PDHonline Course E508 (7 PDH)

Ground Source Heat Pump Project Analysis

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1. Ground Source Heat Pump Project Analysis

This course covers the analysis of potential ground-source heat pump projects including a technology background and a detailed description of the calculation methods.

2. Ground-source Heat Pump Background

Maintaining a comfortable temperature inside a building can require a significant amount of energy. Separate heating and cooling systems are often used to maintain the desired air temperature, and the energy required to operate these systems generally comes from electricity, fossil fuels, or biomass. Considering that 46% of sun's energy is absorbed by the earth, another option is to use this abundant energy to heat and cool a building.

In contrast to many other sources of heating and cooling energy which need to be transported over long distances, earth energy is available on-site, and in massive quantities.

Because the ground transports heat slowly and has a high heat storage capacity, its temperature changes slowly—on the order of months or even years, depending on the depth of the measurement. As a consequence of this low thermal conductivity, the soil can transfer some heat from the cooling season to the heating season. Heat absorbed by the earth during the summer effectively gets used in the winter. This yearly, continuous cycle between the air and the soil temperature results in a thermal energy potential that can be harnessed to help heat or cool a building. Another thermal characteristic of the ground is that a few meters of surface soil insulate the earth and groundwater below, minimizing the amplitude of the variation in soil temperature in comparison with the temperature in the air above the ground. This thermal resistivity fluctuations further helps in shifting the heating or cooling load to the season where it is needed. The earth is warmer than the ambient air in the winter and cooler than the ambient air in the summer.

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This warm earth and groundwater below the surface provides a free renewable source of energy that can easily provide enough energy year-round to heat and cool an average suburban residential home, for example. A Ground-Source Heat Pump (GSHP) transforms this earth energy into useful energy to heat and cool buildings. It provides low temperature heat by extracting it from the ground or a body of water and provides cooling by reversing this process. Its principal application is space heating and cooling, though many also supply hot water, such as for domestic use. It can even be used to maintain the integrity of building foundations in permafrost conditions, by keeping them frozen through the summer.

A heat pump is used to concentrate or upgrade this free heat energy from the ground before distributing it in a building through conventional ducts. It operates much as a refrigerator or conventional air conditioning system in that it relies on an external source of energy - typically electricity - to concentrate the heat and shift the temperature. Typically, each kilowatt (kW) of electricity used to operate a GSHP system draws more than 3 kW of renewable energy from the ground. Heat pumps typically range from 3.5 to 35 kW in cooling capacity (about 1 to 10 refrigeration tons), and a single unit is generally sufficient for a house or a small commercial building. For larger commercial, institutional or industrial buildings, multiple heat pumps units will often be employed.

Since a GSHP system does not directly create any combustion products and because it draws additional free energy from the ground, it can actually produce more energy than it uses. Because of this, GSHP efficiencies routinely average 200 to 500% over a season. GSHP systems are more efficient than air-source heat pumps, which exchange heat with the outside air, due to the stable, moderate temperature of the ground. They are also more efficient than conventional heating and air-conditioning technologies, and typically have lower maintenance costs. They require less space, especially when a liquid building loop replaces voluminous air ducts, and are not prone to vandalism like conventional rooftop units.

Peak electricity consumption during cooling season is lower than with conventional air-conditioning, so utility demand charges may be also reduced. For the above reasons, significant energy savings can be achieved through the use of GSHPs in place of conventional air-conditioning systems and air-source heat pumps. Reductions in energy consumption of 30% to 70% in the heating mode and 20% to 50% in the cooling mode can be obtained. Energy savings are even higher when compared with combustion or electrical resistance heating systems. This potential for significant energy savings has led to the use of GSHPs in a variety of applications.

In the USA alone, over 50,000 GSHP units are sold each year, with a majority of these for residential applications. It is estimated that a half million units are installed, with 85% closed-loop earth connections (46% vertical, 38% horizontal) and 15% open loop systems (groundwater).

The following sections describe the main components of a GSHP system (heat pumps, earth connection, and distribution system) and discuss the GSHP markets for residential, commercial, and institutional building type applications.

3. Description of Ground-Source Heat Pump Systems

A ground-source heat pump (GSHP) system has three major components:
- Heat pump
- Earth connection
- Interior heating or cooling distribution system (Figure 1).

These three major components, together with the different earth connection configurations of a typical GSHP installation, are explained in the following sections.

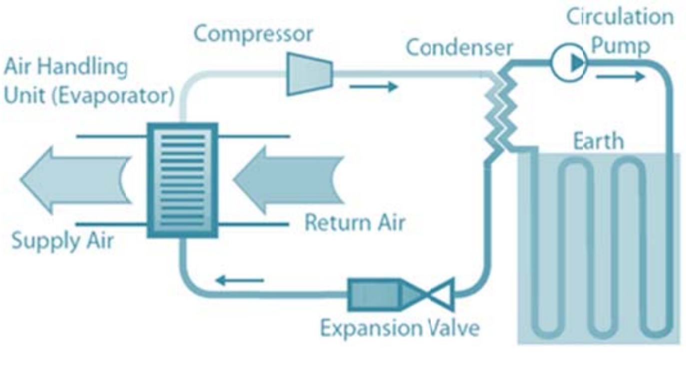


Figure 1. Major GSHP components

4. Heat pump

The heat pump transfers the heat between the heating/cooling distribution system and the earth connection. It is the basic building block of the GSHP system. The most common type of heat pump used with GSHP systems is a “water-to-air” unit ranging in size from 3.5 kW to 35 kW of cooling capacity. The water-to-air designation indicates that the fluid carrying heat to and from the earth connection is water or a water/antifreeze mix and that the heat distribution system inside the building relies on hot or cold air. The heat pump may be an extended range unit, allowing lower entering fluid temperatures in heating mode and higher entering fluid temperatures in cooling mode.

All the components of this type of heat pump are in one enclosure: the compressor, an earth connection-to-refrigerant heat exchanger, controls, and an air distribution system containing the air handler, duct fan, filter, refrigerant-to-air heat exchanger, and condensate removal system for air conditioning. A typical packaged heat pump unit is illustrated in Figure 2.

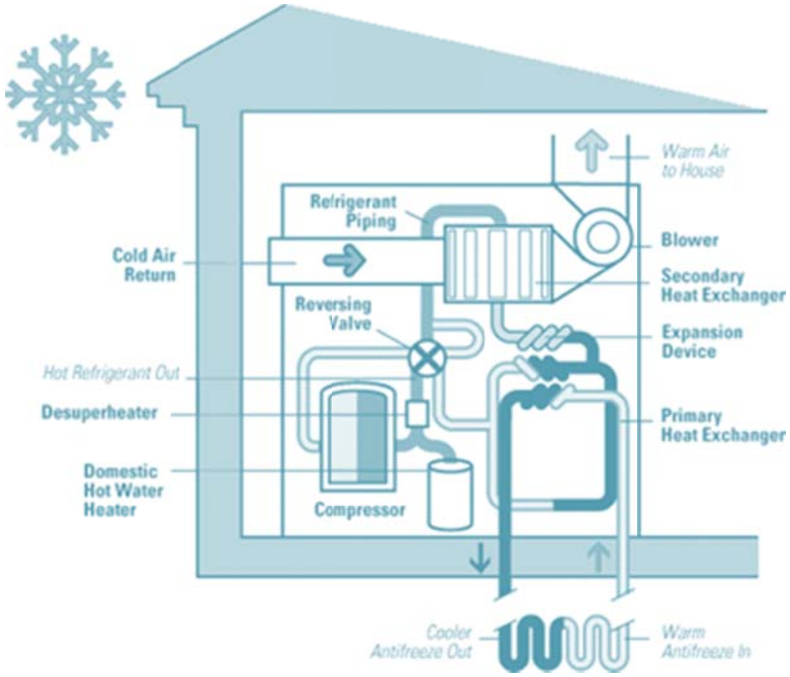


Figure 2. Typical heat pump unit

For residential applications and small commercial systems, a single heat pump unit will suffice. For larger commercial, institutional or industrial systems, multiple heat pump units are typically used in a distributed network connected to a common fluid loop.

The heat pump operates using the same cycle as a refrigerator. The heat pump uses compression and expansion of a refrigerant to drive heat flows between the inside of the building and the earth connection. As per the second law of thermodynamics, heat will flow only from hotter to colder matter, but a heat pump will draw heat from the ground at, say, 5ºC and use it to warm a building to 21ºC. At certain times of the year, the temperature of the ground will be such that heat would flow in the desired direction anyway. The heat pump may still need to operate, however, in order to ensure that the rate of heat flow is sufficient. This rate is related to the temperature difference between the heat pump and the earth connection: during cooling, the higher the temperature of the building, the better the rate of transfer with the earth connection would be.

In heating mode, the heat pump works as follows: heat from the earth connection arrives at an earth connection-to-refrigerant heat exchanger called the evaporator (see Figure 3).

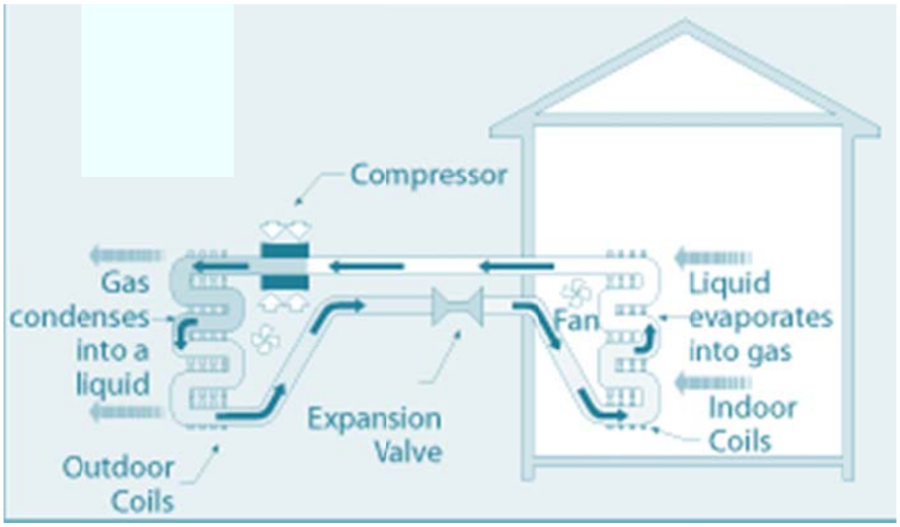


Figure 3. Heating mode of a typical packaged heat pump unit

On the other side of the heat exchanger is cold refrigerant in a mostly liquid state. The refrigerant is colder than the temperature of the heat transfer fluid from the earth connection, so heat flows into the refrigerant. This heat causes the liquid refrigerant to evaporate; its temperature does not increase much. This gaseous, low pressure and low temperature refrigerant then passes into an electrically-driven compressor. This raises the refrigerant's pressure and, as a consequence, its temperature.

The high temperature, high pressure, gaseous output of the compressor is fed into a second heat exchanger, called the condenser. In water-to-air heat pumps, a fan blows air to be heated through this “air coil”. In water-to-water heat pumps, water which will heat the building flows through the condenser. Since the refrigerant is hotter than the air or water, it transfers heat to it. As it loses heat, the refrigerant’s temperature drops somewhat and it condenses.

This high temperature liquid refrigerant then passes through an expansion valve. The valve reduces the pressure of the refrigerant, and as a consequence, its temperature drops significantly. Now, this low temperature liquid flows to the evaporator, and the cycle starts again. In this way, the heat from the water or other heat transfer fluid in the earth connection is transferred to the air or water in the building: hence the name “water-to-air heat pump” or “water-to-water heat pump”.

One significant difference between a ground-source heat pump and a refrigerator is that the ground-source heat pump is meant to run in both directions. When in cooling mode, the earth connection-to-refrigerant heat exchanger becomes the condenser, and the refrigerant-to-air heat exchanger becomes the evaporator. This is accomplished through a reversing valve inside the heat pump.

A desuperheater, provides domestic hot water when the compressor is operating. The desuperheater is a small auxiliary heat exchanger at the compressor outlet. It transfers excess heat from the compressed gas to water that circulates to a hot water tank. During the cooling season, when air-conditioning runs frequently, a desuperheater may provide all the hot water needed in a residential application. Some residential heat pumps are designed to provide hot water year round in quantities sufficient to meet a household’s needs.

5. Earth connection

The earth connection is where heat transfer between the GSHP system and the soil occurs. GSHPs comprise a wide variety of systems that use the ground, ground water, or surface water as a heat source and sink. One common type of earth connection entails tubing buried in horizontal trenches or vertical boreholes, or alternatively, submerged in a lake or pond. An antifreeze mixture, water, or another heat-transfer fluid is circulated from the heat pump, around the tubing, and back to the heat pump in a "closed loop." "Open loop" earth connections draw water from a well or a body of water, transfer heat to or from the water, and then return it to the ground or the body of water. The following nomenclature has been adopted to distinguish among the various types of earth connection systems:

- Ground-Coupled Heat Pumps (GCHPs) - use the ground as a heat source and sink, either with vertical or horizontal Ground Heat exchangers (GHXs);
- Groundwater Heat Pumps (GWHPs) - use underground (aquifer) water as a heat source and sink;
- Surface Water Heat Pumps (SWHPs) - use surface water bodies (lakes, ponds, etc.) as a heat source and sink
- Ground Frost Heat Pump (GFHPs) - maintain sound structural fill in natural permafrost around foundations by extracting heat from the fill.

Since all earth connections in a GSHP system are usually very difficult to access after installation, the materials and workmanship used in construction must be of the highest quality. High-density polyethylene piping and fusion-bonded pipe connections are used almost exclusively. Experienced GSHP installers should implement ground-heat exchangers and groundwater wells using specialised equipment.

6. Ground-Coupled Heat Pumps (GCHPs)

In a GCHP system, a series of buried pipes circulates a heat transfer fluid in a closed loop: the fluid never leaves the system, but rather travels back and forth in a loop between the earth connection and the heat pump. This circulating fluid is either water or an antifreeze solution, if freezing temperatures are expected. The ground heat exchanger can make use of a series of deep vertical holes (boreholes) or a horizontal arrangement of pipes buried a few of metres below the surface.

The vertical GHX is well suited to larger buildings where the bedrock is close to the surface, when minimal disruption of the landscaping is desired, or where little land is available for the GHX (Figure 4). Because the ground temperature is steady year round below the surface, vertical GHXs are more efficient than horizontal GHXs, which may experience seasonal temperature fluctuations.

Vertical loops are generally more expensive to install than horizontal ones, but require less piping due to the stable temperatures.

Figure 4. Vertical Ground Heat Exchanger

The boreholes, 45 to 150 m in depth, are drilled by rigs normally used for drilling wells. They contain either one or two loops of pipe with a U-bend at the bottom. After the pipe is inserted, the hole is backfilled and grouted. The grout prevents surface water from draining into the borehole and the groundwater, and also prevents the water from one borehole from leaking into an adjacent borehole. Following backfilling and grouting, the vertical pipes are connected to horizontal underground supply and return header pipes. The header pipes carry the GHX heat transfer fluid to and from the heat pump. Figure 5 illustrates a typical vertical GHX system.

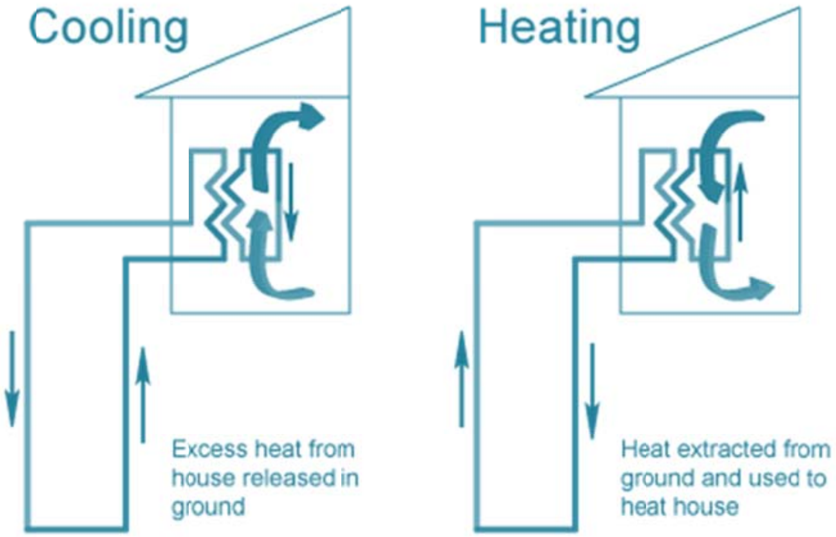


Figure 5. Vertical Ground Heat Exchanger (GHX)

The horizontal GHX configuration is often less expensive to install than the vertical arrangement, but requires a larger land area (Figure 6). For this reason, it is usually better suited to smaller applications such as residential and small commercial buildings. It can be especially attractive if excavating and trenching equipment is available and when the upper few metres of the ground are amenable to excavation.

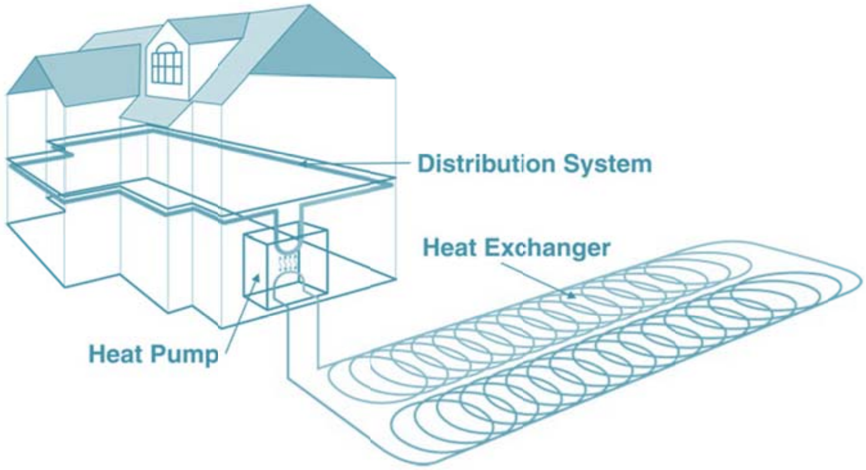
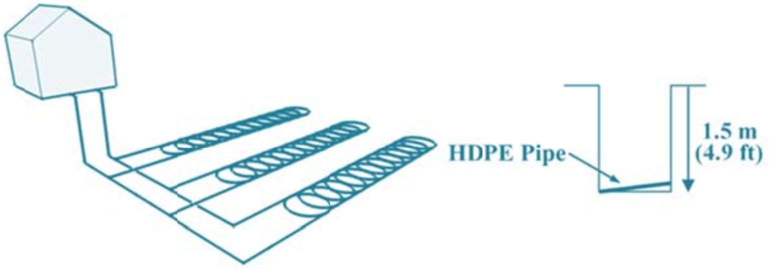
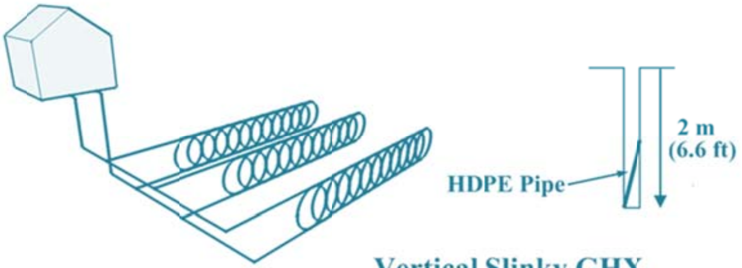


Figure 6. Horizontal Ground Heat Exchanger (GHX)

A horizontal GHX consists of a series of pipes laid out in trenches, usually one to two meters below the surface. Typically, about 35 to 55 meters of pipe are installed per kW of heating and cooling capacity. Many configurations of the horizontal GHX are possible, as illustrated in Figure 7. When land area is limited, a coiled pipe, also called “slinky” or spiral, may be used in order to fit more piping into a trench area. While this reduces the amount of land used it requires more pipes, which results in additional costs. The trench is backfilled once the pipe has been laid out.



Horizontal Slinky GHX



Vertical Slinky GHX

Figure 7. Various configuration of horizontal ground heat exchangers

7. Groundwater Heat Pumps (GWHPs)

Groundwater heat pump systems are, in contrast to GCHPs, open loop systems: they use a constant supply of groundwater as the heat transfer fluid (Figure 8). A GWHP earth connection simply consists of water wells where groundwater from an aquifer is pumped directly from the well to the heat pump’s earth connection-to-refrigerant (or, in this case, water-to-refrigerant) heat exchanger or to an intermediate heat exchanger. The intermediate heat exchanger transfers the heat from the open groundwater loop to a closed building loop, and thus isolates the heat pump from the well water, protecting its heat exchanger from the potentially fouling, abrasive or corrosive well water. After leaving the building, the water is pumped back into the same aquifer via a second well, called an injection well.

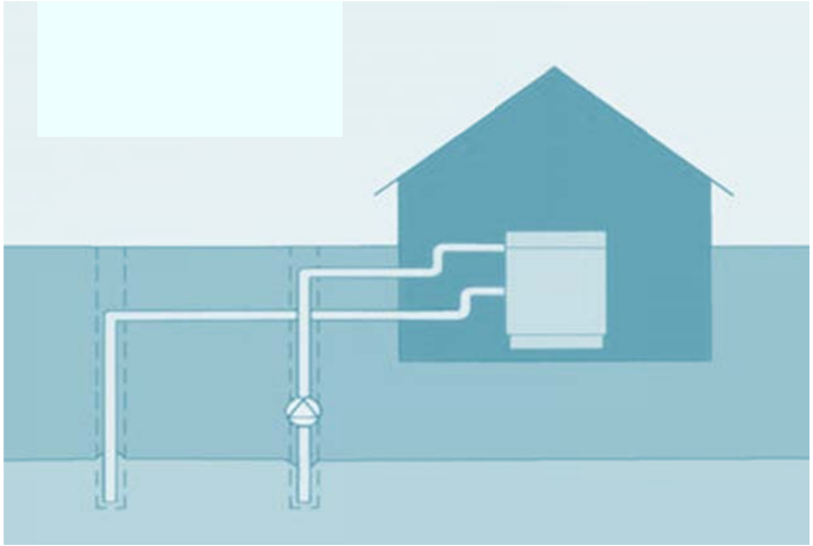


Figure 8. Ground water heat pump system

The GWHP was the first type of GSHP to appear on the market and GWHPs have been used successfully for decades. They are the simplest type of system to install. However, local environmental regulations and insufficient water availability may limit their use in some areas.

Standing column wells are a newer variation of the GWHP system. Standing wells are typically six inches in diameter and may be as deep as 450 meters. In this system, water from the bottom of the well is pumped to the building's heat exchanger and returned to the top of the same well. The well may also provide potable water. For this system to work adequately, ground water must be in abundant supply. This type of system is not used where the water table is especially deep, since the required pumping power renders the system prohibitively expensive.

8. Surface Water Heat Pumps (SWHPs)

The surface water heat pump is a viable and relatively low-cost GSHP option. A series of coiled pipes submerged below the surface of a lake or pond serves as the heat exchanger. This requires minimal piping and excavation, but the pond or lake must be deep and large enough. The heat transfer fluid is pumped through the pipe in a closed loop, as in a GCHP system, avoiding adverse impacts on the aquatic ecosystem. Many successful systems are currently in operation.

9. Ground Frost Heat Pumps (GFHPs)

Another specialized application of GSHPs is the cooling of building foundations in areas with permafrost. Building foundations transmit heat, melting any permafrost and thus undermining the structural soundness of the foundation. By extracting heat from the ground around the foundation, a GFHP can ensure that the permafrost remains frozen. Moreover, the extracted heat can provide up to 20 to 50% of the building's space heating requirements and the costs of traditional measures for maintaining the structural soundness of foundations in permafrost can be avoided. Mechanically chilled foundations can be much less expensive, both initially and on a life-cycle cost basis, than conventional permafrost foundations.

The GFHP earth connection is buried in the fill below the foundation, and the heat pump keeps the fill frozen while supplying supplemental heat to the building. The heat transfer fluid, circulated in a closed loop, is usually a mix of water and glycol that will not freeze at the lowest temperatures experienced by the granular fill.

The use of GSHPs in permafrost introduces several additional considerations. Heat gain to the ground from building foundations must be considered when designing the earth connection in GFHPs or in GHXs installed beneath foundations. Heat must be extracted at the same rate as it is gained from the foundation in order to maintain a constant ground temperature. Also, given the low mean earth temperature, conventional GCHPs may not be justified in these situations. Finally, long-term operation depends on the ground being reheated by solar energy incident during summertime. Local ecological disturbances may occur if the ground is kept frozen beyond its natural cycle. Because the consequences of GFHP failure are severe (sinking foundations), the heat exchanger should use premium quality hermetic piping and be installed by experts. Insulation between the frozen gravel pad and the foundation slab should be adequate to maintain the pad in a frozen state should the heat pump become temporarily inoperative.

10.Heating and cooling distribution system

The heating/cooling distribution system delivers heating or cooling from the heat pump to the building. It usually takes the form of an air duct distribution system, although water loop systems (also known as hydronic systems), which heat or cool floors and ceilings are also used. Heating and cooling distribution in a GSHP system is generally the same as in conventional systems. However, larger installations may use multiple heat pumps, perhaps one for each building zone, where each heat pump is attached to a common building loop. The various types of air delivery systems that can be used are well documented and consist mainly of air ducts, diffusers, fresh air supply systems and control components.

11. Ground-Source Heat Pump Application Markets

Even though strong markets for GSHP systems exist in many industrialised countries where heating and cooling energy requirements are high, the main constraint hindering increased market penetration of GSHPs is their high initial cost, which is generally:

- Almost double that of conventional central systems in residential applications
- 20% to 40% more than constant volume, single zone rooftop units
- Up to 20% more than multi-zone or central two-pipe chilled water arrangements.

GSHPs generally have lower life-cycle costs than conventional systems due to their efficiency and lower maintenance requirements.

Markets for GSHPs tend to be particularly strong when climate, energy prices and the nature of the project are favourable. First, a climate requiring both heating and cooling is preferable to one that requires just one or the other. While the same GSHP system can provide both heating and cooling, two separate conventional systems may be required, each dedicated to only one task—either heating or cooling. This increases the capital cost of the competing conventional technology, making the GSHP a more attractive option. Furthermore, since it operates year-round, the GSHP system can generate larger energy savings, rather than, for example, an air-conditioning unit which only operates in summer and an oil furnace which only operates in the winter.

Second, large seasonal variations in temperature will favour the GSHP system over air-source heat pumps, whose capacity and efficiency decrease at temperature extremes and ensure that there is significant energy demand on which the GSHP can generate savings.

Third, if there is already a useable heating and cooling system installed, the purchase and installation of a GSHP is rarely justified on the basis of its energy benefits alone. Thus, the GSHP is most cost-effective in new construction, especially since this facilitates trenching and drilling, or when an existing heating and cooling system has reached the end of its life and must be replaced.
If heating is the dominant energy requirement, then low electricity prices and high gas or oil prices will make the GSHP more attractive than combustion systems. If cooling is dominant, then high electricity prices will favour ground-source heat pumps over conventional air conditioning, which is less efficient. If both heating and cooling requirements are high, then GSHPs are ideal where electricity prices are low year round, but high peak load charges are levied during summertime.

Whenever building heating and cooling loads are substantially different, it may be financially advantageous to reduce the cost of the earth connection loop by sizing it for the lower of the two loads. In this way, the overall initial cost of the system is reduced but supplemental heating or heat rejection capacity becomes necessary. Supplemental capacity usually entails heating using conventional systems and cooling towers for heat rejection.

GSHPs can also provide moderately hot water, e.g. for domestic use, through a device called a desuperheater. This dual use of the GSHP increases efficiency and energy savings. Other GSHP applications include heating water distribution pipes to prevent freezing, hot water pre-heating, heating of sewage conduits and treatment lagoons, and ice rink cooling.

12.Residential buildings

While GSHPs are used for all types of residential buildings, high-end residential construction tends to be the focus of this market. The higher initial costs of the GSHP do not constitute an especially large fraction of these expensive homes and the homeowners generally view the GSHP system as a long-term investment in their home. Furthermore, they are swayed by the environmental benefits and the improvements in comfort and air-quality associated with the GSHP.

Electric utilities often subsidize the residential market for GSHPs. Utilities benefit through increases to their base load and reductions in their peak load. Utilities also recognize that the system's environmental benefits accrue to society as a whole, and therefore the initial costs should not be borne by the system's owner alone. Regardless, such a subsidy can be a major consideration in the homeowner's decision to install a GSHP.

13. Commercial & institutional buildings

The viability of GSHPs for commercial buildings can be impeded by demands for short simple payback periods, generally less than 5 years, and by limited availability of land for large earth connections. Nevertheless, there are many such installations.

GSHPs offer several advantages that make them particularly attractive in commercial buildings. Since the heat pump is physically smaller than conventional heating and cooling plants, and since heat distribution in a large building can be achieved with a compact liquid loop rather than voluminous air ducts, the ground-source heat pump can free building space for commercial uses. The use of multiple heat pumps distributed around a large building also simplifies control of the interior environment. The elimination of rooftop units, cooling towers and chimneys reduces opportunities for vandalism. Moreover, with increased efficiency over conventional air conditioners, the ground-source heat pump reduces summertime peak load charges often levied by utilities on commercial customers.

Large buildings using GSHPs have multiple heat pump units, located around the building, transferring heat to and from a common building loop. This arrangement is very beneficial. First, large buildings often have simultaneous heating and cooling loads: for example, the core of the building may need cooling while perimeter areas need heating. The common building loop can transfer heat from cooling loads to heating loads, reducing the demand on the earth connection and improving efficiency. Second, climate control is simplified and occupant comfort is improved, since each heat pump affects only the space in its vicinity.

Controls can be local, rather than part of a complex building-wide system. Third, the common building loop transfers heat using a liquid, which permits it to be much more compact than the ducting required by air distribution systems tied to conventional central heating plants; space is freed up for more productive uses.

Specialized markets among certain types of commercial buildings are under development. Buildings with simultaneous heating and cooling requirements—such as those having freezers or ice-making equipment as well as heated areas—can benefit from the liquid building loop commonly used in commercial applications of GSHP: heat is extracted from the cooling loads and passed to the heating loads. Promising possibilities include supermarkets and gas station/convenience store combinations.

Ground-source heat pumps can also be very well suited to institutional buildings. Institutional building owners and operators are often willing to accept longer paybacks than in the commercial sector. They may also be more open to innovative designs and technologies like GSHPs. As in commercial buildings, many institutional buildings have a simultaneous need for heating and cooling, which the building loop of a ground-source heat pump system can take advantage of.

14.Ground-source Heat Pump Project Model

Ground-Source Heat Pump Project Model can be used to evaluate ground-source heat pump projects, from large-scale commercial, institutional or industrial applications to small residential systems. The types of system covered are:

- Ground-Coupled Heat Pumps (GCHPs) - Horizontal GHX;
- Ground-Coupled Heat Pumps (GCHPs) - Vertical GHX; and
- Ground-Water Heat Pumps (GWHPs) - Open Loop or Standing Well.

This section describes the various algorithms used to calculate the energy production (or savings) of GSHP systems. A flowchart of the algorithms is shown in Figure 9. The model initially establishes the building load equation, which describes how building loads vary as a function of outside temperature. It then calculates the load for each temperature bin. Using the building load equation, balance point temperatures are calculated to determine whether or not heating or cooling is required for each bin. From the weather data and the building load, the required heat pump capacity is estimated.

This enables the sizing of the ground loop or the groundwater flow. When this is known, the actual heat pump performance and capacity can be calculated for each bin. The final results from the model consist of the annual electrical energy use of the heat pump system, the heating and cooling energy delivered, the system efficiencies and any auxiliary heating energy requirements.

There are some limitations to the methodology chosen to make the calculation in the GSHP project model. In some instances, the model cannot capture phenomenon such as simultaneous heating and cooling demands, which can sometimes occur in commercial buildings; neither can it capture complex building usage profiles. Residential applications lend themselves readily to a simplified approach given the more homogeneous nature of the buildings and the more limited usage patterns possible. Other limitations of the GSHP project model include:

- The long-term thermal imbalances are not included in the ground heat exchanger (GHX) calculations.
- The ground-coupled heat pump (GCHP) horizontal ground heat exchanger (GHX) configuration considered is a stacked two pipe system
- The ground-coupled heat pump (GCHP) vertical ground heat exchanger (GHX) configuration consists of one U-tube per borehole.
- The building heating and cooling energy consumption and peak loads are evaluated using a simplified version of ASHRAE's modified bin method (ASHRAE, 1985). The interior set point temperature is considered constant at 23°C and remains the same for both heating and cooling.

Despite these limitations, project model can be used for the preliminary evaluation of ground-source heat pump systems and is sufficiently accurate for pre-feasibility and feasibility stages of a project.

15.Bin Method and Design Conditions

The behaviour of the coupled GSHP-Building system is relatively complex and is time and temperature dependent. Trying to capture these dependencies for the purpose of detailed design often requires a dynamic model using relatively short time steps, which is not necessary at the preliminary feasibility stages of a project. Therefore, a simplified approach was investigated, which uses outside temperature as the critical variable.

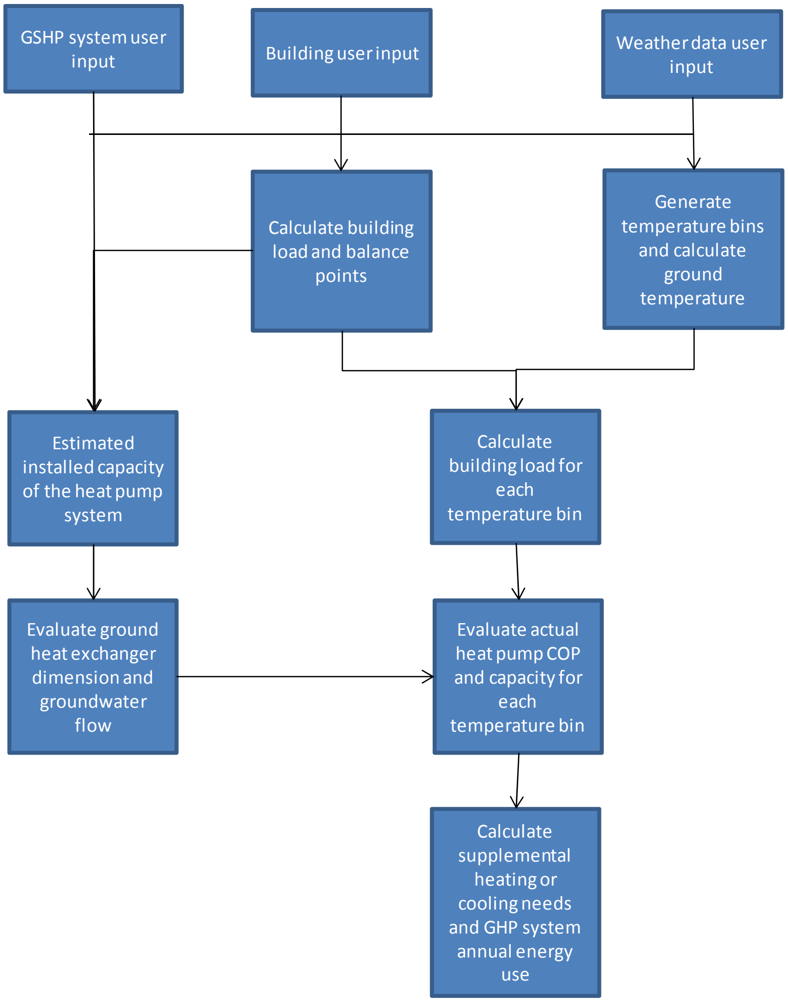


Figure 9. Ground source heat pump energy model flowchart

Such a method, called the bin method, has been used widely for many years to estimate energy use by buildings (ASHRAE Handbook, Fundamentals, 1981, 1985). In this temperature frequency method, the hours in a year are summed into a finite number of bins based on temperatures. Each bin represents the middle, or average, of the temperature range for that bin. For example, Table 1 presents an example of a using 2°C temperature bins.

Table 1. Temperature bins

Bins	# of hours of occurrence in a year
-20	15
-18	35
-16	75
-14	132
[…]	[…]
24	185
26	79
28	24
30	12
Total	8760

Therefore, from Table 1, there would be 15 hours in that year where the temperature is less than –19°C but greater or equal to – 21°C. A basic level of time dependency can also be incorporated in the bin method. This is achieved by splitting up the temperature bins as a function of time. Hence, bins can be compiled, for example, for approximate daytime hours and separately for night time hours.

Using this bin approach, it is possible to capture the GSHP-Building system temperature dependant behaviour and time dependant parameters, and estimate the system's annual energy use. A further refinement of the method, called the modified bin method, is presented in ASHRAE Handbook, Fundamentals (1985). This method allows for off-design calculations by using an estimated diversified load rather than peak load values in establishing the building's load as a function of temperature.

Using the modified bin method allows for estimating the energy demand from the building, but the GSHP system's heat pumps and ground loop performances still need to be addressed. Fortunately, the bin method can readily be extended for treating GSHP systems.

It should be noted that some parts of the GSHP model are concerned chiefly with sizing, for example when determining heating or cooling energy demand or the length of the ground heat exchanger or the groundwater flow in an open-loop system. In these cases, calculations are then performed for extreme circumstances called the design conditions. For example, the heating design temperature represents the minimum temperature that has been measured for a frequency level of at least 1% over the year, for the specific location. Similarly the cooling design temperature represents the maximum temperature that has been measured for a frequency level of at least 1% over the year.

Other parts of the GSHP model are concerned with determining the seasonal energy use or supplemental energy delivered. This requires evaluating the performance of the system over the whole year, that is, for all temperature bins.

16. Weather Data

Basically, GSHP systems are designed by balancing the heating and cooling load of a building with the heating and cooling capacity that could be extracted from the ground. Since this load and this capacity are in direct relation with the air and soil temperatures variations, this data is needed to assess a GSHP project. This section presents how the GSHP project model deals with this data requirement.

17. Generation of temperature bins

Fundamental to the GSHP model philosophy is the availability of temperature bins for daytime and night time hours for the selected location. Additionally, bin data for the coldest and hottest months (corresponding to design heating and cooling conditions) are required for the ground loop calculation. Such a heavy user-data requirement would render the model impractical. Alternatively, storing the data within the model would translate into an excessively large file if even a moderate number of locations around the world were to be included.

18. Ground temperature estimation

The method for sizing the ground heat exchanger (GHX) requires knowledge of the minimum and maximum ground temperature at the GHX depth. Ground temperature is also used in the model to evaluate residential building basement heat losses.

Undisturbed ground temperature, T_g, expressed in °F, can be calculated using:

$$T_s(X_s,t) = \overline{T}_g - A_s \exp\left(-X_s\sqrt{\frac{\pi}{365\alpha}}\right)\cos\left(\frac{2\pi}{365}\left[t - t_0 - \frac{X_s}{2}\sqrt{\frac{365}{\pi\alpha}}\right]\right) \qquad (1)$$

where X_s is the soil depth in feet, t is the day of year, T_g is the mean annual surface soil temperature, A_s is the annual surface temperature amplitude, α is the soil thermal diffusivity, and t_0 is a phase constant expressed in days. From equation (1), the minimum and maximum ground temperatures for any depth can be expressed as:

$$T_{g,min} = \overline{T}_g - A_s \exp\left(-X_s\sqrt{\frac{\pi}{365\alpha}}\right) \qquad (2)$$

$$T_{g,max} = \overline{T}_g + A_s \exp\left(-X_s\sqrt{\frac{\pi}{365\alpha}}\right) \qquad (3)$$

For multiple horizontal heat exchanger pipe systems or shallow vertical boreholes, X_S can be set equal to the average depth in equations (1) to (3). For vertical systems, this usually becomes a trivial task since the sub-surface ground temperature does not vary significantly over the course of the year; ground temperature can then be estimated as equal to the mean annual surface soil temperature, T_g.

19. Building Load Calculation – Descriptive Data Method - Commercial (institutional) & industrial buildings

In a simplified approach, it is difficult to evaluate complex internal building behaviour such as individual zone demand due to the large amount of data a user would need to gather. Therefore, a whole-building approach is adopted. This whole-building approach allows the determination of what are called "block loads".

A block load refers to the peak load occurring in a building at a specific time under design temperature conditions. For example, in a building with many zones (independent thermostats), the sum of each zone's cooling load can exceed the block cooling load since these loads might not happen concurrently (due to differences in occupancy, exposure, solar gain or other factors). For a residential building, block cooling and heating loads are usually the summation of all room loads under the same design conditions. Figure 10a illustrates the block load approach while Figure 10b shows how a building is typically segmented into zones with different thermal loading profiles. Using the block load approach, the whole building can be treated as a simple zone with a single inside air temperature.

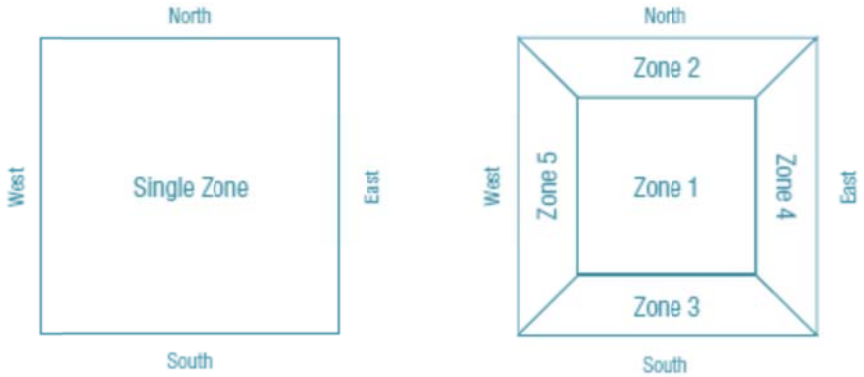


Figure 10. Block load vs. zoned building approach

Relationships between outside temperature and the various building heating and cooling load components must be established. The following load components are treated in GSHP project model:

- Transmission losses (conductive and convective)
- Solar gains (sensible)
- Fresh air loads (latent and sensible)
- Internal gains (latent and sensible)
- Occupant loads (latent and sensible)

Each load component is expressed as a polynomial of zeroth, first or second order, as shown in the following generic equations (4), (5) and (6):

$$q_j = c_{0,j} \qquad (4)$$

$$q_j = c_{0,j} + c_{1,j} T_0 \qquad (5)$$

$$q_j = c_{0,j} + c_{1,j} T_0 + c_{2,j} T_0^2 \qquad (6)$$

where q_j is the building load from source j (e.g. transmission losses, solar gains, fresh air, internal gains, and occupant loads), T_o is the outside air temperature, and $c_{0,j}$, $c_{1,j}$ and $c_{2,j}$ are polynomial coefficients derived from physical building characteristics related to source j. The global building load equation as a function of outside air temperature can be obtained through a summation of all n load components:

$$q_{tot} = \sum_{j=1}^{n} c_{0,j} + \sum_{j=1}^{n} c_{1,j} T_0 + \sum_{j=1}^{n} c_{2,j} T_0^2 \qquad (7)$$

which can be written in short form as:

$$q_{tot} = c_0 + c_1 T_0 + c_2 T_0^2 \qquad (8)$$

where each coefficient c_i is the sum of all individual $c_{i,j}$. Considering these generic equations, the calculation of six load components of a commercial (institutional) and industrial building is shown hereafter, followed by the resulting building load equation and balance points. To facilitate the identification of these six load components specifically associated with commercial (institutional) & industrial buildings, they are noted from CI1 to CI6.

20. CI1 - Transmission losses (conductive and convective)

Transmission losses include all conductive and convective heat losses through the building's envelope. In the simplified approach used in the GSHP project model, no provisions are made for opaque surface solar gains. Therefore, transmission losses q_{trans} are simply:

$$q_{trans} = \sum_i (UA)_i (T_0 - T_{in}) \qquad (9)$$

where $(UA)_i$ is the global heat transfer coefficient for exterior component I (e.g. exterior walls, ceilings, windows) and T_{in} is the inside air temperature. This equation can be simply rearranged to obtain the required form of equation (5), with:

$$c_0 = -\sum_i (UA)_i T_{in} \qquad (10)$$

$$c_1 = \sum_i (UA)_i \qquad (11)$$

For common applications, (UA) for exterior walls is simply:

$$(\mathrm{UA}) = \mathrm{U_{wall}} 4\mathrm{ZH}\sqrt{\frac{\mathrm{S}}{\mathrm{Z}}} \qquad (12)$$

where $\mathrm{U_{wall}}$ is the heat transfer coefficient (also called “U-value”) for exterior walls, which depends on the type of insulation used (U-values are the reciprocal of R-values expressing the thermal resistance of walls).

For ceilings, the area considered is equal to the total floor area divided by the number of floors; this leads to the following expression for (UA):

$$(\mathrm{UA}) = \mathrm{U_{ceil}}\left(\frac{\mathrm{S}}{\mathrm{Z}}\right) \qquad (13)$$

where $\mathrm{U_{ceil}}$ is the average U-value for ceilings. Finally the loss coefficient through windows is expressed as:

$$(\mathrm{UA}) = \mathrm{U_{win}} \mathrm{f_{win}} \mathrm{S} \qquad (14)$$

where $\mathrm{U_{win}}$ is the average U-value for windows; $\mathrm{f_{win}}$ is the ratio of window area to total floor area.

21.CI2 - Solar gains (sensible)

The treatment of solar gains through windows represents a special challenge for a simplified procedure such as the bin method. To obtain the relationship such as in equation (5), the bin method assumes that there is a linear correspondence between outdoor temperature and the amount of solar gains in a building, as shown in Figure 11.

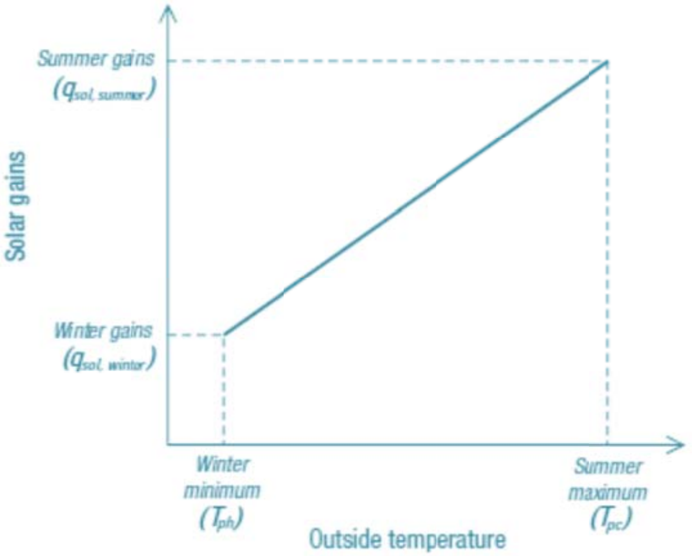


Figure 11. Solar gains as a function of outside temperature

Solar gains through windows are thus expressed as:

$$q_{sol} = S_c\left[q_{sol,winter} + M\left(T_0 - T_{ph}\right)\right] \qquad (15)$$

which can be rearranged in the form of equation (5) as , with:

$$c_0 = S_c\left(q_{sol,winter} - MT_{ph}\right) \qquad (16)$$
$$c_1 = S_c M \qquad (17)$$

In the equations above, S_c represents the building conditioned floor area, and M is the solar heat gain interpolation coefficient, expressed as:

$$M = \frac{\left(q_{sol,summer} - q_{sol,winter}\right)}{\left(T_{pc} - T_{ph}\right)} \qquad (18)$$

where $q_{sol,winter}$ and $q_{sol,summer}$ are the average solar contribution for winter and summer at the building location, and T_{ph} and T_{pc} are the winter (heating) and summer (cooling) design day average temperatures. The design day average temperatures are obtained from the heating and cooling design day temperatures $T_{d,heat}$ and $T_{d,cool}$:

$$T_{pc} = T_{d,cool} + \frac{DR}{2} \qquad (19)$$

$$T_{ph} = T_{d,heat} + \frac{DR}{2} \qquad (20)$$

where DR is the mean daily temperature range, also specified by the user. The calculation of the winter and summer average solar gains is based on the ASHRAE's Cooling Load Factor (CLF) method. For the modelling needs, the solar gain using this method is expressed as:

$$q_{sol,season} = \frac{\sum_{ori}(MSHGF_{ori,season} AG_{ori} SC_{ori} CLF_{tot,ori} FPS_{season})}{nh_{season} S_c} \qquad (21)$$

where ori is the orientation (North, East, South, West assumed in the GSHP project model), season is the warmest or coolest month (e.g. January or July in the northern hemisphere), $MSHGF_{ori,season}$ is the maximum solar heat gain factor for orientation ori and month season at the building's latitude, AG_{ori} is the glass area for exposure ori, SC_{ori} is the shading coefficient of glass for exposure ori , $CLF_{tot,ori}$ is the 24-hour sum of the cooling load factors for orientation ori , FPS_{season} is the fraction of possible sunshine for season, nh_{season} is the number of operating hours of air conditioning equipment for season, and S_c is, as before, the building conditioned floor area.

Typical values can be assumed for the following parameters: $SC_{ori} = 0.81$, $FPS_{season} = 0.64$ for summer and 0.45 for winter, nh_{season} = 12 for summer and 24 for winter. Finally, glass area on all orientations is assumed to be equal (and is therefore one quarter of the total glass area AG for each of the four orientations). It becomes therefore possible to factor out all constant parameters in equation (21), which becomes:

$$q_{sol,season} = \frac{AG\ SC_{ori} FPS_{season}}{4\ nh_{season} S_c} \sum_{ori}(MSHGF_{ori,season} CLF_{tot,ori}) \qquad (22)$$

Values for the maximum solar heat gain factor $MSHGF_{ori,season}$ are tabulated in ASHRAE (1985). They depend on orientation, month, and latitude. Cooling load factors $CLF_{tot,ori}$ are listed in the same reference. Consequently, the summation term in equation (22) depends only on month and latitude.

22.CI3 - Internal gains (sensible)

The treatment of the sensible internal gains is very simple and straightforward. Every internal gain source is assumed independent of outside temperature. As a consequence, the expression for sensible internal gains $q_{int,sens}$ takes the form of equation (4) (zero order polynomial) as, with:

$$c_0 = K_l + K_e + K_{p,sens} \qquad (23)$$

where K_l, K_e and $K_{p,sens}$ are respectively gains from lighting, equipment and occupants. The values selected for these constants were taken from ASHRAE (1985) and PMSK (1991), as indicated in Table 2.

Table 1. Gain level

Gains Level	Lights (W/m2)	Equipment (W/m2)
Light	5	5
Moderate	15	10
Heavy	25	20
Occupants	74.6 W/person	

In the GSHP model, the number of occupants in commercial (institutional) and industrial buildings is linked to the floor area entered by the user. The model assumes that commercial and institutional buildings have 5 persons per 100 m2 while industrial buildings have 1 person per 100 m2 of floor area.

23.CI4 - Fresh air load (sensible)

The load due to outside air entering the building is estimated to be proportional to the number of occupants in the building. The load is divided between sensible and latent component. The generic equation for calculating the sensible load $q_{f,sens}$ from an outside air stream is:

$$q_{f,sens} = \rho C_p V(T_{in} - T_0) \qquad (24)$$

where ρ is the density of air, C_p its specific heat, and V is the volumetric flow rate of entering air. This equation is readily adaptable to the generic form of equation

(5) as:

$$q_{f,sens} = c_0 + c_1 T_0 \qquad (25)$$

with:

$$c_0 = \rho C_p \, V \, T_{in} \qquad (26)$$
$$c_1 = \rho C_p \, V \qquad (27)$$

The model assumes constant values for air density and specific heat (ρ = 1.2 kg/m2, C_p=1.005 (kJ/kg)/°C). The amount of fresh air entering the building, from all sources, is estimated at 20 L/s/person. A 50% heat exchange between this outside air stream and the air extracted from the building is assumed. Therefore, the net effective airflow per occupant is reduced to 10 L/s for thermal balance calculations.

24.CI5 - Fresh air load (latent)

The latent load considered in the GSHP model affects only air-conditioning needs. The model does not consider any type of humidification needs during the heating season. The conventional method of calculating an outside air latent load is to use the wet bulb temperature of the air entering from the outside and indoor air to obtain the water content in both streams. From the water content, and the enthalpy of saturated water vapour, the latent load $q_{f,lat}$ can be calculated as:

$$q_{f,lat} = \rho\dot{V}(W_0 h_{g,o} - W_{in} h_{g,in}) \qquad (28)$$

where W is the air water content expressed in kg of water per kg of dry air, $h_g \approx 2501 + 1.805\ T_{air}$ is the enthalpy of saturated water vapour expressed in kJ/kg, and T_{air} is the air temperature in °C. Subscripts “o” and “in” denote outside and inside air, respectively. While this formulation is exact, it requires knowing the wet bulb temperature, or the relative humidity, of the exterior air at all times.

Therefore, a method was adopted to allow for a basic evaluation of the fresh air latent load. In the GSHP project model, the user needs to define the project location’s humidity level. From this qualitative information, the model generates an equivalent fresh air latent load proportional to the sensible load and linearly correlated to outside temperature, as shown in Figure 12. The maximum fraction of latent load,f, to sensible load is defined as a function of the qualitative user input, as presented in Table 3. The minimum fraction,f_{min}, and the design day average temperature range, DT , were determined empirically to be 0.1 and 30°C respectively. The 30°C wide range insures that no negative latent load will occur for the building's temperature bins, even though the function shown in Figure 12 can produce negative loads at sufficiently low exterior temperature.

Table 3. Maximum latent to sensible fraction

Humidity Level	Maximum latent to sensible fraction
Low	0.5
Medium	1.5
High	2.5

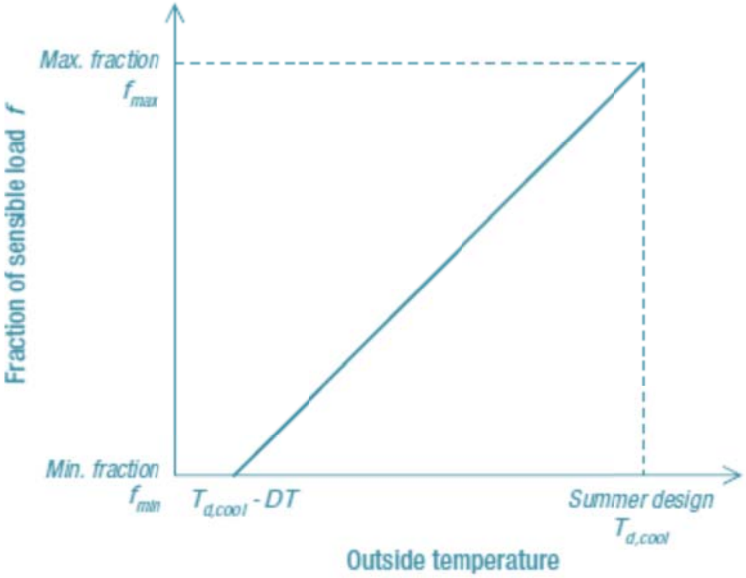


Figure 12. Relationship between latent and sensible fresh air load as a function of outside temperature

The values selected for these fractions were obtained by calculating the actual fraction of latent to sensible load for a unit air flow at different locations using ASHRAE (1985), design summer dry bulb and mean coincident wet bulb conditions.

The mathematical formulation for , the fraction of latent to sensible load, is:

$$\mathrm{f} = \mathrm{aT_0} + \mathrm{b} \quad \text{for} \quad \mathrm{T_0} > 10°C \qquad (29)$$

$$\mathrm{f} = 0 \quad \text{for} \quad \mathrm{T_0} < 10°C \qquad (30)$$

where coefficients a and b are calculated from maximum latent to sensible fraction $\mathrm{f_{max}}$ and from summer design temperature $\mathrm{T_{d,cool}}$ through:

$$\mathrm{a} = \frac{\mathrm{f_{max}} - \mathrm{f_{min}}}{\mathrm{DT}} \qquad (31)$$

$$\mathrm{b} = \mathrm{f_{min}} - \left(\frac{\mathrm{T_{d,cool}} - \mathrm{DT}}{\mathrm{DT}}\right)(\mathrm{f_{max}} - \mathrm{f_{min}}) \qquad (32)$$

The actual latent load is obtained by multiplying equations (29) and (30) with equation (24) for the sensible load, resulting in a second order polynomial (form of equation 6):

$$\mathrm{q_{f,lat}} = \mathrm{c_0} + \mathrm{c_1 T_0} + \mathrm{c_2 T_0^2} \qquad (33)$$

with:

$$\mathrm{c_0} = \mathrm{b}\,\rho\,\mathrm{C_p}\,\dot{\mathrm{V}}\,\mathrm{T_{in}} \qquad (34)$$

$$\mathrm{c_1} = \mathrm{a}\,\rho\,\mathrm{C_p}\,\dot{\mathrm{V}}\,\mathrm{T_{in}} - \mathrm{b}\,\rho\,\mathrm{C_p}\,\dot{\mathrm{V}} \qquad (35)$$

$$\mathrm{c_2} = -\mathrm{a}\,\rho\,\mathrm{C_p}\,\dot{\mathrm{V}} \qquad (36)$$

Where all variables were previously defined.

25.CI6 - Internal gains (latent)

For sensible internal gains, latent internal gains are assumed constant. Only latent internal gains from occupants are considered in the model. As a consequence, the expression for latent internal gains $\mathrm{q_{int,lat}}$ takes the form of equation 4 (zero order polynomial) as , with:

$$\mathrm{c_0} = \mathrm{K_{p,lat}} \qquad (37)$$

where $\mathrm{K_{p,lat}}$ is a constant describing latent gains from occupants. A value of 74.6 W/occupant was selected for this constant (ASHRAE, 1985). The calculation of the number of occupants was described before for the Internal gains (sensible) load components CI4.

26.Commercial (institutional) & industrial (CI) building load equation and balance points

Combining all of the c0, c1 and c2 coefficients calculated from the above load components CI1 to CI6, results in the final building load relationship as a function of outside air temperature (equation 7). This relation can then be used for each temperature bin to evaluate the building energy use. The same equation can also be used at the winter and summer design temperatures to estimate the building design loads.

Since the GSHP project model considers two sets of bins, one for daytime hours and one for night time hours, two corresponding sets of c0, c1 and c2 coefficients are needed. Furthermore, since some load distinction is made between winter and summer, through the latent and solar load components, two additional sets of coefficients are required. The resulting building load behaviour is shown graphically in Figure 13.

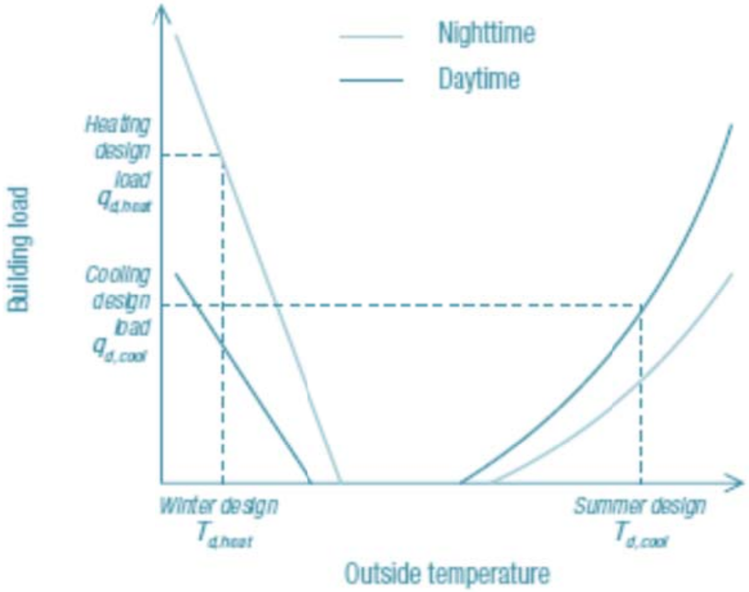


Figure 13. Building load vs. outside temperature

In order for the model to be able to select between the heating and cooling load coefficients, the building balance temperatures must be estimated for heating and cooling conditions.

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These balance points represent the temperature above and below which the building does not require heating and cooling respectively. These balance points can be seen in Figure 13, at the locations where the curves intercept the x-axis. The balance temperature T_{bal} can be found by finding the roots of equation (7):

$$T_{bal} = \frac{-c_1 \pm \sqrt{c_1^2 - 4c_2c_0}}{2c_2} \qquad (38)$$

(One of the two roots is selected based on physical considerations). For the case where there is no quadratic term, the equation simplifies to:

$$T_{bal} = \frac{-c_0}{c_1} \qquad (39)$$

27.Residential buildings

The approach selected for residential buildings is very similar to the one presented for commercial (institutional) & industrial buildings. The assumption of a single zone model, as shown in Figure 10a, is also applied here. However, contrary to CI buildings, this assumption is a fair approximation of what is mostly encountered in the residential sector, especially for homes equipped with central heating systems. Therefore, the simplified building model for residential applications should lead to more robust estimations of building loads and energy use when choosing the descriptive method.

This is attributable in part to the more closely matched zoning assumption but also to the greater homogeneity in building use and architecture in the residential market.

While most of the heat loss and heat gain components are common to residential applications, a number of specific adaptations are suited to this type of building. Most important are the explicit consideration of basement loads, and the modified treatment of fresh air load calculations. Basement heat losses are not considered for CI buildings since they are assumed to be negligible compared to the overall building demand. This is not the case for residential or small commercial buildings, where basement heat losses can account for a significant portion of the total design demand.

As for CI buildings, each heating or cooling load is expressed through an explicit relation between the load and the outside air temperature. However, the presence of below-grade components results in one additional type of relation being considered:

$$q_k = d_{0,k} + d_{1,k} T_g \qquad (40)$$

where q_k is the building load from below-grade component k, T_g is the temperature of the ground surrounding below-grade components, and $d_{0,k}$ and $d_{1,k}$ are polynomial coefficients derived from physical building characteristics for each below-grade component k.

The global building load equation as a function of outside air temperature and ground temperature can then be obtained through a summation of all n above-grade and m below-grade load components:

$$q_{tot} = \sum_{j=1}^{n} c_{0,j} + \sum_{j=1}^{n} c_{1,j} T_0 + \sum_{j=1}^{n} c_{2,j} T_0^2 + \sum_{k=1}^{m} d_{0,k} + \sum_{k=1}^{m} d_{1,k} T_g \qquad (41)$$

or in short form:

$$q_{tot} = c_0 + c_1 T_0 + c_2 T_0^2 + d_0 + d_1 T_g \qquad (42)$$

where each c_i or d_i is the sum of all individual $c_{i,j}$ or $d_{i,k}$. Considering these generic equations, the difference between the calculations of the six load components for a residential building and a commercial (institutional) & industrial (CI) building is shown hereafter, followed by the resulting building load equation and balance points. To facilitate the identification of these six load components specifically associated with residential buildings, they are noted from RES1 to RES6.

28.RES1 - Transmission losses (conductive and convective)

The treatment of transmission losses for residential buildings differs from the one presented for CI buildings only by the addition of basement losses. All above-grade losses adhere to equation (9), resulting in the same c_o and c_1 coefficients as in equation (10) and (11).
Above-grade losses: Most assumptions made for CI buildings still apply, with the difference that wall height is assumed to be 2.5 m instead of 3 m. An additional

term is added to the above-grade wall heat losses to account for the part of the foundation that is exposed to outside air. In the case of a full basement, the model assumes that a height $H_{f,o}$= 0.7 m of the foundation wall is exposed to outside air; equation (12) becomes:

$$(UA) = U_{f,wall}\, 4ZH_{f,o}\sqrt{\frac{S}{Z}} \qquad (43)$$

where $U_{f,wall}$ is the "U-value" for foundation walls. For slab on grade foundation, the model assumes that roughly half the slab area (the "perimeter area") is exposed to outside air, the rest exposed to ground temperature, in which case,

$$(UA) = U_{f,floor}\,\frac{1}{2}\,\frac{S}{Z} \qquad (44)$$

where $U_{f,floor}$ is the "U-value" for the basement floor.

The losses for full basement below-grade components are divided in four parts:

1. Upper below-grade wall, representing approximately 1/3 of the below-grade height;
2. Lower below-grade wall, representing the remaining 2/3 of the below-grade height;
3. Floor perimeter area, assumed in the model to be half the floor area; and
4. Floor centre area, assumed to be half the floor area.

For slab on grade foundation, only the fourth component applies. Transmission losses are expressed in a way similar to (9), except that outside air temperature must be replaced by ground temperature:

$$q_{trans,g} = \sum_i (UA)_i (T_{in} - T_g) \qquad (45)$$

Since the bin method only provides air temperature distribution, a linear correlation between the outside air temperature and the ground temperature is used to obtain the ground temperature for each bin:

$$T_g = T_{g,max} + \frac{(T_{g,min} - T_{g,max})}{(T_{d,heat} - T_{d,cool})}(T_{bin} - T_{d,cool}) \qquad (46)$$

where T_{bin} is the bin temperature. The resulting d_0 and d_1 coefficients for each below-grade components are for below-grade walls (full foundation):

$$d_0 = -4\,U_{f,wall}\sqrt{\frac{S}{Z}}H_{f,g}T_{in} \qquad (47)$$

$$d_1 = -4\,U_{f,wall}\sqrt{\frac{S}{Z}}H_{f,g} \qquad (48)$$

and for below-grade floor (full foundation):

$$d_0 = -\,U_{f,floor}\frac{S}{Z}T_{in} \qquad (49)$$

$$d_1 = U_{f,floor}\frac{S}{Z} \qquad (50)$$

For slab on grade foundations, only the last two equations, divided by 2, applies. The treatment of ceiling and windows is similar to the CI building case (CI1), except that windows are assumed to occupy a constant 20% of the total floor area.

29.RES2 - Solar gains (sensible)

Calculation of solar gains for residential buildings is identical to that of CI buildings ones (CI2), with the exception of window area, which is defined for the load components RES1 as having an equal distribution of the window surface across the four wall orientations.

30.RES3 - Internal gains (sensible)

The treatment of internal gains is similar to the CI building case (CI3), where, but with:

$$c_0 = K_{int} + K_{p,sens} \qquad (51)$$

where K_{int} represents gains from all equipment, lights and appliances, and $K_{p,sens}$ represents gains from occupants. The constants in the equation above were assumed to be 14 W/m2 for internal gains and 74.6 W/person for occupants. Unlike commercial (institutional) & industrial buildings, the number of occupants is not linked to the floor area. The model considers that residential buildings have

2 adults and 2 children at all times; the average heat gain from children is taken as half that of an adult.

31.RES4 - Fresh air load (sensible)

The load due to outside air entering into the building is estimated exactly as described for the CI buildings load component (CI4). However, the volume of fresh air into a residential building is not related to the number of occupants but rather to the level of insulation indicated qualitatively by the user: the higher the insulation level, the lower the amount of air entering the building. Table 4 shows the number of air changes per hour (ACH), as a function of insulation level.
Table 4. Air changes per hour as a function of insulation level

Insulation levels	ACH
Low	0.5
Medium	0.25
High	0.1

The house volume is calculated as $HS + H_b S/Z$ with H the estimated wall height (estimated at 2.5 m), H_b the basement height (estimated at 2.2 m, when present), S the floor area (excluding basement) and Z the number of floors.

32.RES5 - Fresh air load (latent)

The fresh air latent load calculation for residential buildings is similar to that of CI buildings (CI5). Only the calculation of the airflow rate is different, as presented for RES4.

33.RES6 - Internal gains (latent)

As for a CI building, only latent internal gains from occupants are considered. The calculation procedure is identical to the CI building case, but with the evaluation of the number of occupants made as described for RES3.

34.Residential (RES) building load equation and balance points

Combining all the c_0, c_1, c_2, d_0 and d_1 coefficients from the above load components RES1 to RES6 results in the final building load relationship as a function of outside air temperature. This relation can then be used, for each temperature bin, to evaluate the building energy use and can also be used at the winter and summer design temperatures to estimate the building design loads. The residential model results in four sets of coefficients in order to account for daytime, night time, cooling and heating conditions. Figure 13, presented for CI buildings, applies equally to the residential model. The balance point temperature T_{bal} for residential buildings is obtained by finding the root of equation:

$$T_{bal} = \frac{-c_1 \pm \sqrt{c_1^2 - 4c_2(c_0 + d_0 + d_1 T_g)}}{2c_2} \qquad (52)$$

For the case where there is no quadratic term, the equation simplifies to:

$$T_{bal} = \frac{-c_0 + d_0 - d_1 T_g}{c_1} \qquad (53)$$

35.Building Load Calculation – Energy Use Method

The descriptive data method for building load calculation, detailed in the previous, is useful when dealing with a new building. However, this approach may not always be appropriate, especially for commercial (institutional) & industrial buildings which are usually more complex. An alternate method is to have the user enter known building energy related information, namely the building's annual energy use and its design loads. From this information, a relation similar to equation (5) can be derived.

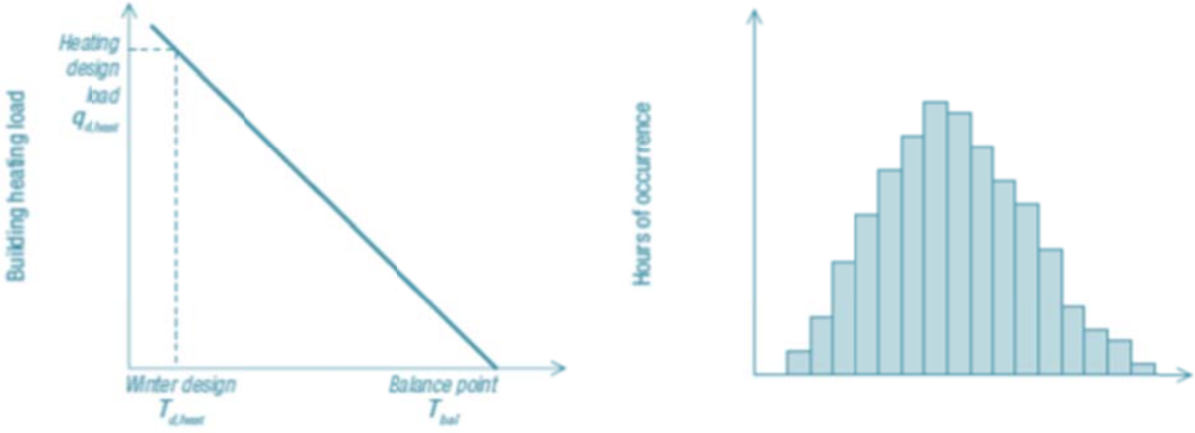

Figure 14. Information available for energy use method

Figure 14 illustrates the basic information available in determining the coefficients in equation (5). To do so, equation (5) is first applied to the design heating load $q_{d,heat}$ and the heating design temperature $T_{d,heat}$:

$$q_{d,heat} = c_0 + c_1 T_{d,heat} \qquad (54)$$

Then, integration of the curve in Figure 14 over the temperature occurrence distribution shown in Figure 14b, is equal to the user-entered annual heating load of the building $q_{tot,heat}$. In discrete form:

$$q_{d,heat} = \sum_{i=1}^{p} \left(c_0 + c_1 T_{o,i}\right) h(T_{o,i}) \qquad (55)$$

where $T_{o,i}$ is the average temperature for each of the p bins available in the model ($1 \leq i \leq p$), and $h\left(T_{o,i}\right)$ is the number of hours of occurrence of outside temperature $T_{o,i}$ during the heating season, as shown in Figure 14b. Equations (54) and (55) constitute a simple set of two equations containing two unknowns, namely c_0 and c_1. Solving the set of equations results in the following explicit form for the coefficients:

$$c_0 = \left[\frac{q_{d,heat} \sum_{i=1}^{p} T_{o,i} h\left(T_{o,i}\right) - q_{tot} T_{d,heat}}{\sum_{i=1}^{p} T_{o,i} h\left(T_{o,i}\right) - T_{d,heat} \sum_{i=1}^{p} h(T_{o,i})}\right] \qquad (56)$$

$$c_1 = \left[\frac{q_{tot} - q_{d,heat} \sum_{i=1}^{p} h(T_{o,i})}{\sum_{i=1}^{p} T_{o,i} h\left(T_{o,i}\right) - T_{d,heat} \sum_{i=1}^{p} h(T_{o,i})}\right] \qquad (57)$$

To obtain the coefficients expressed in equations (56) and (57), only the temperature bins corresponding to a heating load, as in Figure 14a, must be considered. These bins are those corresponding to temperatures below the balance point temperature. Applying equation (39) to the coefficients obtained in (56) and (57) allows delimiting the bins used in the calculation. This, in turn, modifies the c_0 and c_1 coefficients, resulting in an iterative solution procedure. The procedure presented in equations (54) to (57) is then reapplied to obtain a separate set of c_0 and c_1 coefficients specific to the cooling season, with user-entered design cooling load $q_{d,cool}$, summer design temperature $T_{d,cool}$, and annual cooling load of the building $q_{tot,cool}$.

Using two sets of independent coefficients (one for heating, one for cooling) can lead to possible conflicts between the heating and cooling load equations. As shown in Figure 15a, the balance points could overlap if the data entered are inconsistent or if the linear model for the building load does not accurately represent the building behaviour. Since it is not possible, with the information available, to resolve such a conflict, the GSHP project model assumes that both equations fall to 0 in the conflicting region, resulting in the load curves displayed in Figure 15b.

Note that having different sources for cooling and heating energy use tends to make the iterative solution process more difficult.

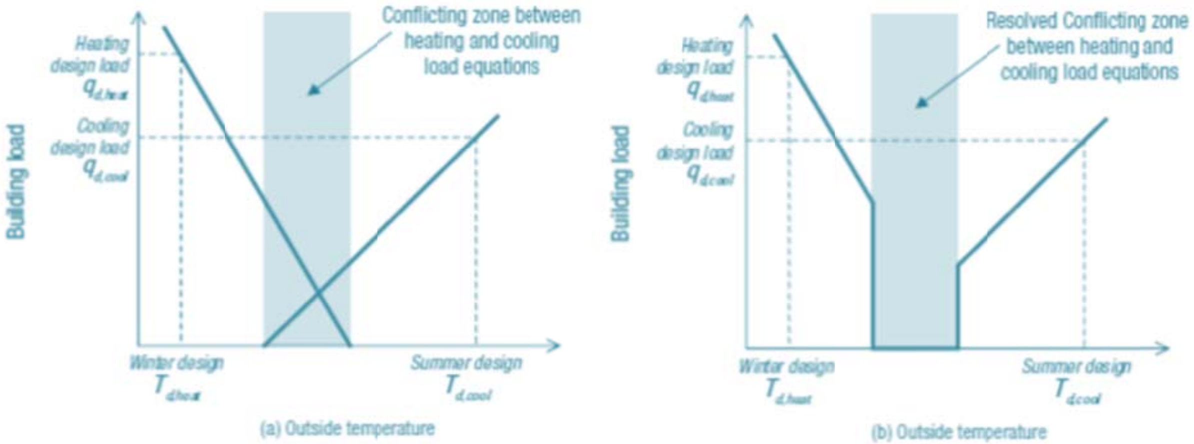

Figure 15. a. Balance point conflict between heating and cooling load curves b. Modified building load curves to resolve balance point conflict

36.Building Load Calculation for each Temperature Bin

The steps described in previous sections lead to the calculation of building load for each temperature bin generated. This is done through equations (7) for commercial (institutional) & industrial buildings, and (41) for residential buildings, taking into account the balance point temperatures.

As an example of such calculation, Table 5 shows the application of the method to a 2°C daytime temperature bin. The building's total energy demand for heating and cooling is simply evaluated by combining the calculated demand with the hours of occurrence of the temperature bins and the balance point temperatures, using the algorithms shown in the previous sections.

Table 5. Example of building load calculation for a 2°C temperature bins

Bins (°C)	January (h)	July (h)	Rest of year (h)	Cooling demand (yes/no)	Heating demand (yes/no)	Building load (-for cooling) (kW)
-12	0	0	0	No	Yes	4.59
-10	2	0	0	No	Yes	4.39
-8	9	0	3	No	Yes	4.18
-6	27	0	12	No	Yes	3.98
-4	56	0	68	No	Yes	3.77
-2	101	0	128	No	Yes	3.57
0	54	0	188	No	Yes	3.36
2	62	0	223	No	Yes	3.16
4	17	0	275	No	Yes	2.95
6	5	0	235	No	Yes	2.75
8	0	0	189	No	Yes	2.54
10	0	0	218	No	Yes	2.34
12	0	0	162	Yes	Yes	0.00
14	0	0	191	Yes	Yes	0.00
16	0	0	167	Yes	Yes	0.00
18	0	0	193	Yes	No	-1.62
20	0	10	208	Yes	No	-1.82
22	0	28	260	Yes	No	-2.02
24	0	57	236	Yes	No	-2.22
26	0	89	195	Yes	No	-2.42
28	0	67	121	Yes	No	-2.62
30	0	57	58	Yes	No	-2.82
32	0	23	21	Yes	No	-3.02
34	0	0	0	Yes	No	-3.22

37.Earth Connection - Closed-Loop Ground Heat Exchangers (GHX)

This section introduces the procedure to estimate the size and the performance of closed-loop ground heat exchangers (GHXs). Since this estimation also requires the calculation of elements that specifically belong to the heat pump system, the sizing procedure introduced here is completed later, where the heat pump system is discussed.

38. Ground heat exchanger (GHX) sizing

Ground heat exchanger sizing is concerned mainly with the determination of heat exchanger length. The required GHX length based on heating requirements, L_h, is:

$$L_h = q_{d,heat}\left[\frac{\frac{(COP_h-1)}{COP_h}(R_p+R_sF_h)}{T_{g,min}-T_{ewt,min}}\right] \qquad (58)$$

where COP_h is the design heating coefficient of performance of the heat pump system, R_p is the pipe thermal resistance, R_s is the soil/field thermal resistance, F_h is the GHX part load factor for heating, $T_{g,min}$ is the minimum undisturbed ground temperature, and $T_{ewt,min}$ is the minimum design entering water temperature (EWT) at the heat pump. A similar equation can be used to calculate the required GHX length L_c based on cooling requirements:

$$L_c = q_{d,cool}\left[\frac{\frac{(COP_c+1)}{COP_c}(R_p+R_sF_c)}{T_{ewt,max}-T_{g,max}}\right] \qquad (59)$$

where COP_c is the design cooling coefficient of performance (COP) of the heat pump system, F_c is the part load factor for cooling, $T_{g,max}$ is the maximum undisturbed ground temperature (equation 3), and $T_{ewt,max}$ is the maximum design entering water temperature at the heat pump.

Equations (58) and (59) do not take into consideration long-term thermal imbalances that could alter the soil temperature field over a period of many years. These thermal imbalances are generally attributable to significant differences between the annual heat extracted from the ground and the heat that is rejected to the ground during the cooling season. However, this simplification could be considered acceptable at the preliminary feasibility evaluation stage.

Equations (58) and (59) require the determination of pipe thermal resistance R_p and soil/field thermal resistance R_s. These are determined from geometrical and physical considerations. For horizontal GHX, the method takes into account surface effects that have a significant influence on horizontal soil/field resistance values. Soil resistance values are tabulated as a function of radial distance for different kinds of soil (e.g. light soil or heavy soil, damp or dry, rock, etc.). Thermal resistances for permafrost were extrapolated from those for regular soil, based on soil conductivity properties.

As shown by equations (58) and (59), there are two possible heat exchanger lengths that can be used for designing a closed-loop system. The choice between using the cooling or heating length is left to the user. This design decision has an impact on both cost and performance of the GSHP system. Selecting a GHX length that will not be sufficient for heating will require an auxiliary heating system. Using a GHX length insufficient for cooling will require a supplemental heat rejector. The GSHP project model takes into account these two possibilities when modelling the GHX.

39.Design entering water temperature (Tewt)

The design of a GHX is in many ways similar to that of a conventional heat exchanger. For a conventional heat exchanger, the inlet and outlet temperatures are usually provided for sizing the heat exchanger. This also applies for a GHX: the final size of the GHX is in great part determined by the user's requirements for the minimum or maximum temperatures allowed at the GHX's outlet during the course of the year.

However, the values for the maximum and minimum GHX outlet temperatures have a fairly limited range of acceptable values. Practical constraints, mainly from the heat pumps, tend to make this design decision more straightforward. For example, extended range heat pumps will usually have a 20°F (-6.7°C) recommended minimum design entering water temperature ($T_{ewt,min}$) and 110°F (92.2°C) recommended maximum design entering water temperature ($T_{ewt,max}$). Specific designs may go below and above these temperatures but are not common. From a literature review, the following design entering water temperature estimates were used in the GSHP model:

- Minimum design entering water temperature:

$$T_{ewt,min} = T_{g,min} - 15°F$$

- Maximum design entering water temperature:

$$T_{ewt,max} = \min(T_{g,max} + 20°F, 110°F)$$

Since the model was also designed to be used in permafrost, the 20°F minimum entering water temperature limitation was not implemented.

40.Part load factor (F)

Determining the GHX length using equations (58) and (59) requires the evaluation of the GHX part load factor. The part load factor (F) represents the fraction of equivalent full load hours during the design month to the total number of hours in that month, as seen by the GHX. It can be evaluated as:

$$F = \frac{\bar{q}}{q_{max}} \tag{60}$$

where $\bar{q}$ and q_{max} are the average load and peak load for the month respectively. The part load factor F is evaluated for the design cooling month and the design heating month, typically July and January in the Northern Hemisphere, leading to the values F_c and F_h used in equations (58) and (59).

41.Earth Connection - Open Loop Systems (Groundwater)

Standing well systems use an intermediate heat exchanger between the earth connection and the heat pump to isolate the building fluid loop from the ground water. This is compulsory whenever the building loop fluid is not water, and is recommended in many cases to prevent damage to the heat pump heat exchanger due to scaling or corrosion caused by the groundwater.

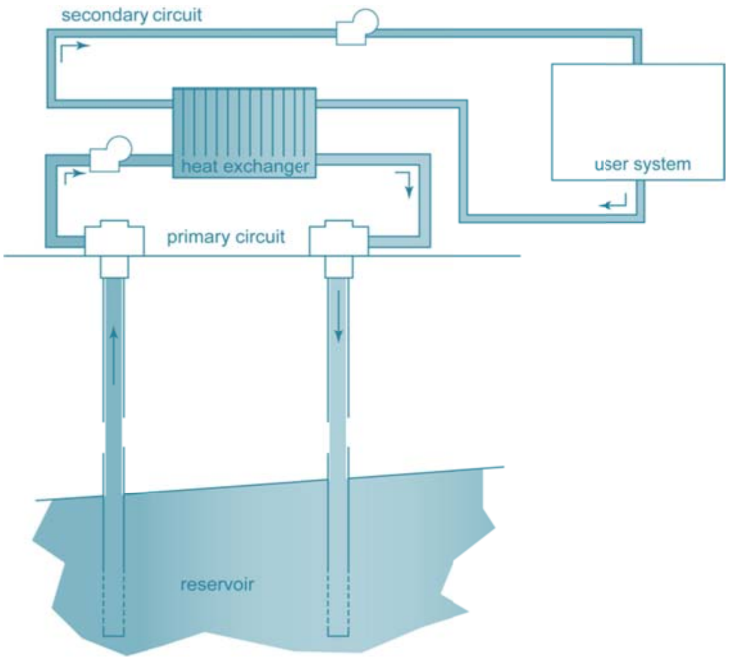

Figure 16. Indirect groundwater heat pump system used in an open loop system

The sizing criterion for a groundwater system is the groundwater flow; the system size is not measured in units of length (e.g. metres of tubing for closed-loop systems), but rather in units of flow, measured in litres of groundwater per second. Groundwater flow is determined by the greater of the flows required for cooling design conditions and for heating design conditions. Determination of the flow requirements is based on the fundamental equation for thermal capacity:

$$\dot{m}_{heat} = \frac{Q_{d,heat}}{\rho C_p (T_{g,wi} - T_{g,wo})} \frac{(COP_h - 1)}{COP_h} \qquad (61)$$

$$\dot{m}_{cool} = \frac{Q_{d,cool}}{\rho C_p (T_{g,wo} - T_{g,wi})} \frac{(COP_c + 1)}{COP_c} \qquad (62)$$

where m_{heat} and m_{cool} are the required well water flow rate for heating and cooling, $Q_{d,heat}$ and $Q_{d,cool}$ are the design heating and cooling heat pump capacities, COP_h and COP_c are the heat pump performances at design heating and cooling conditions, ρ is the density of water, C_p is the specific heat of water, and $T_{g,wi}$ and $T_{g,wo}$ are the groundwater temperatures entering and leaving the intermediate heat exchanger located between the earth connection and the heat pump as shown in Figure 16.

As a first approximation, the groundwater temperature $T_{g,wi}$ is assumed to be equal to the mean annual surface soil temperature T_g.

In order to complete the evaluation of equations (61) and (62), the temperature of groundwater leaving the intermediate heat exchanger ($T_{g,wo}$) must be evaluated. This can be achieved by the following two design methods, referring to Figure 16:

- Select an approach temperature ΔT_a between the building return temperature ($T_{b,r}$) and the groundwater temperature leaving the intermediate heat exchanger ($T_{g,wo}$). This approach temperature design method is explained below in this section;

Or

- Select a value for the heat pump heating and cooling design entering water temperature (T_{ewt}). Since this design entering water temperature T_{ewt} value selection design method requires the calculation of elements that specifically belong to heat pump system, it is explained later that the building supply temperature $T_{b,s}$ is close to T_{ewt}.

42. Approach temperature design method

Typical values for the approach temperatures as well as for the design entering water temperatures are:

$$T_{b,s} \approx T_{ewt} = 23.9°C \qquad \text{(cooling)} \qquad (63)$$

$$T_{b,s} \approx T_{ewt} = (7.2°C, \overline{T_g} - 2.8°C) \qquad \text{(cooling)} \qquad (64)$$

$$\Delta T_a = 2.8°C \qquad \text{(cooling)} \qquad (65)$$

where $\overline{T_g}$ is the mean annual surface soil temperature.

For heating conditions, the required intermediate heat exchanger groundwater leaving temperature ($T_{g,wo}$) can then be derived from:

$$T_{g,wo} = T_{b,r} + \Delta T_a \qquad (66)$$

$$(T_{b,r} - T_{b,s}) = \frac{Q_{d,heat}}{\rho_{building} C_{p,building} \dot{m}_b} \frac{(COP_h - 1)}{COP_h} \qquad (67)$$

where $\dot{m}_b$ is the flow rate in the heat pump building loop, and $\rho_{building}$ and $C_{p,building}$ are the density and the specific heat of the liquid in the building loop.

Substituting equation (67) into (66) leads to:

$$T_{g,wo} = T_{b,s} + \frac{Q_{d,heat}}{\rho_{building} c_{p,building} \dot{m}_b} \frac{(COP_h - 1)}{COP_h} + \Delta T_a \qquad (68)$$

The typical flow rate value of the fluid in the heat pump building loop (m_b) recommended by groundwater-source heat pump manufacturers is 3 usgpm/Ton of installed cooling capacity.

Similarly for cooling conditions, the temperature of groundwater leaving the intermediate heat exchanger ($T_{g,wo}$) is expressed as:

$$T_{g,wo} = T_{b,s} + \frac{Q_{d,cool}}{\rho_{building} c_{p,building} \dot{m}_b} \frac{(COP_c - 1)}{COP_c} - \Delta T_a \qquad (69)$$

Resolving equations (68) and (69) gives the temperature of groundwater leaving the intermediate heat exchanger ($T_{g,wo}$) that is necessary to resolve equations (61) and (62), which in turn allow to size the earth connection (e.g. the open loop system) by the determination of the required design well flow rate (m) for heating and cooling.

43.Heat Pump System

This section presents the modelling elements associated with the heat pump system. The calculation of these elements is necessary to finalize the earth connection sizing of either closed-loop ground heat exchangers (GHXs) or open loop systems (groundwater). The heat pump coefficient of performance (COP), and their related capacity ($Q_{c/h}$) are evaluated first, followed by the determination of the heat pump entering water temperature for both types of earth connection.

44.Coefficient of performance (COP) and capacity (Qc/h)

The coefficient of performance (COP) of a heat pump system is a function of the entering water temperature. The ground heat exchanger load and heat pump useful capacity are linked through:
For cooling:

$$Q_c = Q_{he,c} \frac{COP_c}{COP_c + 1} \qquad (70)$$

For heating:

$$Q_h = Q_{he,h} \frac{COP_h}{COP_h - 1} \quad (71)$$

where Q_c is the heat pump cooling capacity at the evaporator, $Q_{he,c}$ is the heat rejected to the GHX at the heat pump condenser in cooling mode, Q_h is the heat pump heating capacity at the condenser, and $Q_{he,h}$ is the heat extracted from the GHX at the heat pump evaporator in heating mode.

The method used to model the COP and the capacity as a function of the entering fluid temperature uses a quadratic polynomial correlation:

$$COP_{actual} = COP_{baseline}(k_0 + k_1 T_{ewt} + k_2 T_{ewt}^2) \quad (72)$$
$$Q_{c/h} = \lambda(\lambda_0 + \lambda_1 T_{ewt} + \lambda_2 T_{ewt}^2) \quad (73)$$

where COP_{actual} is the actual COP of the heat pump, $COP_{baseline}$ is the nominal COP of the heat pump (e.g. measured at standard rating conditions, 0°C for heating and 25°C for cooling), $Q_{c/h}$ is the capacity of the heat pump for cooling or heating, and k_i and λ_i are correlation coefficients listed in Table 6. Finally, λ is a capacity multiplier, calculated so that the system meets either the building's heating or cooling load.

Table 6. Polynomial correlation coefficients used in equations (72) and (73)

Correlation coefficients		Cooling	Heating
COP	k_0	1.53105836E+00	1.00000000E+00
	k_1	-2.29609500E- 02	1.55970900E- 02
	k_2	6.87440000E- 05	-1.59310000E- 04
Capacity	λ_0	1.41186164E+00	6.67872140E- 01
	λ_1	-2.56202000E- 03	2.79889800E- 02
	λ_2	-7.24820000E- 05	-1.06360000E- 04

When the cooling load is used as the design criteria, the heat pump capacity is selected based only on the required heat pump capacity necessary to meet the cooling load. If the resulting heating capacity is insufficient, the model assumes that auxiliary heat will be available. The auxiliary heat will then have the same efficiency and energy source as the base case Heating, Ventilation, Air Conditioning (HVAC) system. The resulting capacity multiplier λ is then expressed as:

$$\lambda = \frac{q_{d,cool}}{\lambda_0 + \lambda_1 T_{ewt,max} + \lambda_2 T_{ewt,max}^2} \qquad (74)$$

where $q_{d,cool}$ is the design cooling load and $T_{ewt,max}$ is the maximum entering water temperature.

When heating is selected as the design criteria, the capacity multiplier λ is the greater of equations (74) and (75):

$$\lambda = \frac{q_{d,heat}}{\lambda_0 + \lambda_1 T_{ewt,min} + \lambda_2 T_{ewt,min}^2} \qquad (75)$$

where $T_{ewt,min}$ is the minimum entering water temperature. The maximum value of the capacity multiplier λ from equations (74) or (75) is retained since the GSHP model assumes that the cooling needs must, at a minimum, be met by the installed heat pumps.

45.Entering water temperature (Tw,i) for closed-loop ground exchanger

To evaluate the heat pump coefficient of performance (COP) and their related capacity ($Q_{c/h}$) for each temperature bin, a linear interpolation method was developed based on a procedure presented in IGSHPA (1988). The interpolation method is summarised in Figure 17. For a given bin temperature $T_{bin,i}$, the temperature $T_{w,i}$ of water entering the heat pump is simply:

$$T_{w,i} = T_{min} + \left(\frac{T_{ewt,max} - T_{ewt,min}}{T_{d,cool} - T_{d,heat}}\right)\left(T_{bin,i} - T_{d,heat}\right) \qquad (76)$$

where T_{min} represents the point where the curve cuts the y-axis and all other variables were previously defined.

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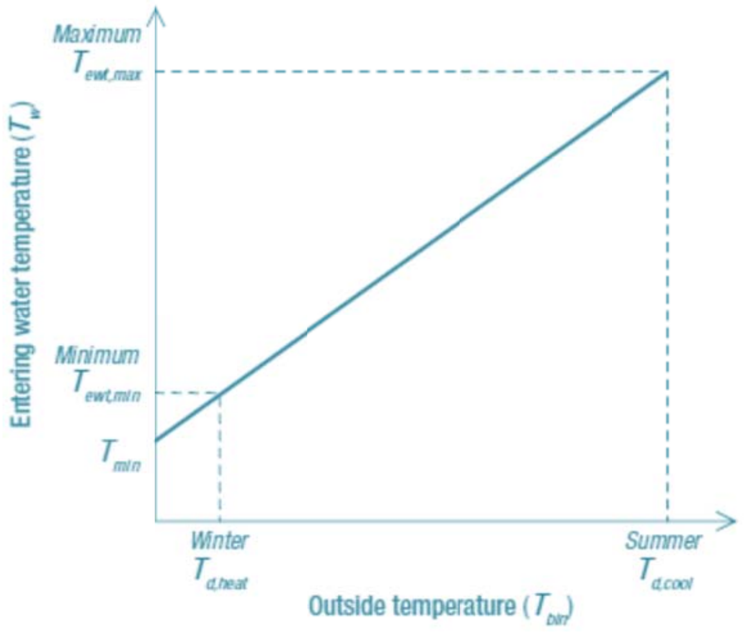

Figure 17. Determining entering water temperature as a function of outside temperature

46. Entering water temperature (Tewt) for open-loop (groundwater) systems

For groundwater systems, the entering water temperature into the heat pump is linked to the groundwater temperature and the building load by combining equation (68) with the following equation for the intermediate heat exchanger capacity on the ground loop side:

$$Q_{g,he} = \rho C_p \dot{m}_g (T_{g,wi} - T_{g,wo}) \qquad (77)$$

where $Q_{g,he}$ is the intermediate heat exchanger capacity, ρ is the density of water, C_p the specific heat of water, and $m_g$is the water flow on the ground loop side of the heat exchanger.
Solving for $T_{b,s}$ as a function of $T_{g,wi}$ gives the required relation for the entering water temperature (T_{wi}):

For heating:

$$T_{b,s} = T_{g,wi} - \left(\frac{Q_{he,h}}{\rho C_p \dot{m}_g}\right) - \left[\left(\frac{q_{d,heat}}{\rho C_p \dot{m}_b}\right)\left(\frac{COP_h - 1}{COP_h}\right)\right] - \Delta T_a \qquad (78)$$

For cooling:

$$T_{b,s} = T_{g,wi} - \left(\frac{Q_{he,c}}{\rho C_p \dot{m}_g}\right) - \left[\left(\frac{q_{d,cool}}{\rho C_p \dot{m}_b}\right)\left(\frac{COP_c+1}{COP_c}\right)\right] + \Delta T_a \qquad (79)$$

An additional term can be added to equations (78) and (79) to account for the temperature rise attributable to the groundwater pump. This term is expressed as:

$$\Delta T_{pump} = T_{ewt} - T_{b,s} = \frac{q_{pump}}{\rho C_p \dot{m}_g} \qquad (80)$$

The pump power q_{pump} is obtained as the work required to rise the water over a height Δh from the pumping depth to the surface, plus a constant additional height Cst to account for the remainder of the groundwater loop losses:

$$q_{pump} = \frac{\rho g m_g (\Delta \dot{h} + Cst)}{\eta_{pump}} \qquad (81)$$

where η_{pump} is the pump efficiency and g is the acceleration due to gravity (9.81 m/s2). The value of Cst is set to 50 feet (15.24 m) of water.

47.Energy Use Evaluation

The energy use evaluations presented in this section concern the energy use by auxiliary pumps that serve to meet the heating or cooling loads that are not covered by the GSHP system.

48.Heat pump run time and energy use of auxiliary pumps

The theoretical heat pump Run Time is simply calculated for each temperature bin as:

$$RunTime = \frac{q_{tot}}{Q} \qquad (82)$$

where q_{tot} is the building load and Q is the heat pump capacity. The heat pump part load factor F is calculated as:

$$F = \frac{RunTime}{1 - c_d(1 - RunTime)} \qquad (83)$$

where c_d is an empirical factor (set to 0.15) accounting for the transient start/stop performance penalties. This factor is commonly known as the degradation coefficient. The smaller the values of Run Time the greater the penalty due to the degradation coefficient.

The electric energy use of the heat pump and auxiliary pumps is evaluated for every temperature bin. The heat pump electric demand is simply calculated as:

$$\mathrm{HP}_{\mathrm{e,demand}} = \frac{\mathrm{Capacity}}{\mathrm{COP}} \qquad (84)$$

The auxiliary building loop pumping power is assumed to be 17W per kW of installed cooling capacity. The groundwater system pumping power is obtained by dividing equation (81) by a motor efficiency.

49.Supplemental heating or cooling needs

The supplemental heating or cooling needs are determined for each temperature bin simply by the difference of the building load minus the capacity of the heat pump. The electric energy $\mathrm{Q_e}$ used by the heat pump and auxiliary pumps is:

$$\mathrm{Q_e} = \mathrm{Bin(h)}\left[\left(\mathrm{HP}_{\mathrm{e,demand}}\mathrm{F}\right) + \mathrm{AUX_e}\right] \qquad (85)$$

where $\mathrm{Bin(h)}$ is the number of hours in the bin, F is the heat pump part load factor and $\mathrm{AUX_e}$ is the sum of all auxiliary electrical demands.

The design auxiliary heating load is calculated by subtracting the heat pump system’s heating capacity at minimum entering water conditions from the building design load. The design supplemental heat rejector load is calculated by subtracting the GHX capacity at maximum entering water conditions from the building design cooling load.

50.Summary

In this course the algorithms for Ground-Source Heat Pump (GSHP) project model have been shown in detail. As inputs, the model requires weather data, building data, and GSHP related data. The modified bin method allows the estimate of building loads. Weather data are used to generate temperature bins and calculate the temperature of the ground. Building data are used to calculate heating and cooling load vs. temperature relationships and the building's balance points. Combining weather and building data enables the calculation of building loads for each temperature bin. With the GSHP related data, it then becomes possible to evaluate the actual heat pump performance and capacity for each temperature bin, and finally calculate the yearly performance of the GSHP system assessed.