GEOTHERMAL HEAT PUMPS

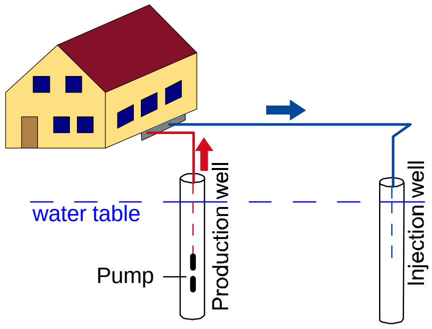
The ground system links the heat pump to the underground and allows for extraction of heat from the ground or injection of heat into the ground. These systems can be classified generally as open or closed systems, with a third category for those not truly belonging to one or the other.

- **Open systems:** Groundwater is used as a heat carrier, and is brought directly to the heat pump. Between rock/soil, ground water, and the heat pump evaporator is no barrier, hence this type is called „open".
- **Closed systems:** Heat exchangers are located in the underground (either in a horizontal, vertical or oblique fashion), and a heat carrier medium is circulated within the heat exchangers, transporting heat from the ground to the heat pump (or vice versa). The heat carrier is separated from the rock/soil and groundwater by the wall of the heat exchanger, making it a „closed" system.
- **Other systems:** Not always the system can be attributed exactly to one of the above categories, e.g. if there is a certain distinction between groundwater and the heat carrier fluid, but no true barrier. Standing column wells, mine water or tunnel water are examples for this category.

To choose the right system for a specific installation, several factors have to be considered: Geology and hydrogeology of the underground (sufficient permeability is a must for open systems), area and utilisation on the surface (horizontal closed systems require a certain area), existence of potential heat sources like mines, and the heating and cooling characteristics of the building(s). In the design phase, more accurate data for the key parameters for the chosen technology are necessary, to size the ground system in such a way that optimum performance is achieved with minimum cost. The individual types of ground systems are described in more detail on this and the following pages.

Open systems

This type is characterised by the fact that the main heat carrier, ground water, flows freely in the underground, and acts as both a heat source/sink and as a medium to exchange heat with the solid earth. Main technical part of open systems are groundwater wells, to extract or inject water from/to water bearing layers in the underground („aquifers"). In most cases, two wells are required („doublette"), one to extract the groundwater, and one to re-inject it into the same aquifer it was produced from.



Groundwater heat pump (doublette)

With open systems, a powerful heat source can be exploited at comparably low cost. On the other hand, groundwater wells require some maintenance, and open systems in general are confined to sites with suitable aquifers. The main requirements are:

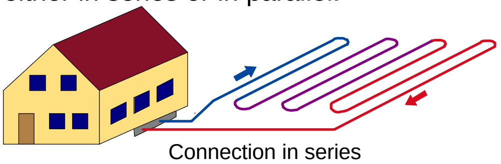
- Sufficient permeability, to allow production of the desired amount of groundwater with little drawdown.
- Good groundwater chemistry, e.g. low iron content, to avoid problems with scaling, clogging and corrosion.

Open systems tend to be used for larger installations. The most powerful ground source heat pump system world-wide uses groundwater wells to supply ca. 10 MW of heat and cold to a hotel and offices in Louisville, Kentucky, USA.

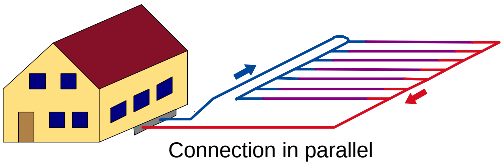
Closed systems

a) horizontal

The closed system easiest to install is the horizontal ground heat exchanger (synonym: ground heat collector, horizontal loop). Due to restrictions in the area available, in Western and Central Europe the individual pipes are laid in a relatively dense pattern, connected either in series or in parallel.



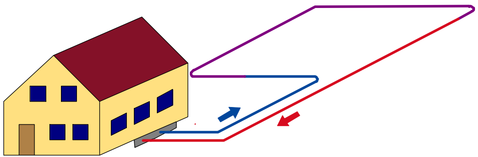
Connection in series



Connection in parallel

Horizontal ground heat exchanger (European style)

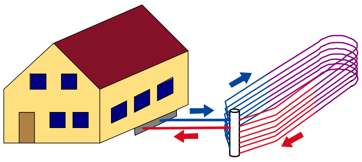
For the ground heat collectors with dense pipe pattern, usually the top earth layer is removed completely, the pipes are laid, and the soil is distributed back over the pipes. In Northern Europe (and in North America), where land area is cheaper, a wide pattern („loop“) with pipes laid in trenches is preferred. Trenching machines facilitate installation of pipes and backfilling.



Pipe in trench

Horizontal ground heat exchanger (North European and North American style)

To save surface area with ground heat collectors, some special ground heat exchangers have been developed. Exploiting a smaller area at the same volume, these collectors are best suited for heat pump systems for heating and cooling, where natural temperature recharge of the ground is not vital. Hence these collectors are widely used in Northern America (s. page 16), and one type only, the trench collector, achieved a certain distribution in distribution in Europe, mainly in Austria and Southern Germany. For the trench collector, a number of pipes with small diameter are attached to the steeply inclined walls of a trench some meters deep.



Trench collector

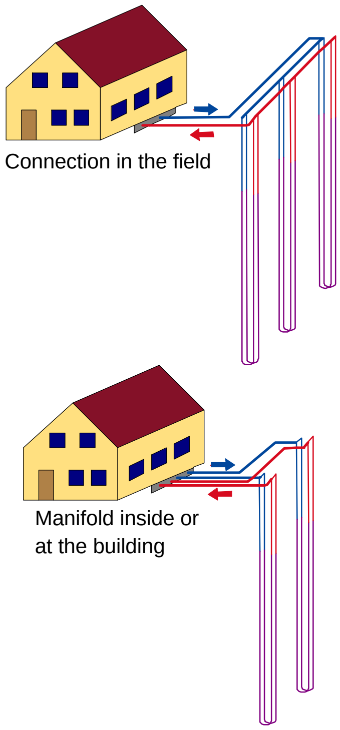
The main thermal recharge for all horizontal systems is provided for mainly by the solar radiation to the earth´s surface. It is important not to cover the surface above the ground heat collector, or to operate it as a heat store, if it has to be located e.g. under a building.

A variation of the horizontal ground source heat pump is direct expansion. In this case, the working medium of the heat pump (refrigerant) is circulating directly through the ground heat collector pipes (in other words, the heat pump evaporator is extended into the ground). The advantage of this technology is the omission of one heat exchange process, and thus a possibility for better system efficiency. In France and Austria, direct expansion also has been coupled to direct condensation in the floor heating system. Direct expansion requires good knowledge of the refrigeration cycle, and is restricted to smaller units.

b) vertical

As can be seen from measurements dating as far back as to the 17th century, the temperature below a certain depth („neutral zone“, at ca. 15-20 m depth) remains constant over the year. This fact, and the need to install sufficient heat exchange capacity under a confined surface area, favours vertical ground heat exchangers (borehole heat exchangers).

In a standard borehole heat exchanger, plastic pipes (polyethylene or polypropylene) are installed in boreholes, and the remaining room in the hole is filled (grouted) with a pumpable material. In Sweden, boreholes in hard, crystalline rock usually are kept open, and the groundwater serves for heat exchange between the pipes and the rock. If more than one borehole heat exchanger is required, the pipes should be connected in such a way that equal distribution of flow in the different channels is secured. Manifolds can be in or at the building, or the pipes can be connected in trenches in the field.

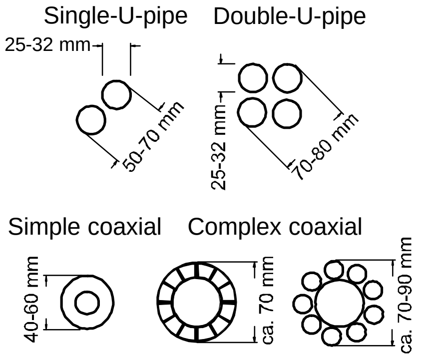


Borehole heat exchangers (double-U-pipe)

Several types of borehole heat exchangers have been used or tested; the two possible basic concepts are:

- U-pipes, consisting of a pair of straight pipes, connected by a 180°-turn at the bottom. One, two or even three of such U-pipes are installed in one hole. The advantage of the U-pipe is low cost of the pipe material, resulting in double-U-pipes being the most frequently used borehole heat exchangers in Europe.
- Coaxial (concentric) pipes, either in a very simple way with two straight pipes of different diameter, or in complex configurations.

Ground source heat pump plants of every size have been realised with borehole heat exchangers, ranging from small houses with just one borehole to large buildings, requiring whole fields of borehole heat exchangers. The highest number of boreholes for a single plant in Europe may be the head office of the German Air Traffic Control (Deutsche Flugsicherung), with 154 borehole heat exchangers each 70 m deep. The largest single plant in the world heats and cools the Richard Stockton College in New Jersey and comprises 400 boreholes each 130 m deep.



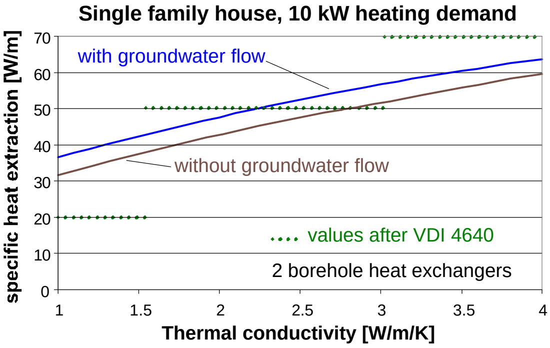
Cross-sections of different types of borehole heat exchangers

Another trend are residential areas with heat supply from ground source heat pumps; an example with ca. 130 houses with individual ground source heat pumps and one or two borehole heat exchangers for each house can be found in Werne, Germany, on an area of ca. 50’000 m^2.

Architect´s concept of the residential area „Am Fürstenhof“ in Werne (Behr+Partner, Schwerte)

The design of borehole heat exchangers for **small, individual applications** can be done with tables, empirical values and guidelines (existing in Germany and Switzerland). A popular parameter to calculate the required length of borehole heat exchangers is the specific heat extraction, expressed in Watt per meter borehole length. Typical values range between 40-70 W/m, dependent upon geology (thermal conductivity), annual hours of heat pump operation, number of neighbouring boreholes, etc. With the known capacity of the heat pump evaporator, the required length can easily be calculated:

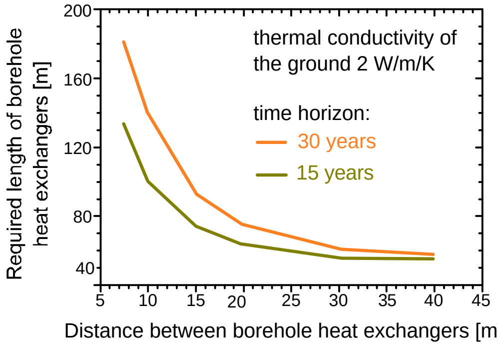
$$Length\,[m] = \frac{HP\ evaporator\ \ capacity\quad [W]}{specific\ heat\ extraction\ \ rate\ \ [W/m]}$$



Example of specific heat extraction values for a small ground source heat pump, no domestic hot water (heat pump run time 1800 h/a); VDI 4640 is a German guideline for ground source heat pumps

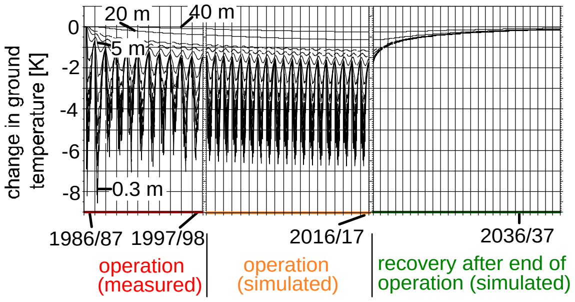
For **larger borehole heat exchanger plants**, for all cases with heating and cooling or with more than ca. 2000 h/a of heat pump operation, calculations have to be made to determine the required number and length of borehole heat exchangers. Programs for use on PC exist in USA and Europe, and for difficult cases, simulation with numerical models can be done. With a large number of small plants, a smaller distance between the boreholes makes deeper borehole heat exchangers necessary.

The heat source for thermal recovery of borehole heat exchangers is solar heat (in the upper part) and the geothermal heat flux (in the lower part), with some influence from flowing ground water or percolating water. However, the influence of groundwater in most cases is not very big, and the thermal conductivity of the ground is the main parameter.



Required borehole length in a field of 60 houses (7 kW heat load each) with 2 borehole heat exchangers for each house; no ground-water flow, no artificial thermal recharge

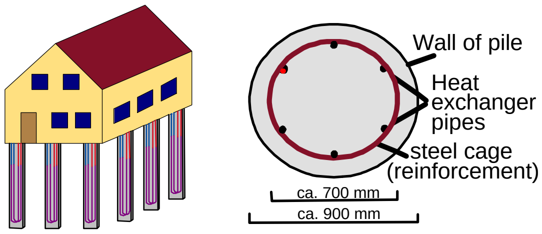
During operation of the ground source heat pump, the temperature in the surrounding ground is decreased to generate a thermal gradient from the natural ground temperature to the heat carrier fluid inside the heat exchanger. The thermal conductivity determines the radius of the influenced zone and the temperature drop. Measurements and simulations can visualise the temperature development during operation as well as the thermal recovery after operation:



Measured and simulated operation (30 years) for a ground source heat pump plant in Elgg ZH, Switzerland (1 borehole heat exchanger 105 m deep), and simulated thermal recovery after end of operation

The borehole filling and the heat exchanger walls account for a further drop in temperature, which can be summarised as borehole thermal resistance. Values for this parameter usually are on the order of 0.1 K/(W/m); for a heat extraction of 40 W/m, this means a temperature loss of 4 K inside the borehole. Thermally enhanced grouting (filling) materials have been developed to reduce this losses.

A special case of vertical closed systems are „energy piles“, i.e. foundation piles equipped with heat exchanger pipes. All kind of piles can be used (pre-fabricated or cast on site), and diameters may vary from 40 cm to over 1 m.

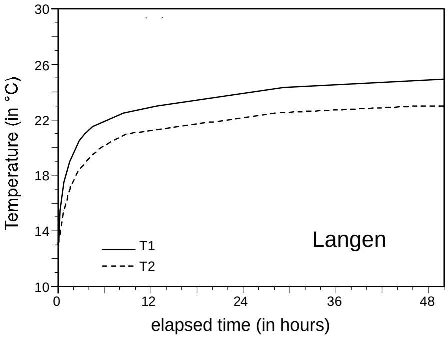


Energy piles and cross-section of a pile with 3 loops

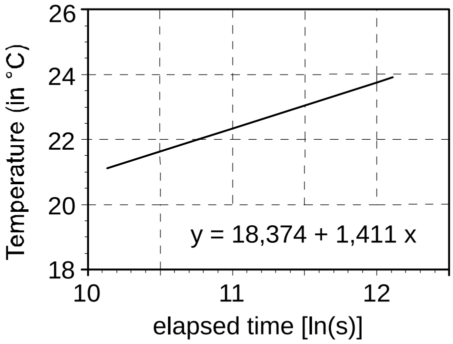
To design borehole heat exchangers (BHE) for Underground Thermal Energy Storage (UTES) or Ground Source Heat Pumps (GSHP), the knowledge of underground thermal properties is paramount. In small plants (residential houses), these parameters usually are estimated. However, for larger plants (commercial GSHP or UTES) the thermal conductivity should be measured on site.

A useful tool to do so is a thermal response test, carried out on a borehole heat exchanger in a pilot borehole (later to be part of the borehole field). For a thermal response test, basically a defined heat load is put into the hole and the resulting temperature changes of the circulating fluid are measured. Since mid 1999, this technology now also is in use in Germany for the design of larger plants with BHEs, allowing sizing of the boreholes based upon reliable underground data.

The first test in Germany was made for a large office building in Langen (south of Frankfurt). It was operated with the equipment of UBeG GbR in summer 1999. The figure below shows the measured data from Langen:



The regression curve of the mean fluid temperature from 6.9 to 50 hours, on a logarithmic scale, is shown in the next figure.

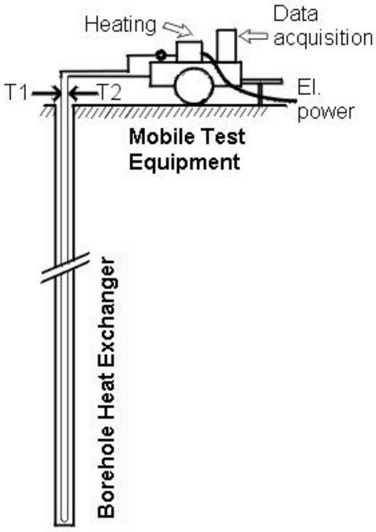


Regression curve of mean fluid temperature in Thermal Response Test in Langen

The inclination of the curve after 7 hours is 1.411, and using the approximation of Kelvin´s line source formula, the thernal conductivity can be calculated:

$$\lambda_{eff} = \frac{4900}{4\pi \; 99 \cdot 1.411} = 2.79$$

A second value that can be determined by a response test is the borehole thermal resistance. For Langen, it was calculated as r_b = 0,11 K/(W/m). This value gives the temperature drop between the natural ground and the fluid in the pipes. It is also possible to calculate r_b from the dimensions and materials used (e.g. with the program EED), the result is r_b = 0,115 K/(W/m)

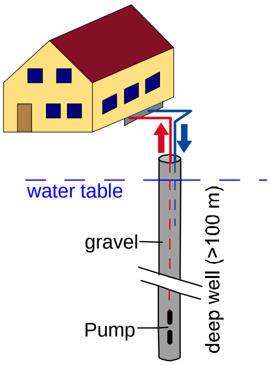


Schematic of Thermal Response Tests setup of UBeG

Other systems

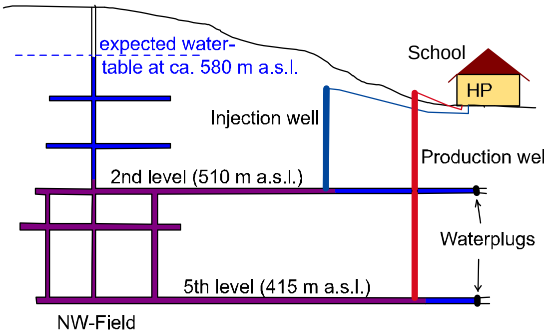
There is a number of ground systems neither to be categorized as open or closed.

In a standing column well, water is pumped from the bottom of the well and, after leaving the heat pump, percolated through gravel in the annulus of the well. Standing column wells need a certain depth to provide enough power without freezing of the water, and thus most plants have boreholes several hundred meter deep. Examples are known from Europe (Switzerland and Germany) and from USA. With the expensive borehole, the technology is not suited to small installations.



Standing column well

A very promising concept is the use of water from mines and tunnels. This water has a steady temperature the whole year over and is easily accessible. Examples with mine water use exist in Germany (Saxonia) and Canada. Tunnel water is used in the village of Oberwald at the Western entrance of the Furka rail tunnel in Switzerland and in Airolo, where water from the Gotthard road tunnel provide the heat source for a heat pump in the road maintenance facility. With the huge tunnel constructions ongoing in the Alps, new potential for this type of heat source is developing.

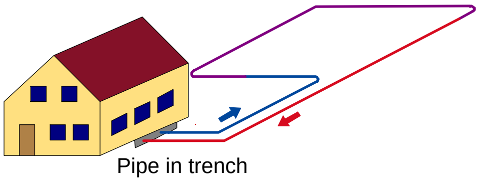


Heat pump using mine water (example of Ehrenfriedersdorf, Germany, with abandoned tin mine)

North American Experience

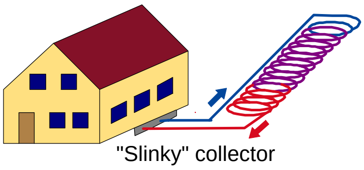
Geothermal heat pumps (also known as geoexchange systems) have achieved high popularity with Americans. System sizes range from small residential houses to large commercial or institutional buildings.

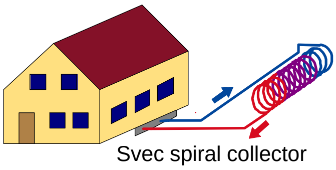
The ground systems are rather similar to those in Europe, and comprise also open and closed systems as well as some special cases. Horizontal closed systems („horizontal ground loops") differ somewhat from the European style, mainly due to less restricted ground area and due to the prevailing use for cooling and heating.



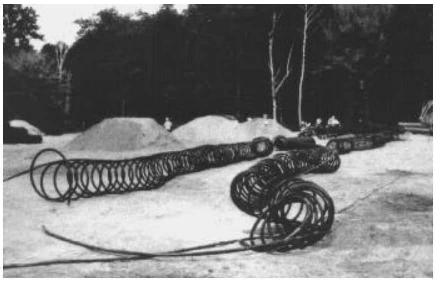
Horizontal ground heat exchanger (North American style)

The double use for heating in wintertime and cooling during summer allows for more compact ground collectors. Spiral forms are popular, mainly in the form of the so-called „slinky" collectors (placed horizontally in a wide trench like in the figure, or vertically in a narrow trench).





Spiral collectors



Svec collectors for a school in the Toronto area; the spirals are made ready for installation in the trenches.

For the vertical closed systems („vertical ground loops“), single-U-pipes are the type of borehole heat exchangers used most frequently. For large installations, whole fields of boreholes are drilled (usually, but incorrectly called „wellfields“). The largest single „wellfield“ comprises 400 borehole heat exchangers with 130 m depth each at the Richard Stockton College in New Jersey. The highest number of borehole heat exchangers in a limited area can be found in a military installation; 8000 borehole heat exchangers supply heat and cold to ca. 4000 houses on the ground of Fort Polk in Lousiana, USA.

Borehole heat exchangers („wellfield“) for a school in Northern New Jersey, USA

Natural thermal recharge of the ground is no issue, because of the seasonally alternating heating and cooling operation. Systems in the Southern states of the USA have in fact more problems to get rid of excess heat in the ground.

Other methods used comprise mine water (e.g. from abandoned coal mines in Springhill, Nova Scotia, Canada), standing column wells, etc.; also the first energy piles now are documented in North America. Using lake water or closed loops of plastic pipes on lake bottoms is also considered a „geoexchange system“ in the USA.

In North America, there are many reasons that ground source heat pump systems are chosen. For commercial systems, reduced energy costs are cited as the principal reason in many cases. However, energy savings payback alone does not often justify the purchase, and there are other factors:

- maintenance cost savings;
- desire by utility or manufacturer to showcase the technology or use it as a teaching tool;
- less space required for building heating, ventilation and air conditioning equipment;
- need to preserve environmental integrity and physical beauty of site (elimination of unsightly and noisy outdoor equipment);
- government or utility grants or incentives to offset capital or energy costs;
- need to meet carbon dioxide or energy use reduction targets set by the government for federal facilities.

In 1998, the Geothermal Heat Pump Consortium (GHPC) in Washington conducted a survey of ground source heat pump owner satisfaction. Results as summarized in the table below indicated a very high level of satisfaction. Installation and maintenance cost and dealer service issues received the lowest ratings, but none lower than 84%.

Ground-source heat pump user/owner satisfaction levels from GHPC (1998) survey:

Survey item	Residential	Commercial
Installation cost	86 %	89 %
Operating cost	91 %	92 %
Mainten./reliabil.	86 %	87 %
Cleanliness	96 %	97 %
Noise levels	95 %	93 %
Comfort	99 %	95 %
Safety	96 %	95 %
Dealer service	88 %	84 %
Envir. friendliness and performance	97 %	97 %
Size and appear.	96 %	93 %

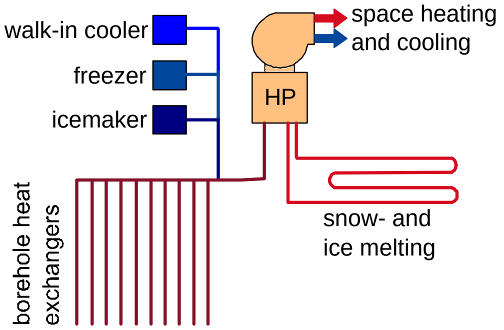
(percentage of survey respondents indicating 'very' or 'somewhat' satisfied)

The survey also attempted to measure general public awareness of GHSP or geothermal heating and cooling technologies. About 40% of 877 residential contacts indicated familiarity with the technology. Of 551 commercial respondents, about 50% were familiar. The GHPC concluded from this fact, that more work is needed to increase general public awareness of ground source heat pumps and their advantages. However, for the European situation, such percentages can be considered as very good and still have to be achieved in the future.

The cost situation in North America is more favourable than in Europe. Due to the similarity of air conditioners and heat pumps, resulting in a great number of units built, the cost for the equipment are lower than in Europe.

Two selected examples shall serve to illustrate North American practices. The first is a hotel located in Albany, NY (Holiday Inn Express with 126 rooms). It is heated and cooled by 134 individual heat pumps with a total capacity of 440 kW. The heat source and sink is provided by 5 standing column wells each 457 m deep. With $178,000 installed cost and estimated energy savings of more than $38,000/yr, the system yielded a positive cash flow from the first month for the owner. The simple payback period for the system is 3.8 years.

The second example is the use for ground source heat pumps for filling stations. The first plant was installed for the chain Philipps 66 in Prarie Village, Kansas. The heat pump used for space heating and cooling is coupled to ten borehole heat exchangers each 99 m deep. The convenience store appliances (14 kW walk-in cooler, freezer and icemaker) have their own separate water-cooled compressors, and waste heat from the appliances is discharged into the same ground loops used by the space conditioning system. This installation has reduced electricity consumption by 40 % compared to air-cooled equipment of the same size. For the wintertime car wash operations, the ground source heat pump is coupled to radiant floor heating in the car wash bays and below the concrete at the car wash entrances and exits.



Schematic of ground source system for filling station in USA

Further Philipps 66 stations use ground source heat pumps in Colorado, Oklahoma and Texas, and another example is Conoco's "Skunk Creek" Service Station in Sandstone, Minnesota.

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Main fields of services:

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