REVIEW OF GEOTHERMAL HEATING AND COOLING OF BUILDINGS

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Abstract

The exponential growth that has been occurring in the geothermal heat pump (GHP) sector is expected to continue into the foreseeable future and is permitting economical harnessing of low temperature, renewable geothermal energy for hot water heating and heating and cooling of buildings. GHPs can be used anywhere in the world, sometimes at a cost of one third of the cost of heating with electricity. GHP systems are dependable, secure, and robust and their future development in conjunction with wind and solar energy options will help address the problem of climate change and compensate for the diminishing oil reserves.

1. Introduction

Four potential sources of geothermal energy for electricity and heating are hot water (hydrothermal), hot dry rock (with water added), hot water under pressure (geo-pressured), and magma (magmatic). Only the first two types of sources that have been developed so far [1]. Hydrothermal systems (with temperatures up to about 350ºC) are mostly hot water but at the higher temperature range hot vapour can occur and can produce electricity the most efficiently [2, 1]. Electricity production at a temperature as low as 74ºC is possible using binary plants that employ a secondary, usually organic fluid with a lower boiling point than water, and below 74ºC geothermal energy can provide heating. Cogeneration plants supplying electricity and then "cascaded heating" or heating at progressively lower levels for a series of uses, are especially efficient [3]. At a great enough depth, hot dry rock is found anywhere [2] and if water is available from another nearby source it can be circulated to capture the heat.

Geothermal heat both originates deep in the earth's interior and is transported by conduction and convection to the earth's surface, and is produced by the decay of radioactive isotopes, particularly of uranium, thorium and potassium. Isolated hot spots resulting from molten rock intrusions near the earth's surface are a relatively small fraction of the total heat flow [4] and regions of higher heat flow that occur at the tectonic plate boundaries are another fraction of the total heat flow [2]. The average temperature increase with depth from the earth's surface is about 25-30ºC/km [3, 5] and the estimated highest temperatures in the earth's crust and in the earth's core are 1,000ºC and 4,500ºC respectively [3].

One reason why the development of geothermal energy resources has been slow may be because most people associate geothermal energy with the limited and sparsely distributed high-grade or "true" geothermal resources that can be developed without employing geothermal heat pumps [4, 6]. Another reason for the slow development of geothermal resources is that it requires diverse knowledge and expertise across many disciplines related to the earth's structure (earth scientists), technological know-how (engineers), energy experience (physicists) and costs management (economists). In addition until the 1970's there was a shortage of centers for training the necessary specialists [1] and some poor quality work prior to this time and before proper regulations were brought into effect, almost caused the industry to collapse [7]. Based on the extensive global geothermal energy resources and expected technological improvements, it is thought that geothermal energy will be able to "contribute for centuries" [2].

Historically geothermal heat was used for bathing, laundering and cooking, Rome had space heating with air, residential buildings in Chaude Aigues, France during the 14th century were heated with geothermal water and in 1909 geothermal heating with radiators began in Reyakjavik, Iceland, where now the entire city is heated from geothermal sources [8, 1]. Geothermal waters being used to heat greenhouses in Iceland in the 1920's and for municipal district heating in Reyakjavik in 1930, air conditioning with steam was used in Rotorua, New Zealand in the late 1960's, [9], and more recently geothermal heating has been used at fish farms and health spas [8].

The introduction of geothermal heat pumps (GHPs) (ground source heat pumps or ground coupled-heat pumps) has precipitated exponential growth in the use of geothermal energy for heating and cooling that has been predicted to continue into the foreseeable future [3]. With GHPs the ground provides the heat source in heating mode and a heat sink in cooling mode [10]. GHPs are much more efficient than air source (air-to-air) heat pumps because ground temperatures at only a few meters depth are more moderate and constant relative to fluctuating outdoor temperatures, and so require less energy for heating and cooling [2]. GHPs are reversible "refrigeration units" [3] and their use reduces energy demand by 23-44% compared to air source heat pumps [2] and greater than 75% compared to electrical heating [4]. Heating costs were reduced by 80% for geothermal heating of greenhouse in Utah [2].

Space heating represents 52% of the direct utilization of geothermal energy [3], GHP usage represents 32% of all direct utilization [11] and the most noticeable recent growth has occurred in China where areas of space they have been used to heat in 2004, 2006 and 2007 were 8 million m^2, 20 million m^2 and 30 million m^2 respectively [3]. In Canada GHPs are now in use in every province [11] and in the United States, as of 2005, more than 1 million units had been installed [4].

Geothermal energy is less dependent on weather than renewable energies such as solar, wind and hydro [8] and is ideal for providing a base load energy supply. In Iceland geothermal plants run about 8,000 hours a year giving them a capacity factor of 91%. An electricity supply combining geothermal energy and hydroelectric power, usually has hydro supplying the variable load [12]. Capacity factors for renewable energy production in 2007, as given by the World Energy Council, were solar (14%), wind (21%), hydro (42%), biomass (~52%) and geothermal (73%), illustrating the dependable nature of geothermal energy plants [3].

In terms of electricity generation, geothermal energy can be more economical than wind, solar, biomass, photovoltaic, and tidal options and can be comparable to hydro [1]. The 2004 UN World Energy Assessment Report update estimated the costs of using geothermal energy, biomass and solar energy for direct heating to be 0.5-5 UScents/kWh, 1-6 UScents/kWh and 2-

25 UScents/kWh respectively [3]. Local conditions would determine more precisely the relative benefit of a particular technology. For example equatorial regions are at an advantage when it comes to solar energy and windy Newfoundland could have an advantage with respect to wind energy. Since geothermal energy production uses very similar equipment and technology to that used by the oil and gas industry [4] it could be advantageous for oil rich regions of the world to develop their geothermal energy resources.

Geothermal energy systems can occupy a small land area and are quiet as they can include underground operations. There is no scarring and polluting of large land masses (as seen with coal and uranium mining). Since GHPs can make use of geothermal energy anywhere, transport costs and risks are eliminated and there is no buildup of unmanageable wastes (as occurs with nuclear energy) [4].

Particulate matter and nitrogen and sulfur oxide emissions are minimal, though emissions of hydrogen sulfide (H_2S), ammonia (NH_3) or other chemicals and groundwater contamination, subsidence and induced seismicity could be problematic [4, 1]. However, gas concentrations are low for low temperature geothermal sources [3] and gas emissions are virtually eliminated with closed loop systems employing GHPs. In closed loop systems there is less risk of seismicity because water is not being continuously withdrawn and there could also be reduced risk of groundwater contamination. In open loop and other systems it has been suggested that seismic activity might even be reduced because smaller stresses in the earth could be dissipated over time, preventing the build-up of major stresses [1, 2].

This paper focuses on the heating and cooling of buildings using geothermal heat pumps because of the wide applicability of these types of systems and their great growth potential. More details related to the closed loop systems are provided because they can be more widely used and could be more environmentally friendly and so could have lower costs over the long term. Of the closed loop systems the vertical down-hole boreholes are emphasized as they are the most common, they make more efficient use of the ground's heat than do the horizontal systems and they have the most compact space requirements and so their use would be less restricted.

2. Drilling

In general, drilling for geothermal energy can mean drilling through harder rock, higher temperatures (the maximum having been 500ºC) and more corrosive fluids than when drilling for oil and gas so could be technologically more challenging. Drilling is the expensive part of geothermal energy installations with costs increasing with well depth and increasing 25% when directional drilling is employed [1]. The current technology will permit geothermal well drilling into the earth's crust to depths of a little more than 10 km although normally wells do not need to be drilled to depths of more than 3 km [4]. For low temperature geothermal systems it is usually only economical to drill to depths of less than 2 km [1] and for low temperature systems with GHPs the wells are usually only between 2 and 200 m deep [4].

The equipment and technology used to drill the vertical boreholes for low temperature geothermal systems with GHPs is more simple that used in the drilling of water wells. However, some geological formations could give problems, there may be drilling through bedrock, and very importantly the work requires an experienced driller and installer [6]. For growth within the industry, one deficit that still remains to be addressed is the shortage of trained drillers and installers [15].

Before the borehole drilling is undertaken, a geological investigation of the site is conducted and this may include a preliminary test drilling [7]. Drilling is still an important factor with regards to cost though less so than for high grade geothermal energy developments [1, 6].

3. Low temperature geothermal energy system configurations

Open loop and closed loop systems are used with GHPs. In an open loop system water is pumped from an open groundwater extraction well, passed through a building (to supply heating or cooling) and discharged into an injection well or surface body of water. This water must be clean and there must be enough groundwater recharge occurring so that the geothermal well supply will not be diminished [5, 3]. These types of systems can be the most economical if groundwater is available.

In closed loop systems the water is recycled and is usually pumped from a borehole heat exchanger (BHE) or vertical loop [13] to supply heat to a building, and then piped back into the ground to where it was initially pumped from [3, 10]. Another heat carrier or antifreeze water mixture may be used in place of water and the closed loop system is more widely used than the open loop system since groundwater is not required [5, 14]

Vertical BHE pipe systems (as illustrated in Figure 1) are usually 50-250 m deep [3] and take advantage of increasing ground temperature with depth but when horizontal ground heat exchanger pipe systems are used they are still more efficient for air conditioning than air source heat pumps [10]. Horizontal systems are usually installed in the zone of fluctuating ground temperatures, typically within the top 10 meters of the earth's crust [15] and employ 35-60 m of pipe for every kW of useful heat [5]. GHPs have a simple design, are not exposed to outdoor conditions, require less maintenance than air source heat pumps and have a 25% longer life [6]. When pile foundations are needed to support a high-rise building, "geo-structures" or "energy piles" or pile foundations combined with vertical heat exchange pipe have also been used [10].

GHPs are also used with deep (up to 500 m) standing column wells (15 cm in diameter). A pump in the bottom of the well pumps the water up through a pipe that is surrounded by gravel and through which the percolating water has been warmed [5]. The well water is extracted for use at a rate that allows for natural geothermal recharge or "thermal regeneration" of the well [6]. Abandoned mines and tunnels containing water have also been used with GHPs [5].

For combined heating and cooling, either cool water is fed directly to the building or a heat pump is used to remove excess heat [14]. In northern climates passive cooling or circulating cool water from groundwater wells or deep lakes to cool buildings in the summer has been practiced and is much more energy efficient and economical than active cooling so should be the first choice if active cooling is not essential [6, 7]. Further south, and especially for commercial buildings that require more cooling than heating, heat rejection to the ground is greater than the heat extraction and a cooling tower may be used [6]. Another option would be to locate apartments above commercial spaces so they could use the excess heat. Mixed zoning in cities has numerous advantageous as it allows people to work near to where they live, save on transportation costs and greenhouse gas emissions, and become more physically fit by walking. Mixed zoning reduces urban sprawl, preserves green spaces for agriculture, forestry, wildlife and biodiversity and has facilitated redevelopment of previous brownfield sites.

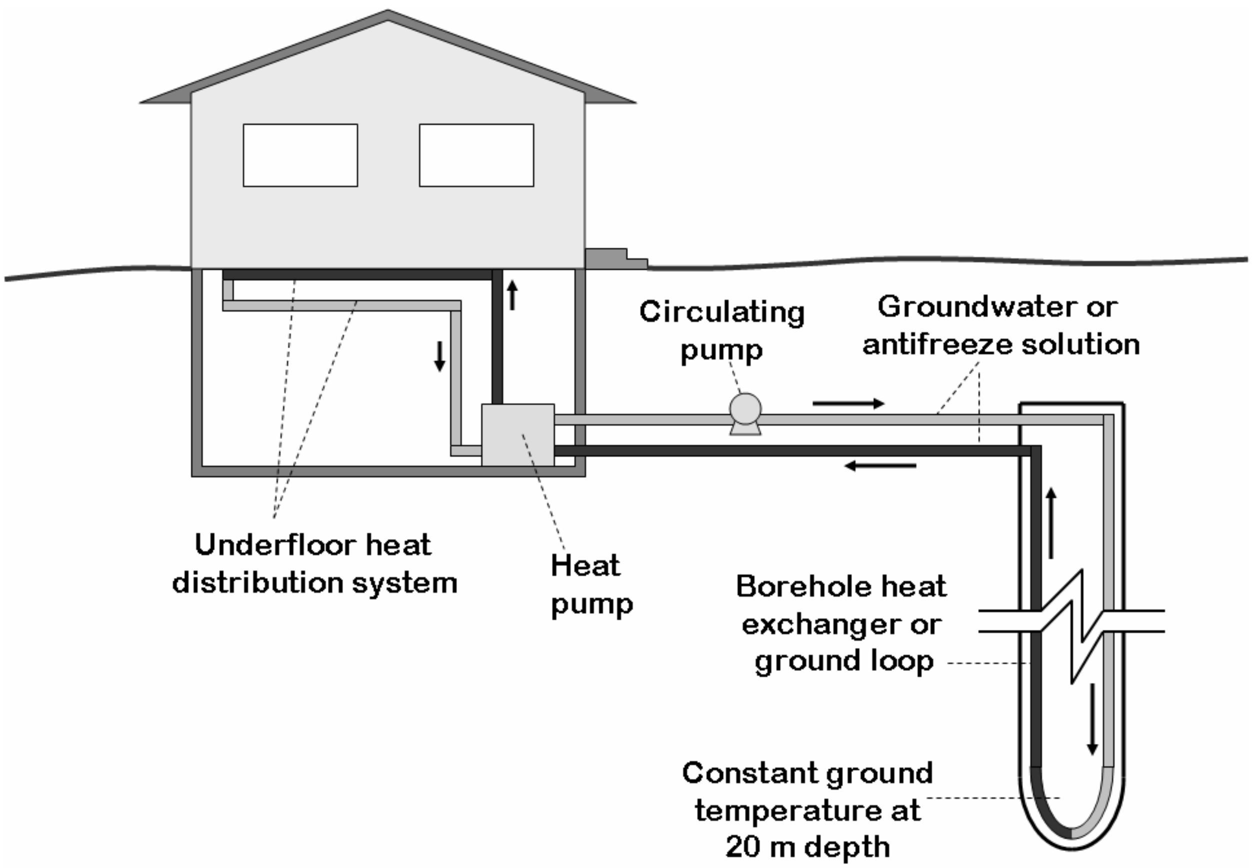


Figure 1. Closed loop vertical borehole heat exchanger system (adapted from [10]).

4. Geothermal heat pumps (GHPs)

A GHP system may consist of the ground heat exchanger (open or closed ground loop or other) with groundwater or an antifreeze solution, a heat exchanger between the refrigerant and the ground heat exchanger fluid (referred to as the evaporator in the heating mode and the condenser in the cooling mode), a compressor, a refrigerant air heat exchanger (the condenser in the heating mode and the evaporator in the cooling mode), an expansion valve, a reversing valve and circulating pumps [16, 11]. The reversing valve allows the flow of the refrigerant to be redirected when switching between heating and cooling modes. Heat is transferred from the ground loop to the refrigerant in the heat pump, the refrigerant gas in the heat pump is compressed to intensify its heat, and from the condenser this heat may be transferred to ductwork for under floor heating or to warm water radiators and may provide hot water heating [14]. In North America air heating and cooling through a ductwork system is common whereas in Europe water heating with radiators and hydronic under floor systems is common. Use of CO_2 as a refrigerant has been researched but is still in the developmental stage because of the high pressures involved [7].

The borehole heat exchanger fluid may be groundwater, or if there is risk of freezing then a solution of 80 – 90% water and "methyl alcohol, ethyl alcohol, sodium chloride, calcium chloride, ethylene glycol or propylene glycol" so that the solution will have a lowering freezing point [16].

Non-toxic, non-flammable and non-ozone depleting refrigerants are available and biodegradable esther oil can be used to lubricate the compressor. Heat pumps, like refrigerators, are usually supplied with the refrigerant already installed and as long as the installers are trained to take care to prevent any release of the refrigerant when the heat pump is being disposed of, risk to the environment is minimal [7].

In the water to air units used in North America the refrigerant may also be routed through a de-superheater to provide some of the domestic hot water heating before it is circulated to the condenser to provide space heating (as shown in Figure 2). A small pump is required to circulate the hot water between the hot water tank and the de-superheater. In the cooling mode rejected heat is used to heat the hot water and in both heating and cooling modes hot water heating is economical though is only provided during heat pump operation. In the larger scale heating projects a dedicated water to water heat pump unit may be installed to supply all of the hot water heating requirements and in Europe where water to water units or air to water units are used they can be run in the hot water heating mode at anytime [6, 7, 17].

The maximum temperature that can be achieved in the secondary heat carrier of a single stage heat pump is about 50 to 55ºC and to heat buildings with existing radiators and small pipe diameters about 70 to 80ºC is normally required [18, 1, Elaine Sullivan, Geothermal Solutions Inc., personal communication, March 2009]. Since lower temperatures are obtained with GHPs, larger surface areas are required for heat transfer, and radiant heating in floors and or walls are options for new constructions. Not only does this type of heat distribution provide the most comfort but it is also least affected by temporary power interruptions [7].

To convert older homes to geothermal heating where it is difficult to install the necessary ductwork, a two stage heat pump with a mutual heat exchanger may be employed as illustrated in Figure 3 [18]. Alternatively auxiliary boilers relying on electricity from a renewable energy source can be used to supplement the heating capacity [1, 7]. GHP systems will work in older houses if they are relatively air tight and well insulated. They are best suited to moderate climates (such as those in British Columbia and the Canadian Atlantic provinces) and under more extreme climatic conditions they can be supplemented with a secondary heat source [7]

The heat pump efficiency is measured by the coefficient of performance (COP) or the heat output divided by the energy input. Typical COPs for heat pumps range from 3-4.5 for heating and from 2-3.5 for cooling. Heating water using a GHP with a COP of 3 uses ⅓ of the electrical energy and heating water with a GHP in the cooling mode uses waste heat so is also efficient [6].

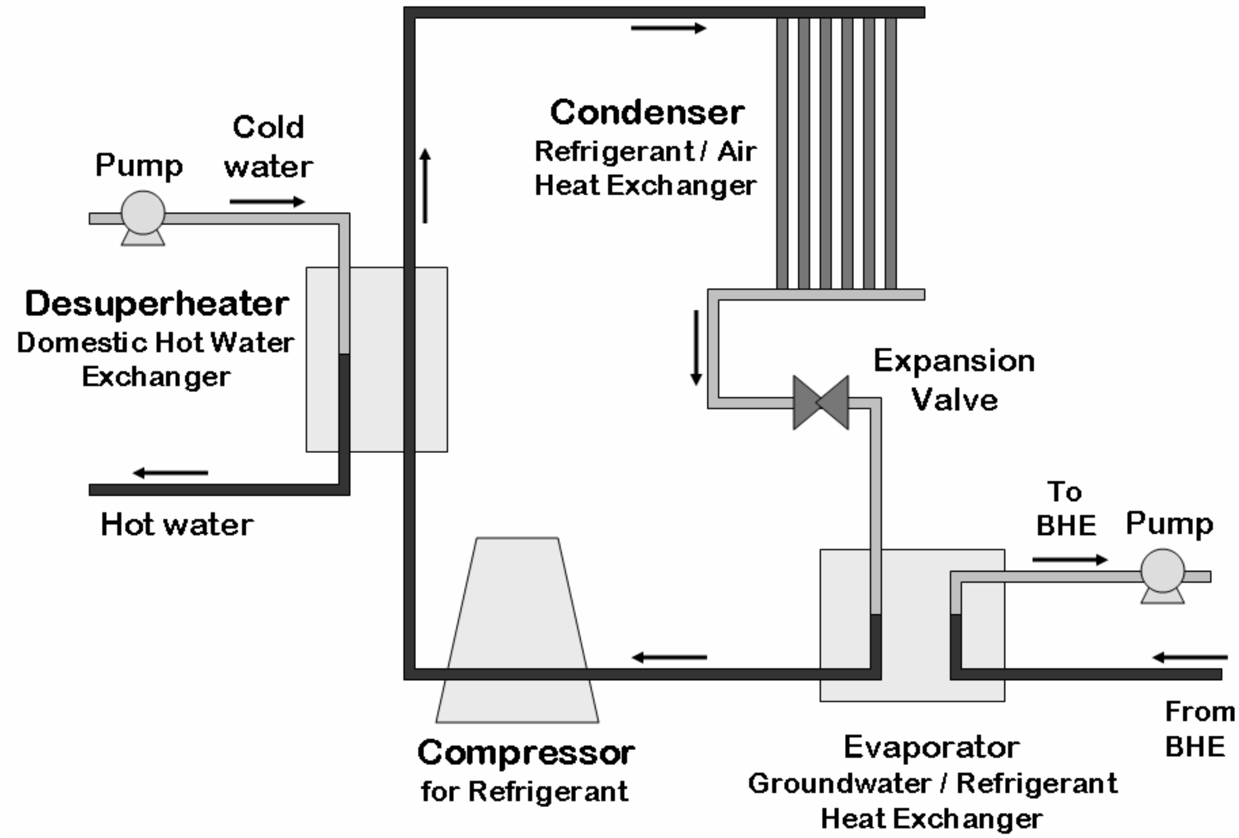


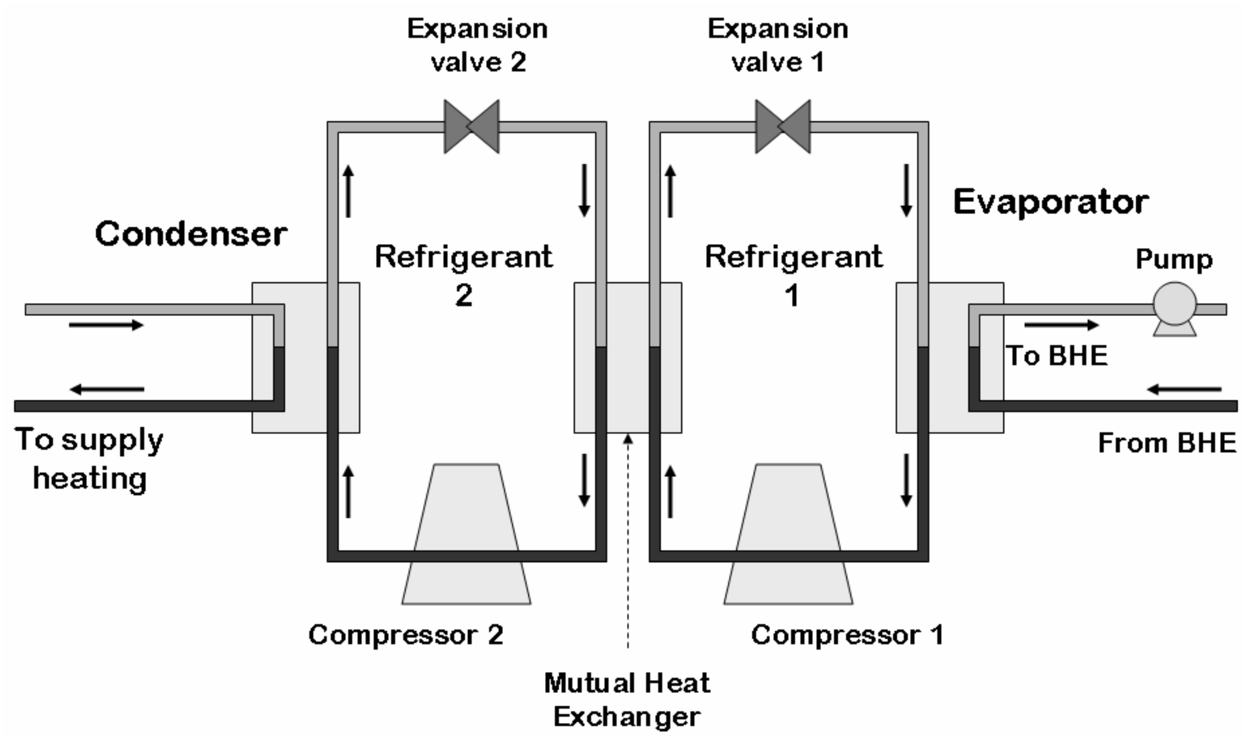
Figure 2. Schematic of geothermal heat pump in heating mode (Adapted from [17])

5. Borehole heat exchangers (BHEs)

With GHPs the vertical BHE system is the most common. One or more BHEs are used and each borehole contains single, double or triple "U-tubes" or some other pipe arrangement [6, 5]. Double U-tubes in parallel are more efficient than double U-tubes in series or single U-tube boreholes and it is economical to place a number of pipes in a single borehole as it saves on excavation and space [5]. Compared to the horizontal trench systems, BHEs have a smaller footprint, they make more efficient use of the stable, higher ground temperature, and they can exchange heat with the ground and groundwater, although they are more costly to install [6].

At a depth of greater than 5 to 20 m (depending on the ground characteristics) the temperature is constant year round and more moderate than air temperatures because of the ground's thermal insulating capacity [5]. To give an idea as to how the ground temperatures may vary with latitude at a depth of 15 m ground temperatures in Italy, Germany and Scandinavia are in the ranges of 13 to 17ºC, 9 to 11ºC, and 2 to 9ºC respectively [7].
The pipes used underground are usually high density polyethylene or polypropylene with heat fused joints and the offer durability, chemical resistance, thermal conductance and may be

warranted for 50 years. Pipe diameters of 10–15 cm and depths of 20–300 m [5] or ≥ 100 m in central Europe [10] and borehole diameters of 75–150 cm are typical [5]



. Figure 3. Schematic of a two stage heat pump (Adapted from [18]).

After the pipes are installed, the borehole is filled with thermally conductive grout and backfill materials. Materials that are good conductors such as those containing quartz or sandstone ensure the most efficient heat transfer whereas materials with clay, shale, organic matter or coal are poor conductors. Since some materials, in order of decreasing thermal conductivity, are natural ground, natural backfill, thermally enhanced grout and standard bentonite grout, the borehole diameter and use of thermally enhanced grout are minimized and the remaining space is filled with sand or cuttings. Some grout is stipulated to protect aquifers from contamination [6].

BHEs are more efficient than horizontal loop heat exchangers and they require, on average, 20 m of pipe for one kW of heating or cooling capacity [5]. The soil composition, temperature and moisture content all influence the length of pipe required and for more specific ground conditions more precise pipe length estimates are provided in Table 1. To ensure efficient design, a mobile unit equipped with design software should be employed to test the thermal response of an installed BHE [10].

The balances of ground heat extraction and rejection and the thermal properties of the ground need to be known to optimize the system's lifetime performance. The maximum heating and cooling requirements are used to size equipment. Design for multiple buildings makes use of the peak system load and software programs although "rules-of thumb and local experience" have been used for single buildings [6].

Table 1. Pipe lengths required to provide 1 kW of specific heat collection capacity for various ground conditions (Adapted from [7]).

Dry, sediment	Shale, slate	Solid stone with high thermal conductivity	Underground with high groundwater flow
33.3 m	18.2 m	12.5 m	10.0 m

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A concrete or concrete and masonry collection vault with an access port of at least 0.60 m in diameter, a gravel floor for drainage, minimum internal dimensions of 1.50 m and located at least 1.2 m away from the building to provide frost protection, is a good idea in order to contain the BHE supply and return collector pipes. The collector pipes are sloped slightly so that they can be easily bled and they need be sufficiently distanced from water pipe and electrical cables [7].

6. Electrical and other energies

In industrialized countries the break down of energy consumption is approximately 39% for mechanical energy, 32% for space heating, 27% for process heating and 2% for lighting and the break down of household energy consumption is approximately 76% for space heating, 11% for hot water heating, 8% for electrical appliances and equipment, 3% for cooking and 2% for lighting [7]. Geothermal heating could significantly decrease dependency on fossil fuels while ensuring a reduced CO_2 production, though heat pump compressors and circulating pumps require electricity and so will result in some increase in dependency on electricity. Overall though, employing a heat pump may still improve energy efficiency by 1.4 to 2 times [7].

The world needs to move towards greater development of electrical power anyway since peak oil or the global oil demand surpassing supply could occur in the next few years [19]. Although GHPs have been widely and economically used in Canada because of relatively low electricity costs [6], in fact all the data that is available indicates that for heating purposes they can be more economical than oil or electricity in almost any country [15].

In Newfoundland, Canada the weather makes wind energy an excellent choice for supplementing the electricity supply. Wind energy has been largely unexploited compared to hydropower and there is a huge potential to be tapped into [Gerry Skinner, Labrador Coastal Equipment Ltd., personal communication]. Developing this potential in advance of an oil shortage would make for a smoother transition and would help keep energy prices down.

Renewable energy alternatives for Newfoundland customers, in order of increasing cost, are geothermal, wind and solar energy. Wind energy is becoming more economical. Solar energy can be visually appealing and might have its place in some Canadian communities for hot water heating though could be more economical in tropical climates. However, the costs of all of these technologies will decrease dramatically as they become more widely used.

There is also a need to diversify. The natural environment thrives on diversity and the world's energy supplies need to come from multiple sources. This is one of the basic principles of green engineering [20] and was apparent to those that experienced 1998 Montreal ice storm. During that time a line to the Miron Quarry Landfill that generated electricity from methane gas was one of the few sources of electricity that remained available and was able to supply a small nearby community and provide essential services [21]. Residents with wood stoves and fireplaces were also able to keep themselves warm.

7. Future prospects

Increasing commercial and institutional use of GHPs is the current trend and savings and environmental benefits increase with scale [6, 15]. Where groundwater heat use is an option, it is considered more economical than ground heat use [6] however, the full environmental costs are not usually evaluated in these types of estimates so it would be important to procede in an environmentally friendly manner with groundwater use applications. The importance of preventing pollution rather than trying to clean it up is another green engineering principle [20].

The quiet operation of GHP systems is an important advantage since with the current population growth and technological development noise levels to which people (and animals) are being exposed are steadily increasing. The detrimental health effects of noise pollution on humans and other creatures sharing this planet are far from fully appreciated. Another important advantage of GHP systems and especially the vertical loop systems is that they are not land intensive and they will not have to compete with other increasing demands for land space. Their decentralized nature might also offer some protection in terms of energy security.

Satisfaction among users of GHP technology is high and may be partly because it enables them to contribute to environmental sustainability. The investment improves property values and after covering the installation costs, users pay only a fraction of what they would otherwise have paid for heating and air conditioning [15, 1]. The Canadian Government provides a grant of $3,500 to residential customers who install an earth-energy system and $500 towards the installation of a solar domestic hot water system [22]. Canadian provincial governments provide similar grants and the amount is about $1,500 in Newfoundland but both the Federal and Provincial grants are not well publicized (Brad Dunn, Amerispec, personal communication, March 11, 2009). Environmental legislation could do much to promote growth in the use of GHP technology in commercial, institutional and residential sectors [15].

Some other current needs for growth in the use of GHPs include more involvement and awareness on the part of governments, standardization of design and in some cases cluster or co-development of systems as these can be more efficient [14].

8. Conclusion

In all countries for which data was available, it was found that heating with GHPs was more economical than heating with oil or electricity. Employing GHPs for space and hot water heating of buildings could significantly reduce dependence on non-renewable energy resources and CO_2 emissions. Federal and provincial grants are available in Canada to help home owners undertake energy efficient upgrades to their houses. GHP systems are dependable, quiet, relatively unaffected by weather conditions, utilized virtually anywhere in the world and can promote sustainability and self sufficiency.

The heat pumps and circulating pumps require an electricity supply and that could be supplied by another renewable energy such as wind energy. Hot water heating could also be supplemented with solar or another energy. Short term and long term solutions need to be considered and an arsenal of energy resources need to be rapidly developed and deployed not only to address climate change but to be ready and in place for the time when global oil reserves will not be able to supply global demand.

9. References

[1] Barbier, E., "Geothermal energy, technology, and current status: An overview", *Renewable & Sustainable Energy Reviews,* Vol. 6, 2002, pp.3-65.

[2] Mock, J.E., Tester, J.W., and Wright, P.M., "Geothermal energy from the earth: Its potential impact as an environmentally sustainable resource", *Annual Review of Energy and the Environment,* Vol.22, 1997, pp.305-356.

[3] Fridleifsson, I.B., Bertani, R., Huenges, E., Lund, J.W., Ragnarsson, A. and Rybach, K., "The possible role and contribution of geothermal energy to the mitigation of climate change", In: Hohmeyer, O. and Trittin, T. (Eds.) IPCC Scoping Meeting on Renewable Energy Sources, Proceedings, Luebeck, Germany, 20-25 January 2008, pp.59-80.

[4] Tester, J.W., Anderson, B.J., Batchelor, A.S., Blackwell, D.D., DiPippo, R., Drake, E.M., Garnish, J., Livesay, B., Moore, M.C., Nichols, K., Petty, S., Toksoz, M.N., Veatch, R.W., Baria, R., Augustine, C., Murphy, E., Negraru, P. and Richards, M., "Impact of enhanced geothermal systems on US energy supply in the twenty-first century", *Philosophical Transactions of the Royal Society A,* Vol. 365, 2007, pp.1057-1094.

[5] Florides, G. and Kalogirou, S., "Geothermal heat exchangers – A review of systems, models and applications", *Renewable Energy,* Vol 32, 2007, pp.2461-2478.

[6] Phetteplace, G., "Geothermal heat pumps", *Journal of Energy Engineering – ASCE,* Vol. 133, 2007, pp.32-38.

[7] Ochsner, K., "Geothermal Heat Pumps: A Guide for Planning and Installing", Earthscan, VA, USA, 2008, 146 p.

[8] Fridleifsson, I.B., "Geothermal energy for the benefit of the people", *Renewable & Sustainable Energy Reviews,* Vol. 5, 2001, pp.299-312.

[9] Hepbasli, A. and Ozgener, L., "Development of geothermal energy utilization in Turkey: A review", *Renewable and Sustainable Energy Reviews,* Vol. 8, 2004, pp.433-460.

[10] Sanner B., Karytsas, C., Mendrinos, D. and Rybach, L., “Current status of ground source heat pumps and underground thermal energy storage in Europe”, *Geothermics,* Vol. 32, 2003, pp.579-588.

[11] Lund, J.W., Freeston, D.H., and Boyd, T.L., “Direct application of geothermal energy: 2005 Worldwide review”, *Geothermics,* Vol. 34, 2005, pp.691-727.

[12] Stefánsson, V., “Investment cost for geothermal power plants’, *Geothermics,* Vol. 31, 2002, pp.263-272.

[13] Sanner, B., Mands, E. and Sauer, M.K., “Larger geothermal heat pump in plants in the central region of Germany, *Geothermics,* Vol. 32, 2003, pp.589-602.

[14] Omer, A.M., “Ground-source heat pumps systems and applications”, *Renewable & Sustainable Energy reviews,* Vol. 12, 2008, pp.344-371.

[15] Hanova, J., and Dowlatabadi, H., “Strategic GHG reduction through the use of ground source heat pump technology”, *Environmental Research Letters,* Vol. 2, 2007, pp.1-8.

[16] Healy, P.F., and Ugursal, V.I., “Performance and economic feasibility of ground source heat pumps in cold climate”, *International Journal of Energy Research,* Vol. 21, 1997, pp.857-870.

[17] Lund, J., Sanner, B., Rybach, L., Curtis, R., and Hellström, G., “Geothermal (ground-source) heat pumps: A world overview”, GHC Bulletin, September, 2004. http://geoheat.oit.edu/bulletin/bull25-3/art1.pdf

[18] Kulcar, B., Goricanec, D., and Krope, J., “Economy of exploiting heat from low-temperature geothermal sources using a heat pump”, *Energy and Buildings,* Vol. 40, 2008, pp.323-329.

[19] Marsdon, W., “The age of oil is ending”, *Montreal Gazette,* January 11, 2009, http://www.montrealgazette.com/Business/ending/1162492/story.html, Accessed March 8, 2009.

[20] McDonough, W., Braungart, M., Anastas, P.T., and Ziommerman, J.B., “Applying the principles of green engineering to cradle-to-cradle design”, *Environmental Science & Technology,* Vol. 37, Iss. 2, 2003, pp.434A-441A.

[21] Previlee, P., “Swinergy”, http://www.montrealmirror.com/ARCHIVES/1998/121098/cover.html Accessed March16, 2009

[22] National Resources Canada, “Retrofit your home and qualify for a grant”, Effective January 1, 2009 http://oee.nrcan.gc.ca/residential/personal/retrofit-homes/retrofit-qualify-grant.cfm?attr=4 Accessed March 16, 2009.