Italy.

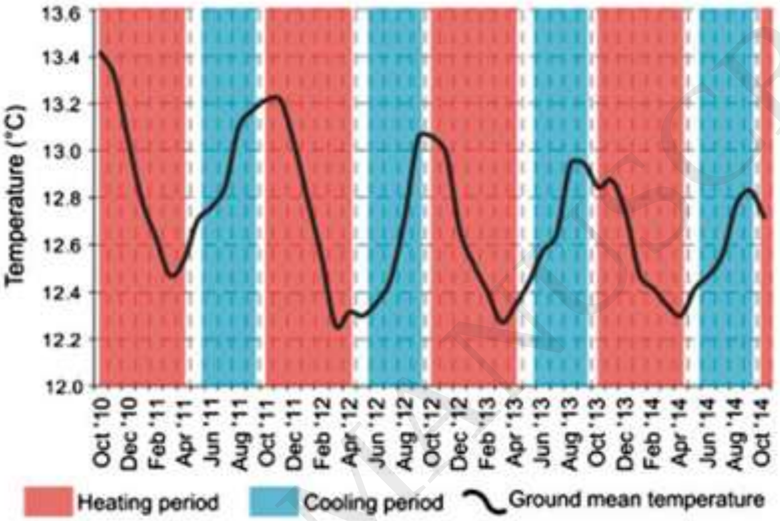


Fig. 24. Gradual decrease in average ground temperature between 10 and 100 m of depth in the monitoring well, which was located 2.2 m from a BHE, in a heating dominated site in Urbino, Italy [112]

To alleviate this phenomenon, one solution is that ground loop heat exchangers can be increased in size to meet demands, but this would result in a disproportionate capital cost. A practical solution for this problem is to add a supplementary heat source or sink to the system [113]. The hybrid ground source heat pump (HGSHP) system is a combination of a ground source heat pump (GSHP) system and a supporting thermal source or sink. There are various types of supplementary heat sources or sinks, such as solar collectors, waste heat, boilers, cooling towers, fluid coolers and shallow ponds [114].

In a building with an HGSHP system where the cooling need is dominant (in which a heat sink is added to the GSHP system), the ground heat exchanger is sized to meet the demands for heating the system. Consequently, the size of the heat exchanger decreases considerably. Similarly, in a building with an HGSHP system where the heating need is dominant, the ground heat exchanger is sized to meet the demands for cooling of the system [115, 116]. Two types of hybrid systems are more common nowadays, which are: the solar assisted ground source heat pump (SAGSHP) and cooling tower supplemented ground source heat pump (CTGSHP) [113].

6.2.1. HGCHP with extra heat rejecters

These systems use an extra cooling device as a supplement to the underground heat rejecters, especially when the cooling load is dominant and is much higher than the heating need [117]. The performance principle and a schematic of a hybrid system with a cooling tower (CT) are shown in Fig. 25, where the GCHP heat exchangers are in series with CT [88]. Excessive heat rejection to the soil results in soil temperature rise and consequently the performance of the system will decrease. Extra heat rejecters can overcome the problem of soil degradation due to excessive heat [118]. A control strategy for the cooling tower and ground heat exchanger is of high importance for the optimized performance of these systems [119]. Atam and Helsen [71, 120] have reviewed various control methods for geothermal performance.

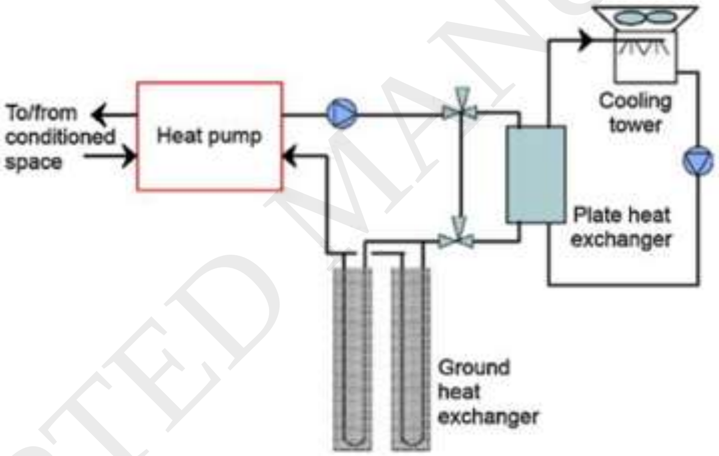


Fig. 25. A schematic diagram of a hybrid GCHP with CT [88]

6.2.2. HGCHP with extra heat absorbers

As mentioned in section 6.2, in cooling dominated areas, excessive heat rejection can result in soil degradation, and therefore a decrease in system performance. Similarly, the GCHP system, alone, can cause thermal depletion of the soil and a decrease in temperature of fluid entering the heat pump, in heating dominated climates. As a result, the efficiency of the system will decrease. To overcome this problem and reduce installation cost (due to reduction in the size of both heat exchangers and boreholes), extra heat load can be supplied by different supplemental sources [88]. The use of a supplemental heat absorber can also decrease the total life cycle cost of the system more than the other types of GSHP systems [121]. Figure 26 illustrates a schematic of an HGCHP system with solar thermal collectors which is more common [113].

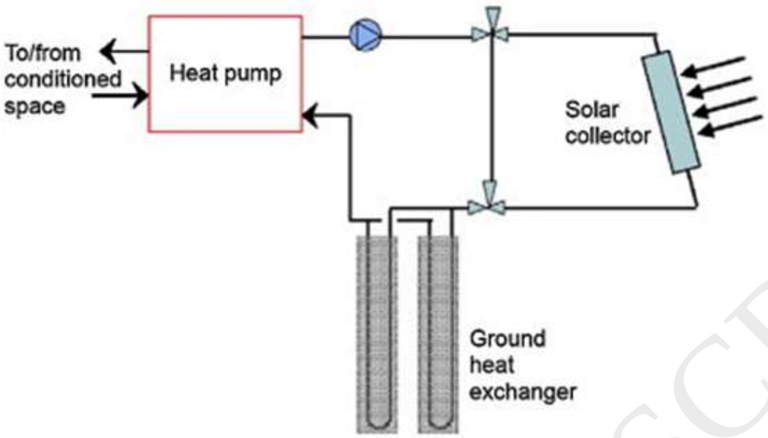


Fig. 26. A schematic of a hybrid GCHP with solar thermal collectors [88]

The application of combined geothermal and solar energy in heat pumps for heating in commercial applications has been studied since the introduction of geothermal systems [122, 123]. Chiasson et al. [124] studied the feasibility of using a supplemental solar collector as the heat source in a GSHP. In this study, the loads were obtained by simulation of a heating dominated school building in a cold climate. The use of a solar collector leads to a 34% decrease in heat exchanger size.

Figure 27 demonstrates the schematic of HGCHP with solar thermal collectors in a more detailed way. The heat gathered from solar collectors is used to lessen the excessive heat load of ground heat exchangers, with priority over water heating. A 35% water-based propylene glycol solution is the fluid used in the solar/ground circuit in order to prevent water from freezing. A more concentrated propylene glycol has a negligible impact on the performance of a heat pump and increases drive electricity of circulation pumps [125].

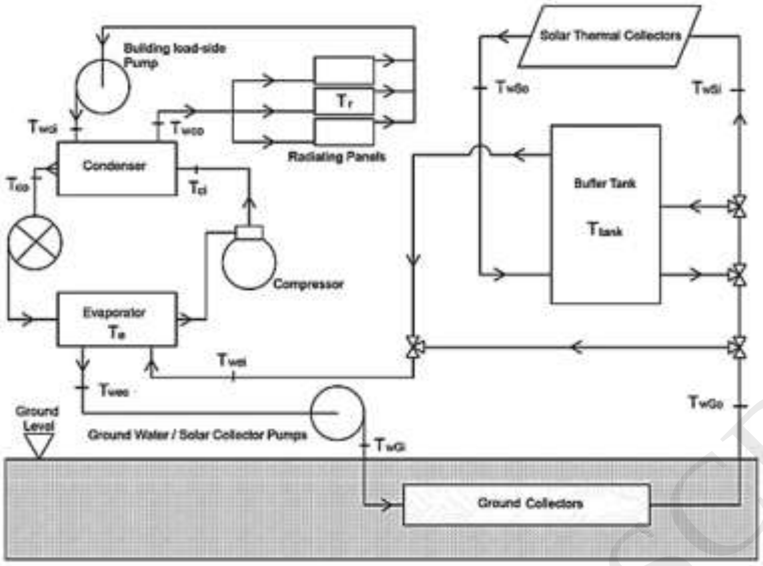


Fig. 27. A schematic diagram of a solar assisted GCHP in detail [94]

The antifreeze solution is injected into the buried pipes in the ground, after thermal extraction in the evaporator. Then, the fluid flows into the solar collectors, but only if the solar radiation is adequate. If not, the solution does not circulate through the solar loop, and enters directly into the evaporator. In this situation, when the fluid does not flow through the solar loop, the buffer tank stores the excessive heat that is harvested throughout the day and solar collectors are used as a by-pass. This harvested heat is not usable during the day, due to the temperature limit of the heat pump system [94].

Girard et al. [94] investigated the feasibility of higher performance from GSHPs with the use of solar collectors in heating mode and within different latitudes. In this study, the COP varied between 4.4 and 5.8 for solar assisted GSHPs, and between 4.3 and 5.1 for GSHPs, from northern to southern locations. The increase of COP resulting from changing the system from GSHP to SGSHP is much higher for southern localities than for northern ones, in the northern hemisphere, and vice versa. Also, the solar assisted GCHPs work well in autumn and spring when more solar radiation is available. The solar assisted GSHP's annual electricity consumption is less than that of GSHP in all latitudes [94]. Figure 28 shows changes in performance of solar assisted GCHPs and GCHPs at different latitudes within Europe.

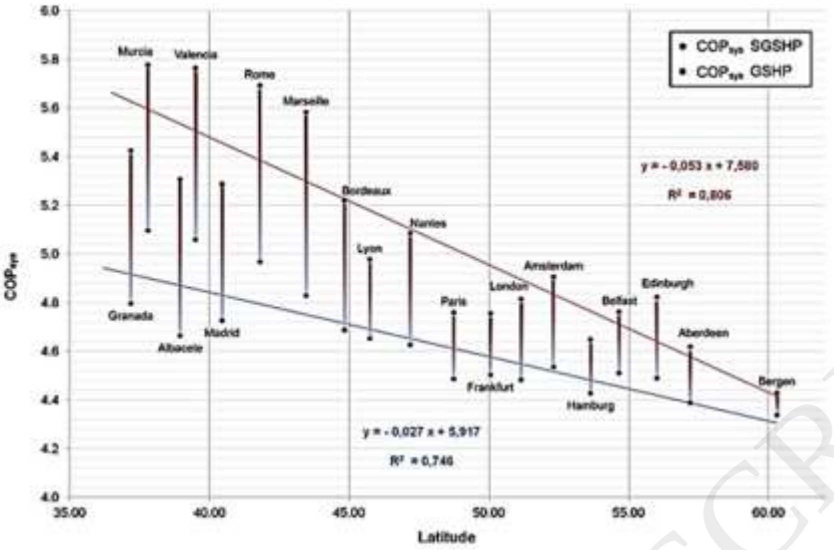


Fig. 28. Variations of COP in with latitude [94]

7. Ground heat exchangers

GHEs can directly extract heat from or release it into a space for cooling/heating applications and also can be coupled to ground source heat pumps. For instance, in two-stage heat pumps, the heat exchanger can be a condenser and an evaporator at the same time for the first and second heat pumps, respectively, as illustrated in Fig. 29 [69]. GHEs use air, water or antifreeze fluids as a working fluid to circulate in the system. High-density polyethylene (HDPE) pipes are usually employed to construct these heat exchangers [88]. GHEs can be categorized based on their circulating fluid, loop types (open/closed), position (horizontal, vertical or oblique), pipe connections (series/parallel) and more [126]. Each of these types and their combinations is applied for a specific usage, depending on its pluses and minuses.

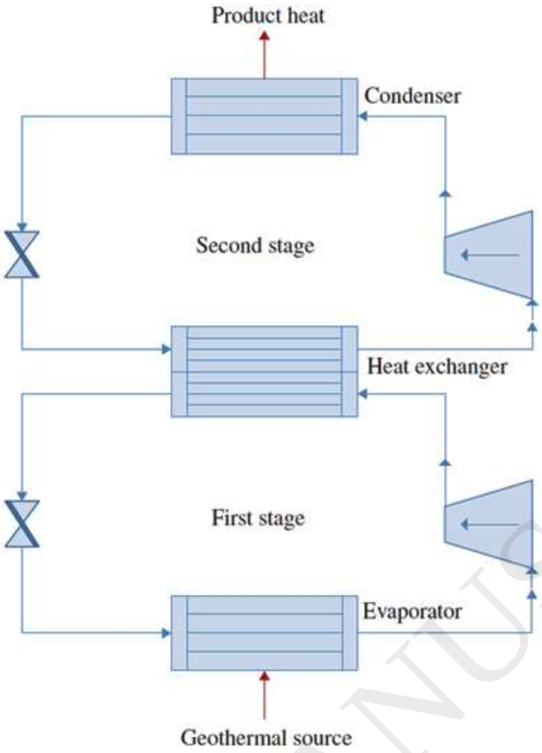


Fig. 29. A two-stage heat pump using a heat exchanger as a connector [69]

7.1. Direct exchange

These heat exchangers employ a refrigerant, flowing in the copper tubes, which contacts the ground source heat exchanger directly. The phase changing state of the refrigerant supplies the greater heat transfer rates, which allows the building of smaller loops with the same heat transfer load. Thus, direct-exchange loops have a lower price [69].

7.2. Open-loop systems

The operation of open- and closed-loop GHEXs are similar. However, there are some differences. One of the basic principles of using open-loop systems is to directly preheat or precool the ambient air with a conventional air conditioning unit [126]. Figure 30 demonstrates a schematic illustration of this system. Open-loop systems also can use groundwater directly to exchange heat [127]. Advection is the main constituent of heat transfer in this case (Fig. 31).

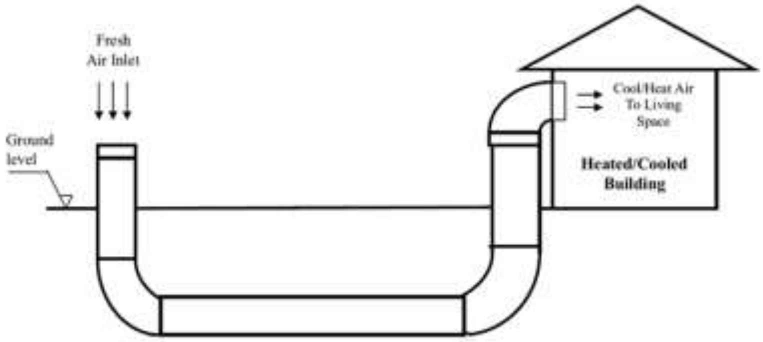


Fig. 30. Fundamental guideline of an open system which preheats or precools the air [128]

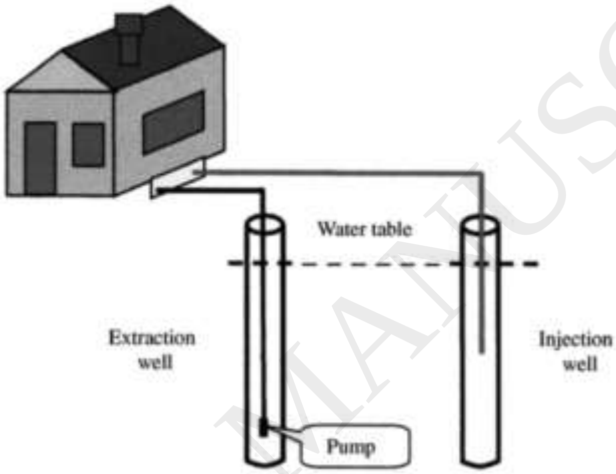


Fig. 31. Ground water heat pump [126]

Closed-loop systems are more common for the operation of GHEXs [129]. Recently, some types of open-loop systems have been taken into consideration [130]. In an open-loop system, wells can be vertical and fewer boreholes are needed, so open-loop systems require less construction space and this is the most noteworthy feature that makes them suitable for built-up areas and less costly [131].

There are three types of open-loop GHEXs based on the pump position and inner casing configuration [132]. Standing column wells (SCWs) are the first type. The second type is concentric thermal wells. To avoid wall collapse, the empty space between the borehole wall and the inner case must be filled with granular aggregates. The newer third type has this difference, there is no inner case component in its structure [131]. These three types are shown in Fig. 32. It is proved by thermally affected zones (TAZ) sensitivity analysis that porosity, hydraulic conductivity, and hydraulic gradient play the main roles in open-loop systems [133].

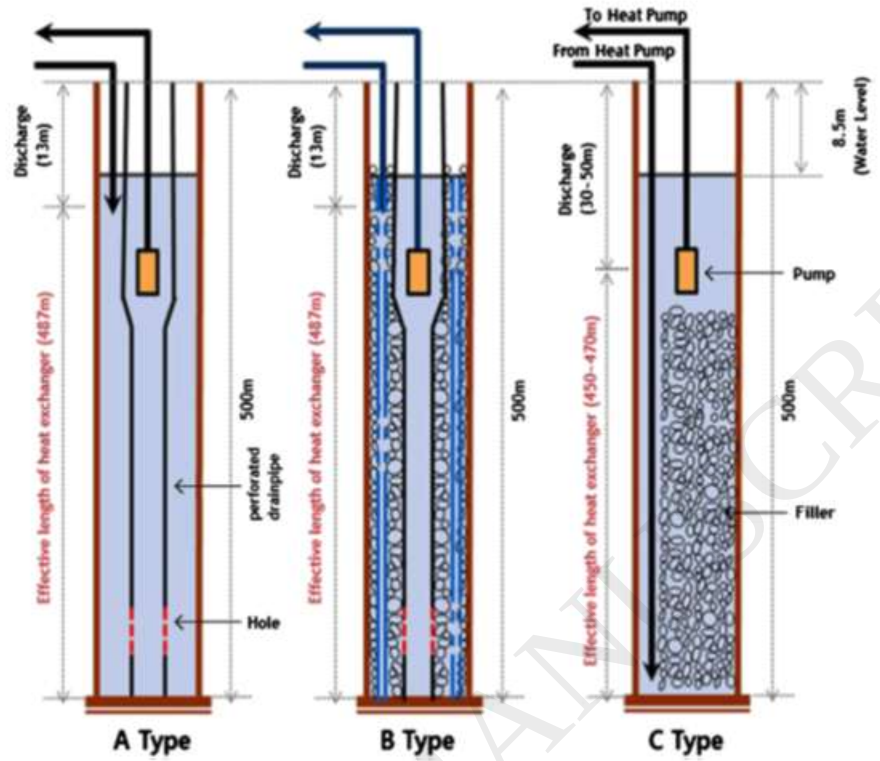


Fig. 32. Characteristics of three types of open-loop GHEXs [131]

7.3. Closed-loop systems

As previously mentioned, the GHEH's position can be grouped as horizontal (trench), vertical (borehole) and oblique. In addition, pipes' connections can be parallel or in series. These categories are more common for closed-loop systems. Unlike open-loop systems, closed ones are utilized where sufficient space is available, where it is easy to excavate trenches, and these are not so costly.

Horizontal and vertical ground loops have different applications. Horizontal loops are employed where an adequate area is accessible to install enough pipes and the trench's depth is 1-2 m in the ground. Series, parallel and trench connections of horizontal GHEXs are schematically illustrated in Fig. 33. To gain 1 kW, it is required to install 35-60 m pipes in a horizontal manner [134]. However, this configuration is the most cost-effective, especially if it is applied during the construction of a building [126].

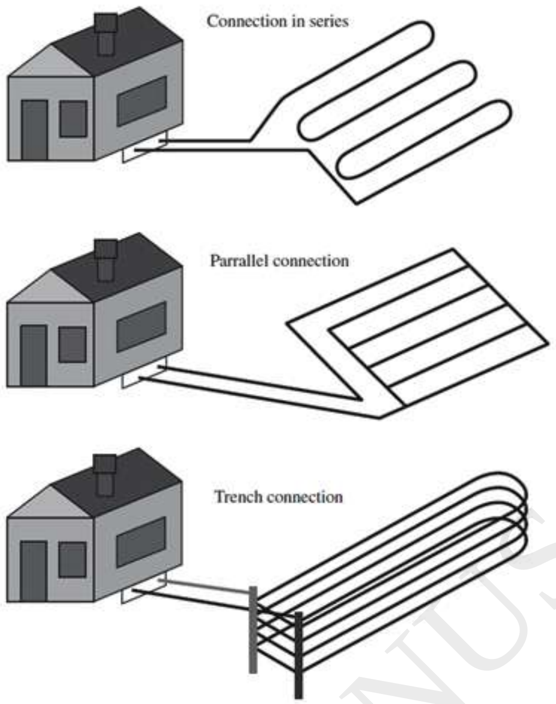


Fig. 33. Horizontal closed-loop ground exchangers [126]

Unlike horizontal ground loops, vertical ones are utilized where land spaces are restricted. Although this configuration needs less piping, it is more costly than horizontal loops because of the difficulty of the deep excavation process [83]. For typical application a depth of 50-150 m is needed in a standard borehole [126]. A sample of a vertical GHE is illustrated in Fig. 34.

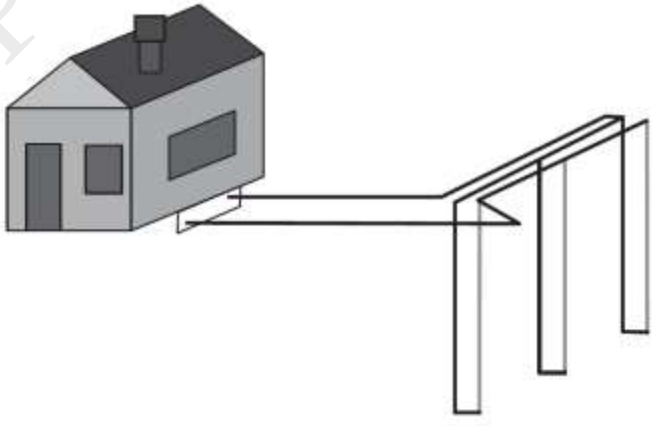


Fig. 34. Vertical closed-loop ground exchangers [126]

Among various kinds of borehole heat exchangers, only some of them have been tested and are fit to be generally utilized so far. These can be divided into two classes, as illustrated in Fig. 35, [126]:

1. U-pipes. These pipes are commonly made of budget materials. Thus, they are ideal to be set up as double or triple for using in a single hole. U-pipes contain two comparable pipes, which are linked with a U-turn from one side.
2. Coaxial/Concentric pipes. As shown in Fig. 35, two straight pipes with diverse diameters can be jointed coaxially or several pipes can be positioned in a complex configuration.

By sensitivity analysis of unnatural heat injection, it is found that thermal conductivity, porosity, the soil/rock heat capacity and then the longitudinal dispersivity are the most vital factors that affect a closed-loop system's performance [135].

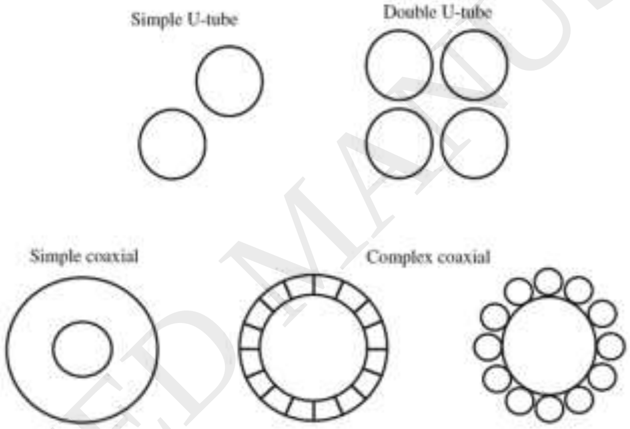


Fig. 35. Cross section of vertical ground heat exchangers that are generally used [69]

7.4. Ground thermal distribution

One of the greatest factors in the design of ground heat exchangers is to determine the temperature distribution at the surface and at diverse depths in the ground. The ground temperature profile generally appertains to how the properties of the ground alter physically as well as the ambient climate conditions. The first factor mainly includes the ground surface cover, such as grass, water, and bare ground, to name a few. In addition, rock types of each layer of the ground directly determine the thermal conductivity of that section. The second factor includes the temperature of the air, solar radiation, humidity, and rainfall as well as wind speed; all of them are variable, depending on seasonal cycle weather conditions [126].

Popiel et al. [136] set up two experimental stations with different surface covers, a car park as a "bare ground surface" having a solar radiation effect and a lawn in the city of Poznan, to investigate the ground cover effects on the ground temperature distribution. The temperatures were measured weekly or every other week at the noon hours. The results can be summarized as follows [136]:

1. Around the depth of 1 m, the ground temperature experiences a short period of erratic behaviour.
2. The heat flux direction is from ground surface to underground over the summer months; however, approximately at the end of September, when the temperature difference becomes zero at nearly 1 m under the ground, the heat flows inversely upward.
3. During summer, lawn's surface cover provides a colder zone which can be utilized as a cold source for air conditioning purposes. The results demonstrate an almost 4˚C lower temperature at the depth of more than 1 m in contrast with the bare ground surface.
4. It is generally suggested to use a depth of about 1.5 to 2 m for horizontal heat exchangers.
5. The constant temperature occurs approximately at a depth of 10 m where a boundary is assumed, which divides the underground space into shallow and deep zones. The temperature of the deep zone remains constant over time.
6. The authenticity of the temperature distribution is verified by the results of Bugg's formula.

The uninterrupted heat being extracted from and being released into the earth in winter and summer, respectively, alter the thermal distribution of the ground in the long term, which could have a great impact on the operation of customary ground source heat pumps (GSHPs), especially in regions having warm summers or cold winters. Therefore, the multi-function ground source heat pump (MFGSHP) system is proposed to solve this issue. Additionally, to their normal duties (space heating/cooling), these systems provide hot water to lessen the instability in the underground temperature distribution. Consequently, a single MFGSHP system can offer all the operations mentioned simply by opening/closing the valves to change the flow direction of the refrigerants, as shown in Fig. 36 [137]:

1. Air conditioning only: For space heating and cooling purposes, the same valves must be on, number 9, 14 and 18. The flow direction in these valves determines the cooling or heating states.
2. Water heating only: Except for valves 14 and 18, all of them must be off.

3. Water heating and space cooling at the same time: By switching off all the valves except number 15 and 18, the heat exchangers 4 and 11 operate as an evaporator and a condenser.

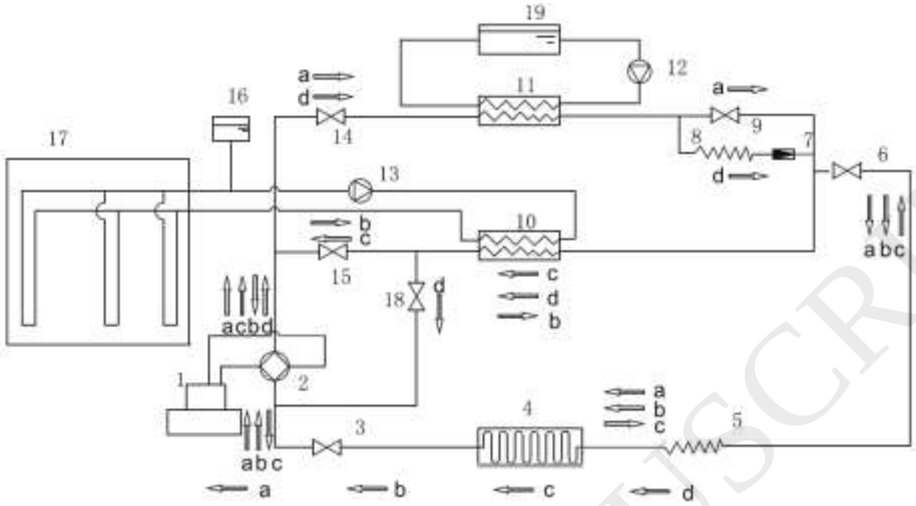


Fig. 36. Schematic of MFGSHP systems [137]. Note: a- cooling and water heating; b- space cooling, emit heat into soil; c- space heating, extract heat from soil; d- water heating only, extract heat from soil; 1- compressor; 2- reverse valve; 3, 6, 9, 14, 15, 18- valve; 4- heat exchanger; 5, 8- throttling capillary; 7- check valve; 10, 11- heat exchanger; 12, 13- water pump; 16- water tank; 17- ground heat exchanger; 19- hot water tank

As mentioned in this section, ground heat exchangers affect the underground temperature distribution. In order to calculate it, three methods are proposed so far, which are: the analytical and numerical solutions and the g-function model [138]. Each solution has its own pros and cons; thus, choosing the right one considering the problem conditions is vital. The analytical solution cannot be a suitable method for accurate applications due to its many simplifications [139-141]. The numerical solutions normally contain some intricacies, which make them take a long time to run [142-144]. Finally, the g-function model is a combination of the analytical and numerical solution. Therefore, in this model some significant items, including the U pipe shape and the non-uniform soil properties, are disregarded [145, 146].

7.5. Modeling ground heat exchangers

Generally, the ground heat exchanger can be simulated analytically and/or numerically for heat transfer inside or outside the borehole. These diverse models mainly focus on designing borehole heat exchangers, including determining the number of the boreholes and also their depth, in-situ ground thermal conductivity analysis, and unification of the air conditioning, heating, and ventilating systems into a whole coupled model to estimate performance. The models differ in accordance with how the acceleration of the methods can be increased, how the heat conduction problem can be solved and the assumption of the interaction between boreholes [69].

7.5.1. Vertical ground heat exchangers models

7.5.1.1. Heat conduction outside borehole

Although the modeling methods of heat transfer outside the borehole are generally in accordance with the analytical or numerical approaches singly, some exceptions are also presented which combine both of the solutions, including Eskilson's model [147]. The following are some of the models that are proposed so far:

- Kelvin's line source

Kelvin's line-source, or the infinite line source, is a theory based on the assumptions that the ground and the borehole are an infinite medium and line source, respectively, while the ground has a specific initial uniform temperature. There are also some simplifications, such as neglecting the heat fluxes toward the borehole axis that make the Kelvin's line-source model one-dimensional [109, 148]. Thus, it is expected that the computation time is reduced. However, these assumptions restrict model applications. For instance, regarding the borehole as an infinite line source makes it suitable only for small pipes [147, 149]. Furthermore, sometimes the error committed is not acceptable [150]. Some modified methods are developed based on Kelvin's line-source adding other conditions in order to enhance the accuracy. The Hart and Couvillion method is one the most accurate ones [151].

- Cylindrical source model

In this model, the properties of the ground are constant, and it is considered that the borehole is an infinite cylinder. Additionally, the heat transfer between the cylinder and its homogeneous surrounding medium is pure heat conduction. This model is ideal provided that either the temperature of the pipe surface or the rate of heat transfer between the pipe and the ground is constant [116]. Carslaw and Jaeger [152] assumed that the heat transfer rate is constant, and then Ingersoll et al. [150] modified it, it became an operational model to apply in relevant studies [153-155].

- Eskilson's model

Unlike the two previous models, Eskilson's model assumed the borehole to be a finite line source, in addition to considering the heat fluxes toward the borehole axis. Thus, it would be an appropriate solution to determine long-term performance [116]. In this model, heat transfer is regarded as pure heat conduction in cylindrical coordinates, and it is assumed that the initial and boundary temperature of the homogeneous ground remain constant.

Generally, a borehole is surrounded by a particular material called grout, which can be a shelter for groundwater from pollutants, shown in Fig. 37 [116]. In this model, the grout and pipe wall as the thermal capacitances are neglected [147]. Moreover, a dimensionless temperature response is solved as a g-function for the borehole wall by special/temporal superimpositions at any arbitrary time. However, the massive database of the g-functions make them take too much computing time, and also some errors may be committed [116].

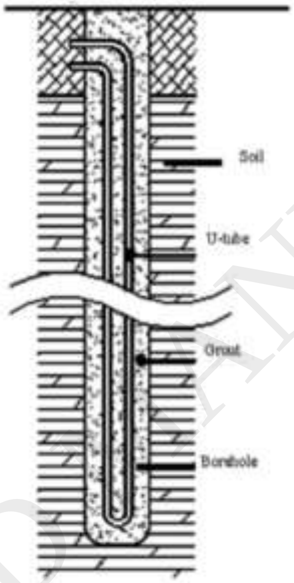


Fig. 37. Schematic of a vertical borehole surrounded by the grout [116]

- Finite line-source solution

Zeng et al. [156] developed the Eskilson's model, emphasizing the effect of the ground surface as a boundary and the borehole as a finite length source. Hence, the ground would be homogeneous, having constant thermophysical properties. However, a semi-infinite medium is assumed this time. Throughout the time considered, the temperature of the ground surface as the medium boundary and the rate of heating per the source length would be constant. Furthermore, the borehole radial dimension was not considered. Later, some researchers developed this method based on different studies [157, 158]. The temperature response of the finite line-source solution is also more realistic for long time durations, in contrast with the Kelvin's theory response, which would tend to infinity in these cases [159].

- Short time-step model

The finite line-source and the Eskilson's model are both designed to estimate the temperature responses, but only for a long period of time, from 2 to 6 hrs, caused by neglecting the borehole thermal capacity [147]. To address this issue, Yavuzturk and Spitler [144, 160] developed the two-dimensional short time-step model to determine transient heat conduction outside the borehole for time period of less than one hour.

- Other typical numerical models

There are some ground loop heat exchangers packages with multiple boreholes, which can operate singly or with a heat pump to heat buildings. Hellstrom [161, 162] and Thornton et al. [163] have developed a simulation model to describe these systems. One of these models, called the duct storage model (DST), categorizes the ground into a medium surrounding one borehole and another medium from the far field to the bulk of the heat store, which are named "local" and "global" regions, respectively. For estimating the ground thermal distribution, a one-dimensional numerical and a two-dimensional finite difference method are utilized for the "local" and "global" regions, respectively.

The nearby legs of a vertical U-tube heat exchanger can affect each other. Hence, a transient finite-element model was presented by Muraya et al. [164]. The authors investigated the effectiveness of the heat exchangers to address this thermal interference. In order to define noncircular geometry for the borehole pipes, Rottmayer et al. [165] introduced a finite difference model with a geometric factor. The model's authenticity has been proved by an existing model for simple conditions.

Li and Zheng [166] introduced an unstructured finite volume model. This three-dimensional model, which has also been validated with experimental data, categorizes the nearby ground into various layers. The working fluid temperature, which varies with depth, definitely has a great impact on the borehole thermal distribution. Thus, the classification of the ground layers determines the variations of temperature with depth. Moreover, the mesh methodology, which is employed in this model, is Delaunay triangulation. This allows the maintenance of the borehole geometric structure, due to its cross-sectional meshes.

7.5.1.2. Heat transfer inside borehole

The main purpose of the heat transport analysis inside the boreholes is to measure the injection and production temperatures of the circulating fluid in accordance with the thermal properties of the borehole, such as the thermal resistance, heat flux and the wall borehole temperature, which can dramatically influence the ground heat exchanger's operation [116]. The following are some of these models with different complexity:

- One-dimensional model

The ground outside the borehole is much larger than the borehole dimensional scale; thus, it can be considered as an infinite medium. Therefore, the borehole thermal capacitance and also the heat flux toward the borehole axis in the grout and along pipe walls can be neglected. In this model, the heat transport and the U-tube are regarded as a one-dimensional process and a single "equivalent" pipe, respectively. Moreover, the heat transfer is assumed to be a steady state [167, 168]. Because of its oversimplification, this model is unable to analyze the thermal interference between the U-tube legs that is called "short circulating", which has a significant effect on the heat exchanger operation.

- Two-dimensional model

A two-dimensional analytical method was presented by Hellstrom [161], which is solved in the cross-sectional direction of the pipes. The heat fluxes of each U-tube pipe per unit length are considered separately to express the U-tube fluid temperature by a superposition of their temperature responses. Thus, in this model, there are some advantages, such as the ability to calculate the inlet and outlet fluid temperature, providing quantitative forms of the cross-sectional thermal resistance, in contrast with assuming the U-tube to be a single equivalent pipe in the one-dimensional model, and allowing determination of the U-tube configurations' impact on the heat conduction. According to Zeng et al. [169], the thermal interference between the U-tube legs can lead to decline of the heat transfer rate between the refrigerant and ground due to the thermal "short-circuit" phenomena. However, like the one-dimensional model, this model is unable to expose this impact on the heat exchanger performance.

- Quasi-three-dimensional model

This model has been developed from the two-dimensional model and again the heat conduction in the grout is neglected along the borehole axis to simplify the analysis [169]. However, this model includes the changes of the fluid temperature in the axial direction in the borehole. Finally, the quasi-three-dimensional model is more accurate than previous models, which is proved by the authors [169]. Therefore, for analysis and design purposes, it is strongly recommended to utilize this model. A summary of different heat transport models inside the borehole is given in Table 9.

Table 9. Comparison of different heat transfer models inside the borehole [139, 161, 170-172].

	One-dimensional (equivalent pipe diameter)	Two-dimensional	Quasi-three-dimensional
U-tube disposal	No	Yes	Yes
Expressing the cross-sectional thermal resistance in quantitative form	No	Yes	Yes
Thermal interference	No	No	Yes
Extinction between the entering and exiting pipes	No	No	Yes
Axial convective heat transfer by fluid flow	No	No	Yes
Axial conductive heat transfer in grout	No	No	No

7.5.1.3. Comparison of the numerical and analytical models

While the analytical models generally contain some assumptions to simplify complex mathematical problems (e.g. neglecting the real size of the U-tubes) [143], the numerical ones are based on polar or cylindrical grids to provide more accuracy. However, most of the numerical models can be inefficient for design and energy analysis purposes, except the models which pre-compute and store massive simulated data. On the other hand, analytical models spend less computation time in contrast with the numerical models. Moreover, the analytical models employ straightforward algorithms that can lead to a compact design or simulation program [116]. A comparison between the features of the analytical and numerical models is summarized in Table 10.

Table 10. Comparison of different heat transfer models inside the borehole [116]

Model	**Method**	**Thermal interference between boreholes**	**Boundary effects**
Kelvin's line source	Infinite line-source	Yes	No
Cylindrical source	Infinite cylindrical source	Yes	No
Eskilson's model	Combination of numerical and analytical methods	Yes	Yes
Finite line-source solution	Analytical method	Yes	Yes
Short time-step model	Numerical method	Yes	Yes

7.5.2. Horizontal ground heat exchangers models

During the last several decades, the main focus has been on vertical ground heat exchangers; thus, far fewer models have been proposed to design, simulate and test horizontal ground heat exchangers experimentally and mathematically. However, some studies have investigated the effect of varying these heat exchangers parameters on performance and operation. In order to calculate the thermal resistance of the surrounding soil, Mei [173] suggested a method based on the energy balance between the soil and the circulating fluid. To do so, thermal properties of the soil, the geometry of the heat exchanger and the system operating procedure should be determined and there is no need to approximate the initial value of the soil resistance and assume the heat transfer rate between soil and fluid. This heat transfer rate can be calculated using the temperature of the inlet water to the heat exchanger and the mass flow rate. This method is also able to calculate the soil thermal distribution directly. Thus, the water temperature profile can be more realistic.

Piechowski [174] proposed a mathematical model by modifying Mei's model. In this model, computational effort was concentrated in the vicinity of the pipe; thus, the accuracy was improved and the computation time decreased. Moreover, the heat and mass transfer were added, because the main heat and mass transfer phenomena occur in the proximity of the pipes. This model also includes the moisture and temperature gradients at the boundary of the pipe and soil.

Eight models of horizontal ground heat exchangers were investigated by Tzaferis et al. [175], which utilized air as a circulating fluid. They categorized their algorithms into two groups:

1. Considering both convection and conduction heat transfers: (a) from circulating air to the pipe (convection heat transfer) and (b) from the pipe to the ground and also in the ground (conduction heat transfer). The thermal characteristics of the ground and the pipe, the system's geometric characteristics and the real-time undisturbed ground temperature are required as the input data.
2. Considering only convection heat transfer from the circulating air to the pipe: The pipe surface temperature, in addition to the thermal and geometric characteristics of the pipe and the system, are required as the input data.

De Paepe and Janssens [176] studied the thermohydraulic aspect of the system based on design parameters of ground heat exchangers which utilize air as a circulating fluid. To do so, they proposed a one-dimensional model and connected the thermal effectiveness to the pressure drop inside the tube. Therefore, specific pressure drop can be calculated. Considering the circulating fluid as a liquid, similar relations can be utilized to estimate the performance of the system. Esen et al. [177] suggested an experimental study to estimate the thermal distribution around horizontal ground heat exchangers. They carried out some thermal measurements for the seasons, in which heating is the major application of the air conditioning systems to determine the temperature distribution, and consequently, they define a coefficient performance of the ground-source heat pump.

8. Summary

Nowadays, using renewable energies is imperative because of ecological issues resulting from GHG emissions. Because renewable energy utilization has increased in the last few decades, it is important that it be more considered. For comparison, the renewable direct heating and cooling systems performances of geothermal and biomass energies are approximately the same and solar energy performs less well. Although using geothermal energy has some barriers, such as high initial cost and lengthy construction time. It has a multitude of advantages that using other renewable energy sources does not have, such as working throughout the year, using less land and being weatherproof, to name a few, and these benefits make geothermal energy more suitable.

In this study, utilization of geothermal energy is reviewed briefly. Additionally, the history of district heating by geothermal energy in different parts of the world is studied and with different kinds of utilization of geothermal energy. For comparison, differences between space heating and district heating are discussed. Then, different options to distribute energy in a space are examined. Over the last few decades, two oil crises pushed governments to invest in renewable energies. Regarding this, pros and cons of sustainable energy sources are compared and the economy of utilizing each one is discussed. Currently, a huge amount of energy is consumed worldwide for space cooling and heating. The authors believe that future works focusing on the development of district cooling could revolutionize consumption of energy, as district heating has done.

Geothermal heat pumps have been widely used since their first introduction. In this study, the development of geothermal heat pumps from their beginning to the present has been reviewed. Different types of GSHPs are compared and classified in four main categories: GWHP, GCHP, SWHP, and SCW. They are dependable technologies for residential and commercial usages, with better performances than air source heat pumps (with COPs up to 4.9). Also, they can be improved significantly by using them as hybrid systems in combination with heat rejecters or heat absorbers, depending on the climate conditions (with COPs up to 6); accordingly, hybrid systems can reduce the consumption of energy.

One thing that seems to be a considerable drawback of geothermal systems is that their first investment is not affordable by a large group of communities and an increased level of development with lower initial cost would make this technology more commonplace worldwide. Ground heat exchangers are employed to extract and release heat and in order to enhance their efficiency, are typically coupled to heat pumps. Moreover, as mentioned in this study, in contrast to ambient air temperature, at a certain depth, the ground temperature is always lower and higher in summer and winter, respectively. That is the fundamental principle of operating GHEs, such as air pre-heating and pre-cooling in open-loop systems.

Over the past few decades, abundant various models have been developed and presented, especially for vertical GHEs, in order to describe heat transportative, both inside and outside the borehole. Thus, a detailed comparison is performed to recognize their pros and cons. These simulation models depict the thermal performance of GHEs and can be applied in sizing applications. A comparison of previous studies shows that there is still so much to do to achieve an appropriate simulation model, such as considering the groundwater effects and also optimizing the heat storage processes using borehole heat exchangers under certain circumstances, which vary with thermal properties of the soil/rock and operating conditions. Moreover, intensive studies should be carried out to find an efficient methodology for drilling holes in order to decrease installation prices.

Though much work has been done to develop and broaden the GCHP systems, work is still needed to improve them and make them fully operational. The sizing of the GHEs is strongly dependent upon the thermal interaction between the groundwater flow and the boreholes; however, there is a lack of proposed simulation models to address this issue. Additionally, the results of abundant computer codes have not been validated by accurate experimental measurements so far; consequently, an extensive investigation should be carried out to verify them. The current technology of drilling boreholes must become increasingly obsolete and efficient alternatives should be presented. Future technology should enhance the life-cycle of GCHP systems. A method should be proposed for designing hybrid GCHPs, which can consider the effects of the supplemental heat rejecters and absorbers, building systems, ground heat exchangers, and the interaction between them.

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