Ground Source Heat Pump Development Assessment

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GROUND SOURCE HEAT PUMP DEVELOPMENT ASSESSMENT

This course covers the assessment of potential ground-source heat pump developments including a technology history and a detailed explanation of the computation methodologies.

Ground-source Heat Pump History

Keeping a comfortable temperature inside a building can require a large amount of power. Separate heating and cooling schemes are usually utilized to keep the required air temperature, and the power requirement to run these schemes usually comes from electricity, fossil fuels, or biomass. Considering that 46% of the sun's power is absorbed by the earth, another alternative is to use this abundant power to heat and cool a building.

In contrast to many other resources of heating and cooling power which require to be transferred over long distances, earth power is available on-site, and in massive amounts.

Because the ground transports heat slowly and has a high heat storage size, 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 utilized in the winter. This yearly, continuous cycle between the air and the soil temperature results in a thermal power potential that can be collected to help heat or cool a building. Another thermal feature 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 required. The earth is warmer than the ambient air in the winter and cooler than the ambient air in the summer.

This warm earth and groundwater below the surface provides a free alternative source of power that can easily give enough power year-round to heat and cool a mean suburban residential home, for example. A Ground-Source Heat Pump (GSHP) converts this earth power into useful power 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 main usage is space heating and cooling, though many also supply hot water, such as for domestic use. It can even be utilized to keep the integrity of building foundations in permafrost circumstances, by keeping them frozen through the summer.

A heat pump is utilized to concentrate or upgrade this free heat power from the ground before transferring it in a building through conventional ducts. It runs much as a refrigerator or conventional air conditioning scheme in that it relies on an external source of power (usually electricity) to concentrate the heat and shift the temperature. Usually, each kilowatt (kW) of electricity utilized to run a GSHP scheme draws more than 3 kW of alternative power from the ground. Heat pumps usually range from 3.5 to 35 kW in cooling size (about 1 to 10 refrigeration tons), and a single kit is usually sufficient for a house or a small commercial building. For larger commercial, institutional or industrial buildings, multiple heat pump sets will usually be employed.

Since a GSHP scheme does not directly produce any combustion products and because it draws free power from the ground, it can actually produce more power than it uses. Because of this, GSHP efficiencies routinely mean 200 to 500% over a season. GSHP schemes 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 usually have lower servicing prices. They require less space, particularly when a liquid building loop replaces voluminous air ducts, and are not prone to vandalism like conventional rooftop sets. Peak electricity consumption during cooling season is lower than with conventional air-conditioning, so utility requirement charges may be also decreased.

For the above reasons, large power reductions can be met through the use of GSHPs in place of conventional air-conditioning schemes and air-source heat pumps. Reductions in power consumption of 30% to 70% in the heating mode and 20% to

50% in the cooling mode can be achieved. Power reductions are even higher when compared with combustion or electrical resistance heating schemes. This potential for large power reductions has led to the use of GSHPs in a variety of usages.

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

The following paragraphs define the main elements of a GSHP scheme (heat pumps, earth connection, and distribution scheme) and discuss the GSHP markets for residential, commercial, and institutional building type usages.

Explanation of Ground-Source Heat Pump Schemes

A ground-source heat pump (GSHP) scheme has three major elements:

- Heat pump
- Earth connection
- Interior heating or cooling distribution scheme (Figure 1).

These three major elements, together with the different earth connection arrangements of a usual GSHP installation, are defined in the following paragraphs.

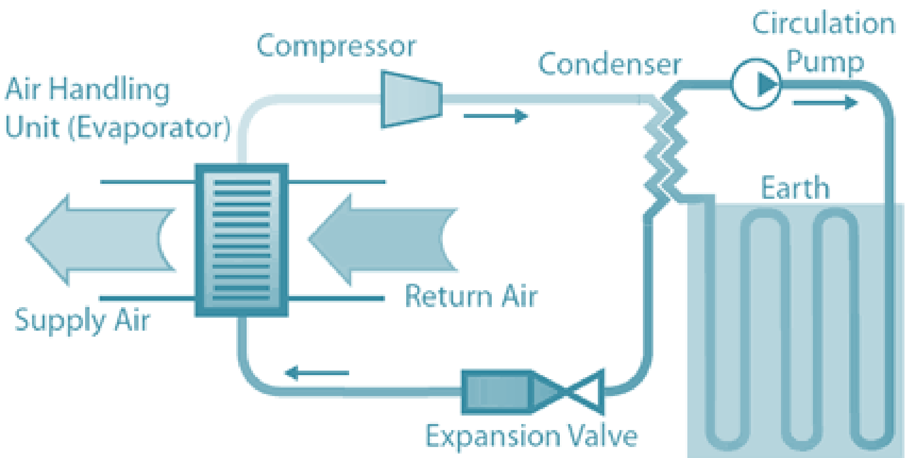

Figure 1. Major GSHP elements

Heat pump

The heat pump carries over the heat between the heating/cooling distribution scheme and the earth connection. It is the basic building block of the GSHP scheme.

The most common type of heat pump utilized with GSHP schemes is a "water-to-air" kit ranging in size from 3.5 kW to 35 kW of cooling size. The water-to-air designation suggests that the fluid carrying heat to and from the earth connection is water or a water/antifreeze mix and that the heat distribution scheme inside the building relies on hot or cold air. The heat pump may be an extended range kit, allowing lower entering fluid temperatures in heating mode and higher entering fluid temperatures in cooling mode.

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

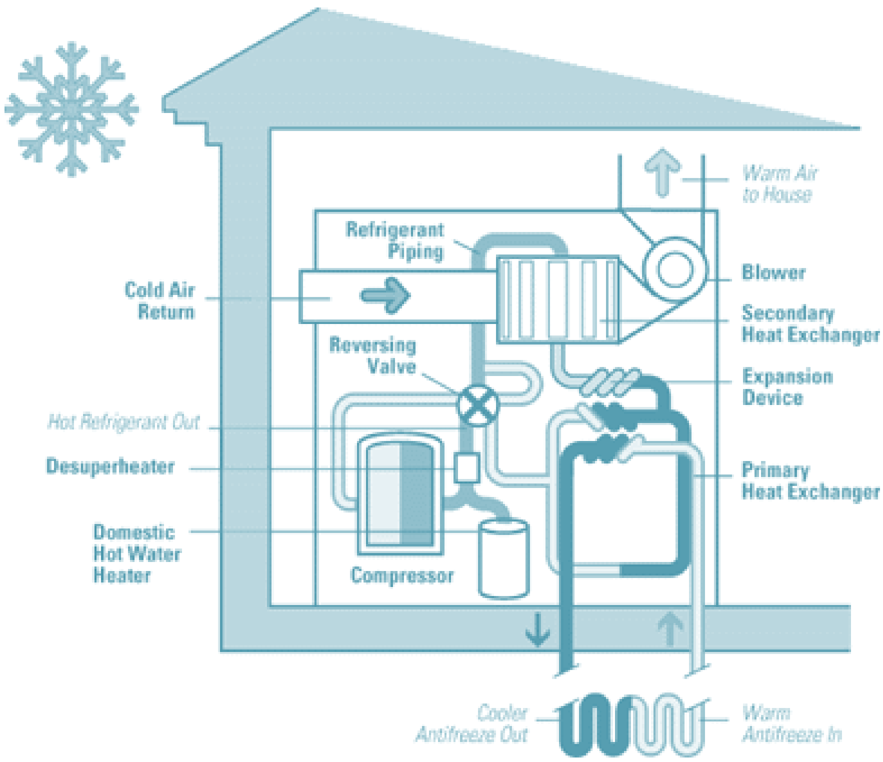

Figure 2. Usual heat pump kit

For residential usages and small commercial schemes, a single heat pump kit will suffice. For larger commercial, institutional or industrial schemes, multiple heat pump sets are usually utilized in a distributed network connected to a common fluid loop.

The heat pump runs using the identical 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 uses 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 required direction anyway. The heat pump may still be required to run, 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).

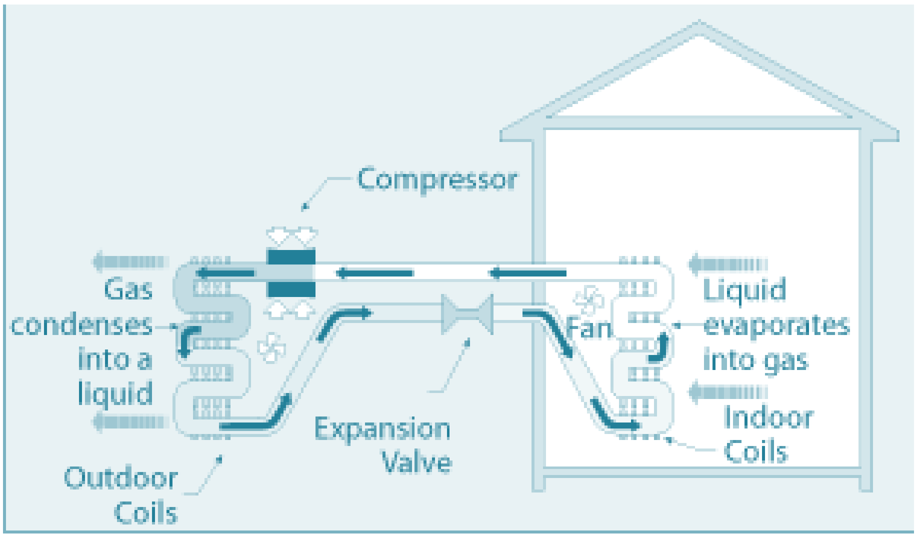

Figure 3. Heating mode of a usual packaged heat pump kit

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 carries over 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 largely. 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 large 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 carries over 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 give all the hot water required in a residential usage. Some residential heat pumps are designed to give hot water year round in amounts sufficient to meet a household's requirements.

Earth connection

The earth connection is where heat transfer between the GSHP scheme and the soil occurs. GSHPs comprise a wide variety of schemes 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 schemes:

- 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) - keep sound structural fill in natural permafrost around foundations by extracting heat from the fill.

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

Ground-Coupled Heat Pumps (GCHPs): In a GCHP scheme, a series of buried pipes circulates a heat transfer fluid in a closed loop. The fluid never leaves the scheme, 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 meters 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 required, 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 usually 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 utilized 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 usual vertical GHX scheme.

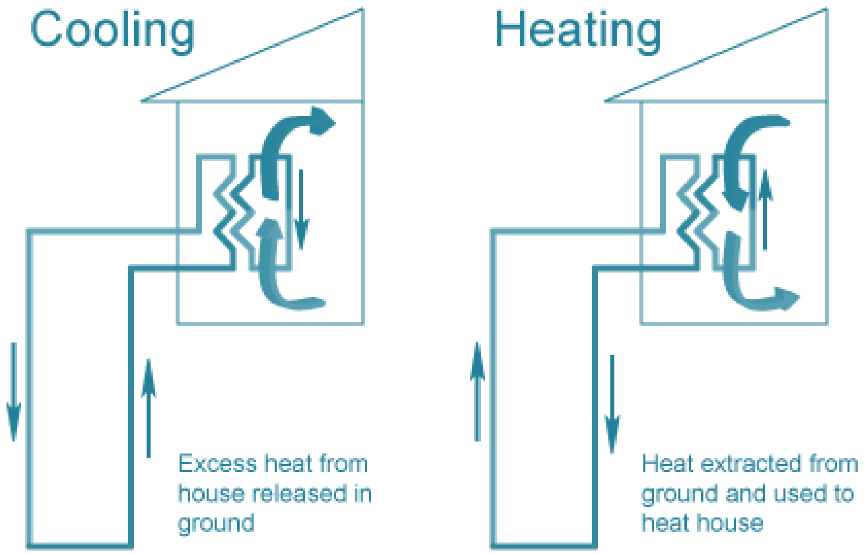

Figure 5. Vertical Ground Heat Exchanger (GHX)

The horizontal GHX configuration is usually 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 usages such as residential and small commercial buildings. It can be particularly appealing if excavating and trenching equipment is available and when the upper few meters of the ground are amenable to excavation.

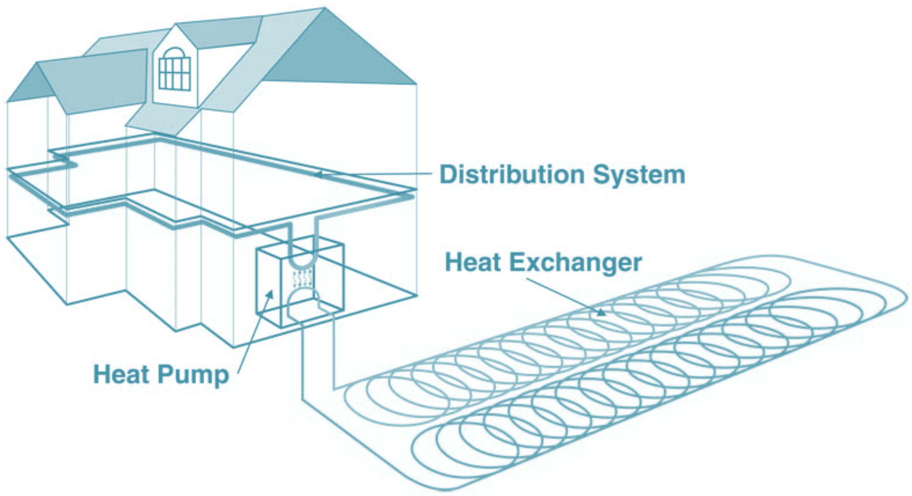

Figure 6. Horizontal Ground Heat Exchanger (GHX)

A horizontal GHX consists of a series of pipes laid out in trenches, usually one to two meters below the surface. Usually, about 35 to 55 meters of pipe are installed per kW of heating and cooling size. Many arrangements 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 utilized in order to fit more piping into a trench area. While this reduces the amount of land utilized, it requires more pipes, which results in free prices. The trench is backfilled once the pipe has been laid out.

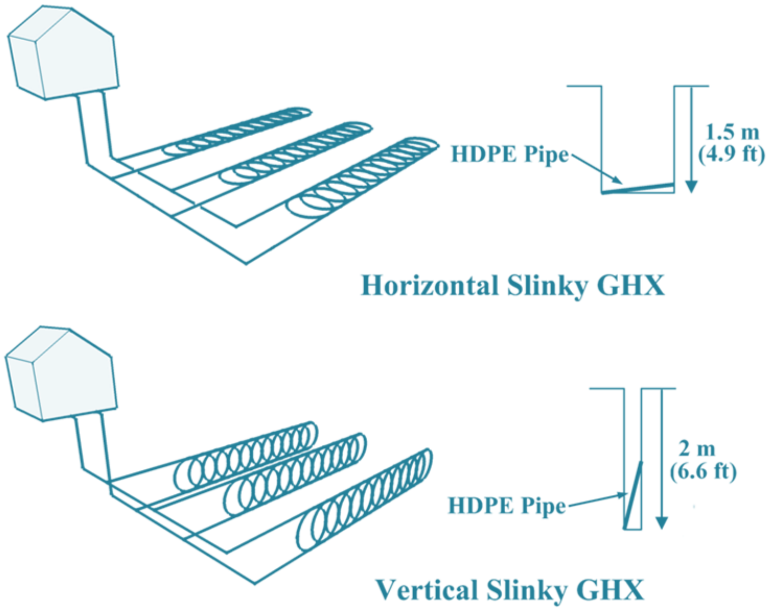

Figure 7. Various configurations of horizontal ground heat exchangers

Groundwater Heat Pumps (GWHPs): Groundwater heat pump schemes are, in contrast to GCHPs, open loop schemes. 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 carries over 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 identical aquifer via a second well, called an injection well.

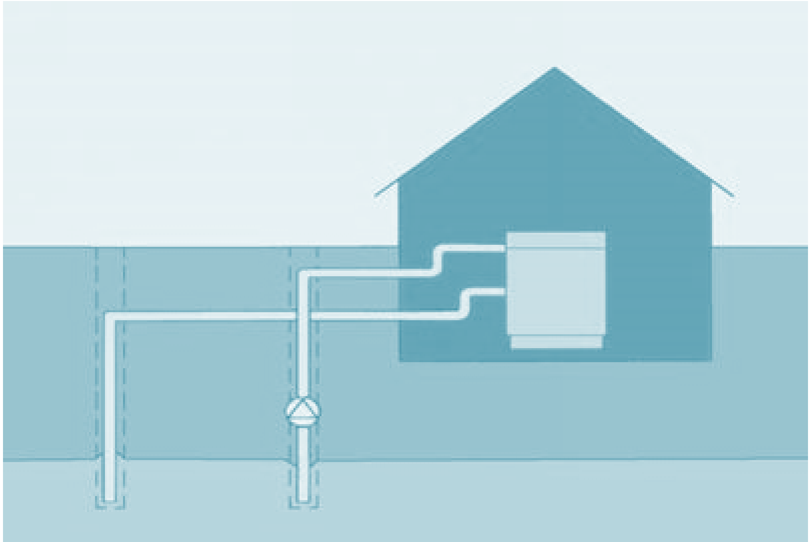

Figure 8. Ground water heat pump scheme

The GWHP was the first type of GSHP to appear on the market, and GWHPs have been utilized successfully for decades. They are the simplest type of scheme 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 scheme. Standing wells are usually six inches in diameter and may be as deep as 450 meters. In this scheme, water from the bottom of the well is pumped to the building's heat exchanger and returned to the top of the identical well. The well may also give potable water. For this scheme to work adequately, ground water must be in abundant supply. This type of scheme is not utilized where the water table is particularly deep, since the required pumping power renders the scheme prohibitively expensive.

Surface Water Heat Pumps (SWHPs): The surface water heat pump is a viable and relatively low-cost GSHP alternative. A series of coiled pipes submerged below the surface of a lake or pond serve 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 scheme, avoiding adverse impacts on the aquatic eco-scheme. Many successful schemes are currently in operation.

Ground Frost Heat Pumps (GFHPs): Another specialized usage 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 give up to 20 to 50% of the building's space heating requirements, and the prices of traditional measures for keeping 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 free 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 identical rate as it is gained from the foundation in order to keep 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 power 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 keep the pad in a frozen state should the heat pump become temporarily inoperative.

Heating and cooling distribution scheme

The heating/cooling distribution scheme delivers heating or cooling from the heat pump to the building. It usually takes the form of an air duct distribution scheme, even though water loop schemes (also known as hydronic schemes), which heat or cool floors and ceilings are also utilized. Heating and cooling distribution in a GSHP scheme is usually identical as in conventional schemes. 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 schemes that can be utilized are well documented and consist mainly of air ducts, diffusers, fresh air supply schemes and control elements.

Ground-Source Heat Pump Usage Markets

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

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

GSHPs usually have lower life-cycle prices than conventional schemes due to their efficiency and lower servicing requirements.

Markets for GSHPs tend to be particularly strong when climate, power prices and the nature of the development are favourable. First, a climate requiring both heating and cooling is preferable to one that requires just one or the other. While the identical GSHP scheme can give both heating and cooling, two separate conventional schemes may be requirement, 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 appealing alternative. Furthermore, since it runs year-round, the GSHP scheme can produce larger power reductions, rather than, for example, an air-conditioning kit which only runs in the summer and an oil furnace which only runs in the winter.

Second, large seasonal variations in temperature will favor the GSHP scheme over air-source heat pumps, whose size and efficiency decrease at temperature extremes and ensure that there is large power requirement on which the GSHP can produce reductions.

Third, if there is already a useable heating and cooling scheme installed, the purchase and installation of a GSHP is rarely justified on the basis of its power benefits alone. Thus, the GSHP is most cost-effective in new development, particularly since this facilitates trenching and drilling, or when an existing heating and cooling scheme has reached the end of its life and must be replaced.

If heating is the dominant power requirement, then low electricity prices and high gas or oil prices will make the GSHP more appealing than combustion schemes. If cooling is dominant, then high electricity prices will favor 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 scheme is decreased but supplemental heating or heat rejection size becomes necessary. Supplemental size usually entails heating using conventional schemes and cooling towers for heat rejection.

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

Residential buildings

While GSHPs are utilized for all types of residential buildings, high-end residential development tends to be the focus of this market. The higher initial prices of the GSHP do not constitute a particularly large fraction of these expensive homes, and the homeowners usually view the GSHP scheme 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 usually 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 scheme's environmental benefits accrue to society as a whole, and therefore the initial prices should not be borne by the scheme's owner alone. Regardless, such a subsidy can be a major consideration in the homeowner's decision to install a GSHP.

Commercial & institutional buildings

The viability of GSHPs for commercial buildings can be impeded by requirements for short simple payback periods, usually 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 appealing 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 met 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 sets, cooling towers and chimneys reduces opportunities for vandalism. Moreover, with enhanced efficiency over conventional air conditioners, the ground-source heat pump reduces summertime peak load charges usually levied by utilities on commercial customers.

Large buildings using GSHPs have multiple heat pump sets, located around the building, transferring heat to and from a common building loop. This arrangement is very beneficial. First, large buildings usually have simultaneous heating and cooling loads: for example, the core of the building may require cooling while perimeter areas require heating. The common building loop can transfer heat from cooling loads to heating loads, reducing the requirement 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 scheme. Third, the common building loop carries over heat using a liquid, which permits it to be much more compact than the ducting requirements by air distribution schemes 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 utilized in commercial usages 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 usually 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 requirement for heating and cooling, which the building loop of a ground-source heat pump scheme can take advantage of.

Ground-source Heat Pump Development Model

Ground-Source Heat Pump Development Model can be utilized to evaluate ground-source heat pump developments, from large-scale commercial, institutional or industrial usages to small residential schemes. The types of scheme 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 defines the various algorithms utilized to calculate the power production (or reductions) of GSHP schemes. A flowchart of the algorithms is displayed in Figure 9. The model initially establishes the building load equation, which defines 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 check whether or not heating or cooling is required for each bin. From the weather data and the building load, the required heat pump size is approximated.

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

There are some limitations to the methodology chosen to make the computation in the GSHP development model. In some instances, the model cannot capture phenomenon such as simultaneous heating and cooling requirements, which can sometimes occur in commercial buildings; neither can it capture complex building usage profiles. Residential usages 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 development model include:

- The long-term thermal imbalances are not included in the ground heat exchanger (GHX) computations.

- The ground-coupled heat pump (GCHP) horizontal ground heat exchanger (GHX) configuration considered is a stacked two pipe scheme

- The ground-coupled heat pump (GCHP) vertical ground heat exchanger (GHX) configuration consists of one U-tube per borehole.

- The building heating and cooling power consumption and peak loads are evaluated using a simplified version of ASHRAE's modified bin methodologies (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, a development model can be utilized for the initial evaluation of ground-source heat pump schemes and is sufficiently accurate for the pre-feasibility and feasibility stages of development.

Bin Methodologies and Design Circumstances

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

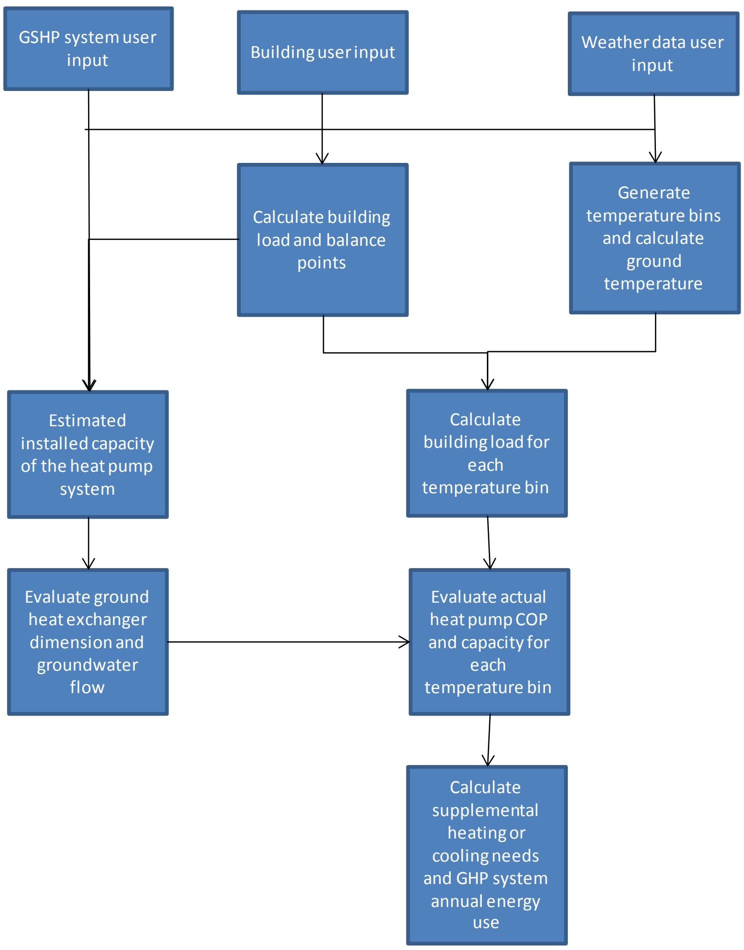

Figure 9. Ground source heat pump power model flowchart

Such a methodology, called the bin methodology, has been utilized widely for many years to estimate power use by buildings (ASHRAE Handbook, Fundamentals, 1981, 1985). In this temperature frequency methodology, the hours in a year are summed into a finite number of bins based on temperatures. Each bin redelivers the middle, or mean, of the temperature range for that bin. For instance, Table 1 delivers an example of 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 higher or equal to – 21°C. A basic level of time dependency can also be incorporated in the bin methodology. This is met 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 scheme temperature-dependant behavior and time-dependant parameters, and estimate the scheme's annual power use. A further refinement of the methodology, called the modified bin methodology, is presented in the ASHRAE Handbook, Fundamentals (1985). This methodology allows for off-design computations by using an approximated diversified load rather than peak load values in establishing the building's load as a function of temperature.

Using the modified bin methodology allows for estimating the power requirement from the building, but the GSHP scheme's heat pumps and ground loop performances are still required to be addressed. Fortunately, the bin methodologies can readily be extended for treating GSHP schemes.

It should be noted that some parts of the GSHP model are concerned chiefly with sizing, for example when determining heating or cooling power requirement or the length of the ground heat exchanger or the groundwater flow in an open-loop scheme. In these cases, computations are then performed for extreme circumstances called the design circumstances. For example, the heating design temperature redelivers 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 redelivers 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 power use or supplemental power delivered. This requires evaluating the performance of the scheme over the whole year, that is, for all temperature bins.

Weather Data

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

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. Freely, bin data for the coldest and hottest months (corresponding to design heating and cooling circumstances) are required for the ground loop computation. Such data requirements would render the model impractical. Alternatively, storing the data within the model would translate into an excessively large file if a moderate number of locations around the world were to be included.

Ground temperature estimation

The methodologies for sizing the ground heat exchanger (GHX) requires knowledge of the minimum and maximum ground temperature at the GHX depth. Ground temperature is also utilized 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 schemes or shallow vertical boreholes, X_S can be set equal to the mean depth in equations (1) to (3). For vertical schemes, this usually becomes a trivial task since the sub-surface ground temperature does not vary largely over the course of the year; ground temperature can then be approximated as equal to the mean annual surface soil temperature, T_g.

Building Load Computation – Descriptive Data Methodologies

Commercial (institutional) & industrial buildings

In a simplified approach, it is difficult to evaluate complex internal building behavior, such as individual zone requirement, due to the large amount of data a user would require 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 circumstances. 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 circumstances. Figure 10a illustrates the block load approach while Figure 10b shows how a building is usually 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.

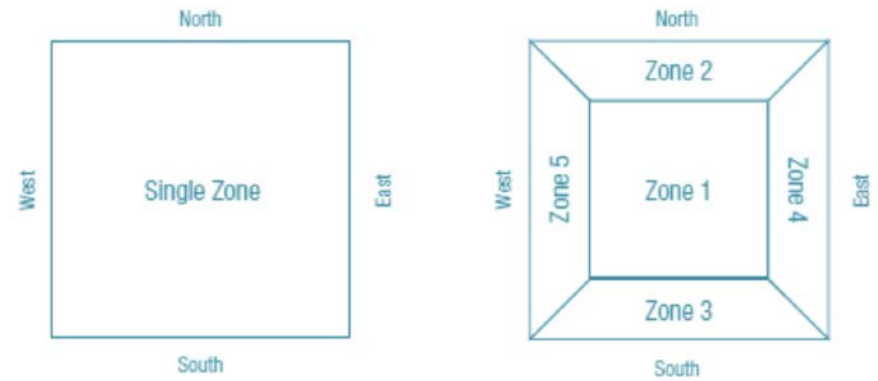

Figure 10. Block load vs. zoned building approach

Relationships between outside temperature and the various building heating and cooling load elements must be made. The following load elements are treated in GSHP development 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 displayed 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 deducted from physical building features related to source j. The global building load equation as a function of outside air temperature can be achieved through a summation of all n load elements:

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

which can be written in short form as:

$$q_{tot} = c_0 + c_1T_0 + c_2T_0^2 \qquad (8)$$

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

CI1 - Transmission losses (conductive and convective)

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

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

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 get the required form of Equation (5), with:

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

$$c_1 = \sum_i (UA)_i \tag{11}$$

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

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

where U_{wall} is the heat transfer coefficient (also called “U-value”) for exterior walls, which depends on the type of insulation utilized (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):

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

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

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

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

CI2 - Solar gains (sensible)

The treatment of solar gains through windows redelivers a special challenge for a simplified process such as the bin methodologies. To get the relationship such as in Equation (5), the bin methodologies assume that there is a linear correspondence between outdoor temperature and the amount of solar gains in a building, as displayed in Figure 11.

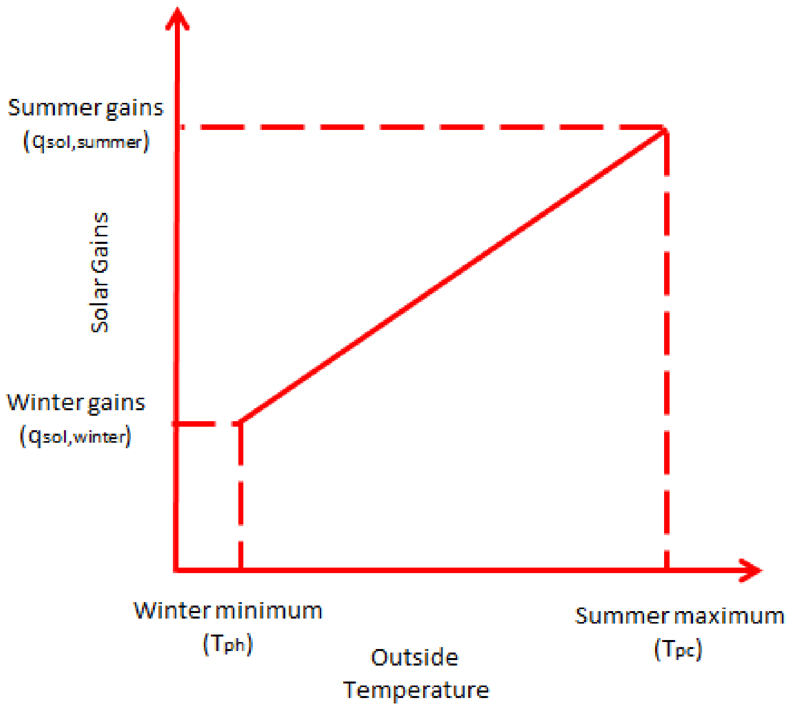

Figure 11. Solar gains as a function of outside temperature

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:

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

$$c_1 = S_c M \qquad (17)$$

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

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

where $q_{sol,winter}$ and $q_{sol,summer}$ are the mean 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 mean temperatures. The design day mean temperatures are achieved from the heating and cooling design day temperatures $T_{d,heat}$ and $T_{d,cool}$:

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

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

where DR is the mean daily temperature range, also defined by the user. The computation of the winter and summer mean solar gains is based on the ASHRAE's Cooling Load Factor (CLF) methodologies. For the modelling requirements, the solar gain using this methodology is expressed as:

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

where ori is the orientation (North, East, South, West) assumed in the GSHP development model, with the season being 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 the season, nh_{season} is the number of operating hours of air conditioning equipment for the season, and S_c is, as before, the building conditioned floor area.

Usual 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, the 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). Therefore, it becomes possible to factor out all constant parameters in Equation (21), which becomes:

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

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 identical reference. Consequently, the summation term in Equation (22) depends only on month and latitude.

CI3 - Internal gains (sensible)

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

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

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

Table 2. Gain level

Gains Level	Lights (W/m^2)	Equipment (W/m^2)
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 defined by the user. The model assumes that commercial and institutional buildings have 5 persons per 100 m^2 while industrial buildings have 1 person per 100 m^2 of floor area.

CI4 - Fresh air load (sensible)

The load due to outside air entering the building is approximated 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/m^2, C_p=1.005 (kJ/kg)/°C). The amount of fresh air entering the building, from all resources, is approximated 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 decreased to 10 L/s for thermal balance computations.

CI5 - Fresh air load (latent)

The latent load considered in the GSHP model affects only air-conditioning requirements. The model does not consider any type of humidification requirements during the heating season. The conventional methodologies 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 get the water content in both streams. From the water content, and the enthalpy of saturated water vapor, 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 vapor 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 methodology was adopted to allow for a basic evaluation of the fresh air latent load. In the GSHP development model, the user needs to define the development location's humidity level. From this qualitative information, the model produces an equivalent fresh air latent load proportional to the sensible load and linearly correlated to outside temperature, as displayed 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 mean temperature range, DT, were checked 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 displayed in Figure 12 can produce negative loads at sufficiently low exterior temperatures.

Table 3. Maximum latent to sensible fraction

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

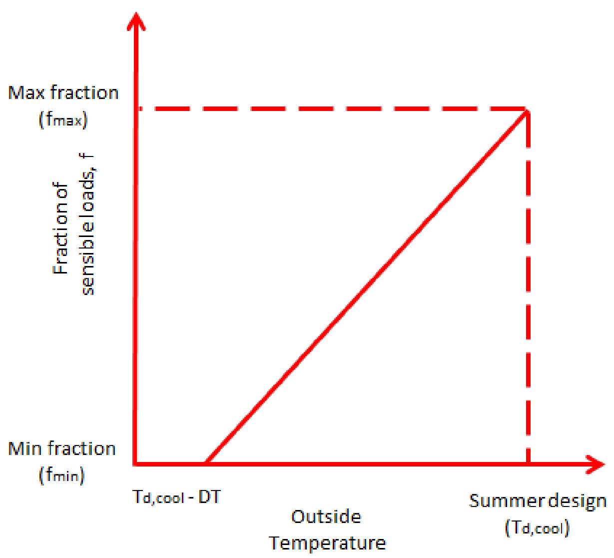

Figure 12. Latent and sensible fresh air load as a function of outside temperature

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

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

$$f = aT_0 + b \quad for \quad T_0 > 10°C \tag{29}$$

$$f = 0 \quad for \quad T_0 < 10°C \tag{30}$$

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

$$a = \frac{f_{max} - f_{min}}{DT} \tag{31}$$

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

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

$$q_{f,lat} = c_0 + c_1 T_0 + c_2 T_0^2 \tag{33}$$

with:

$$c_0 = b\,\rho\,C_p\,\dot{V}\,T_{in} \tag{34}$$

$$c_1 = a\,\rho\,C_p\,\dot{V}\,T_{in} - b\,\rho\,C_p\,\dot{V} \tag{35}$$

$$c_2 = -a\,\rho\,C_p\,\dot{V} \tag{36}$$

where all variables are as previously defined.

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 $q_{int,lat}$ takes the form of Equation 4 (zero order polynomial) as, with:

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

where $K_{p,lat}$ is a constant describing latent gains from occupants. A value of 74.6 W per occupant was selected for this constant (ASHRAE, 1985). The computation of the number of occupants was defined before for the internal gain (sensible) load elements CI4.

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

Combining all of the c_0, c_1 and c_2 coefficients calculated from the above load elements CI1 to CI6, results in the final building load relationship as a function of outside air temperature (Equation 7). This relationship can then be utilized for each temperature bin to evaluate the building power use. The same equation can also be utilized at the winter and summer design temperatures to estimate the building design loads.

Since the GSHP development model considers two sets of bins, one for daytime hours and one for night time hours, two corresponding sets of c_0, c_1 and c_2 coefficients are required. Furthermore, since some load distinction is made between winter and summer, through the latent and solar load elements, two free sets of coefficients are required. The resulting building load behavior is displayed graphically in Figure 13.

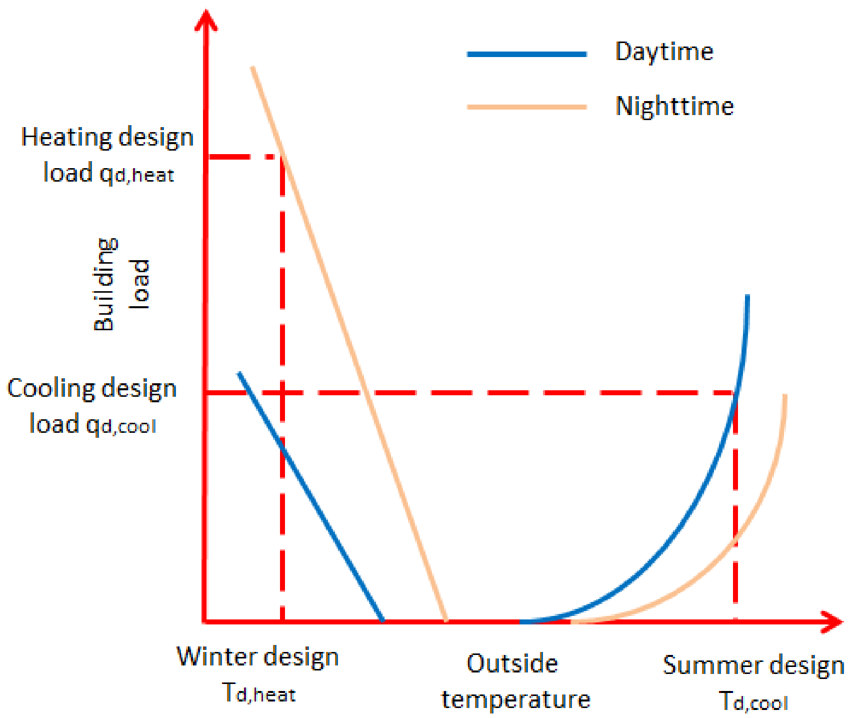

Figure 13. Building load vs. outside temperature

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

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:

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

Residential buildings

The approach selected for residential buildings is very similar to the one presented for commercial (institutional) and industrial buildings. The assumption of a single zone model, as displayed 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, particularly for homes equipped with central heating schemes. Therefore, the simplified building model for residential usages should lead to more robust estimations of building loads and power use when choosing the descriptive methodologies.

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

While most of the heat loss and heat gain elements are common to residential usages, 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 computations. Basement heat losses are not considered for CI buildings since they are assumed to be negligible compared to the overall building requirement. This is not the case for residential or small commercial buildings, where basement heat losses can account for a large part of the total design requirement.

As for CI buildings, each heating or cooling load is expressed through an explicit relationship between the load and the outside air temperature. However, the presence of below-grade elements results in one free 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 elements, and $d_{0,k}$ and $d_{1,k}$ are polynomial coefficients deducted from physical building features for each below-grade component k.

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

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

or in short form:

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

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 computations of the six load elements for a residential building and a commercial (institutional) and industrial (CI) building is displayed hereafter, followed by the resulting building load equation and balance points. To facilitate the identification of these six load elements specifically associated with residential buildings, they are noted from RES1 to RES6.

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 identical c_o and c_1 coefficients as in Equations (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. A free 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:

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

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:

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

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

The losses for full basement below-grade elements are divided to 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:

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

Since the bin methodology only provides air temperature distribution, a linear correlation between the outside air temperature and the ground temperature is utilized to get the ground temperature for each bin:

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

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

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

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

and for below-grade floor (full foundation):

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

$$d_1 = U_{f,floor}\frac{S}{Z} \tag{50}$$

For slab on grade foundations, only the last two equations, divided by 2, apply. 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.

RES2 - Solar gains (sensible)

Computation 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 elements RES1 as having an equal distribution of the window surface across the four wall orientations.

RES3 - Internal gains (sensible)

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

$$c_0 = K_{int} + K_{p,sens} \tag{51}$$

where K_{int} redelivers gains from all equipment, lights and appliances, and $K_{p,sens}$ redelivers gains from occupants. The constants in the equation above were assumed to be 14 W/m^2 for internal gains and 74.6 W/person for occupants.

Unlike commercial (institutional) and 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 mean heat gain from children is taken as half that of an adult.

RES4 - Fresh air load (sensible)

The load due to outside air entering into the building is approximated exactly as defined 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 wall height (approximated at 2.5 m), H_b the basement height (approximated at 2.2 m, when present), S the floor area (excluding basement), and Z the number of floors.

RES5 - Fresh air load (latent)

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

RES6 - Internal gains (latent)

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

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 elements RES1 to RES6 results in the final building load relationship as a function of outside air temperature. This relationship can then be utilized, for each temperature bin, to evaluate the building power use and can also be utilized 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 circumstances. Figure 13, presented for CI buildings, applies equally to the residential model. The balance point temperature T_{bal} for residential buildings is achieved by finding the root of equation:

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

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

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

Building Load Computation – Power Use Methodologies

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

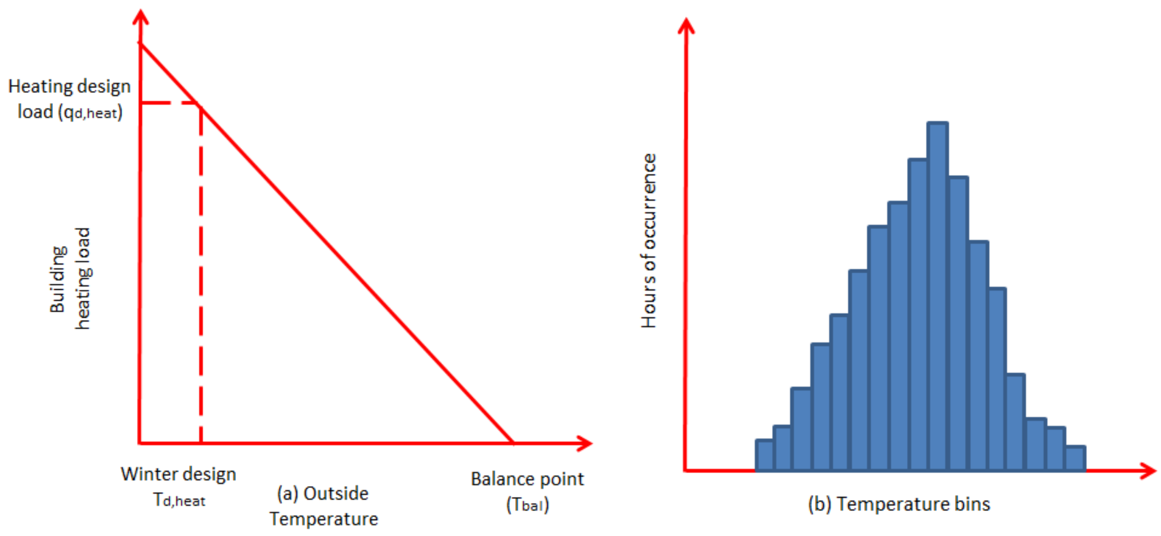

Figure 14. Information available for power use methodologies

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 displayed in Figure 14b, is equal to the user-defined annual heating load of the building $q_{tot,heat}$. In discrete form:

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

where $T_{o,i}$ is the mean temperature for each of the p bins available in the model (1≤i≤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 displayed in Figure 14b. Equations (54) and (55) constitute a simple set of two equations carrying two unknowns, namely c_0 and c_1. Solving the set of equations results in the following explicit form for the coefficients:

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

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

To get 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 achieved in Equations (56) and (57) allows delimiting the bins utilized in the computation. This, in turn, modifies the c_0 and c_1 coefficients, resulting in an iterative solution process. The process presented in Equations (54) to (57) is then reapplied to get a separate set of c_0 and c_1 coefficients specific to the cooling season, with user-defined 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 displayed in Figure 15a, the balance points could overlap if the data defined are inconsistent or if the linear model for the building load does not accurately represent the building behavior. Since it is not possible, with the information available, to resolve such a conflict, the GSHP development 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 resources for cooling and heating power use tends to make the iterative solution process more difficult.

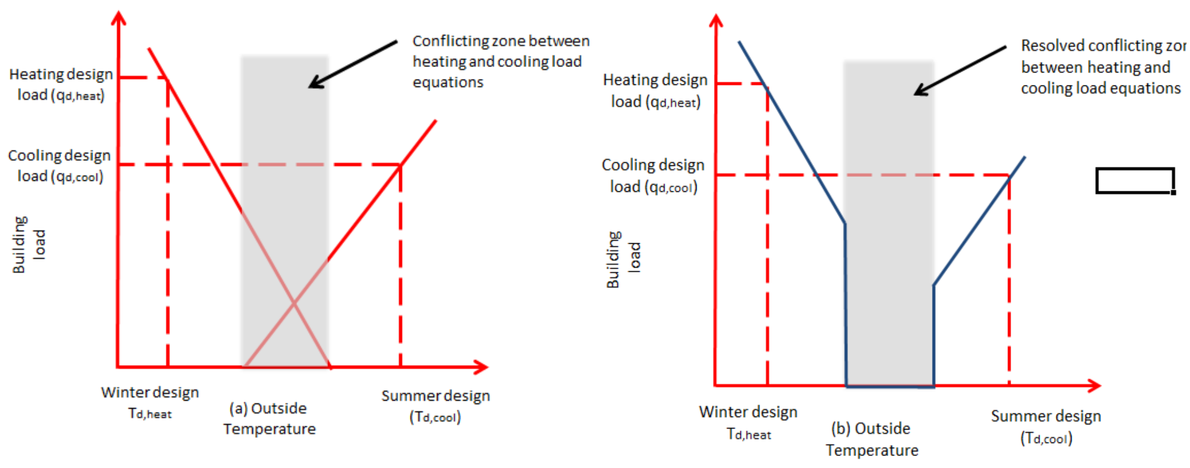

Figure 15 a. Balance point conflict between heating and cooling load curves
Figure 15 b. Modified building load curves to resolve balance point conflict

Building Load Computation for each Temperature Bin

The steps defined in previous paragraphs lead to the computation of building load for each temperature bin produced. This is done through Equation (7) for commercial (institutional) and industrial buildings, and Equation (41) for residential buildings, taking into account the balance point temperatures.

As an example of such computation, Table 5 shows the usage of the methodologies to a 2°C daytime temperature bin. The building's total power requirement for heating and cooling is simply evaluated by combining the calculated requirement with the hours of occurrence of the temperature bins and the balance point temperatures, using the algorithms displayed in the previous paragraphs.

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

Bins (°C)	January (h)	July (h)	Rest of year (h)	Cooling requirement (yes/no)	Heating requirement (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

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

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

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:

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

where COP_h is the design heating coefficient of performance of the heat pump scheme, 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 utilized to calculate the required GHX length L_c based on cooling requirements:

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

where COP_c is the design cooling coefficient of performance (COP) of the heat pump scheme, 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 usually attributable to large 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 initial feasibility evaluation stage.

Equations (58) and (59) requires the determination of pipe thermal resistance R_p and soil/field thermal resistance R_s. These are checked from geometrical and physical considerations. For horizontal GHX, the methodology takes into account surface effects that have a large 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 displayed by Equations (58) and (59), there are two possible heat exchanger lengths that can be utilized for designing a closed-loop scheme. 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 scheme. Selecting a GHX length that will not be sufficient for heating will require an auxiliary heating scheme. Using a GHX length insufficient for cooling will require a supplemental heat rejector. The GSHP development model takes into account the two possibilities when modelling the GHX.

Design entering water temperature (T_{ewt})

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 given for sizing the heat exchanger. This also applies for a GHX: the final size of the GHX is in great part checked 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 utilized in the GSHP model:

- Minimum design entering water temperature:

$$T_{ewt,min} = T_{g,min} - 15°\text{F}$$

- Maximum design entering water temperature:

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

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

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) redelivers 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:

$$F = \frac{\bar{q}}{q_{max}} \quad (60)$$

where $\bar{q}$ and q_{max} are the mean 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, usually July and January in the Northern Hemisphere, leading to the values F_c and F_h utilized in Equations (58) and (59).

Earth Connection - Open Loop Schemes (Groundwater)

Standing well schemes 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 the scaling or corrosion caused by the groundwater.

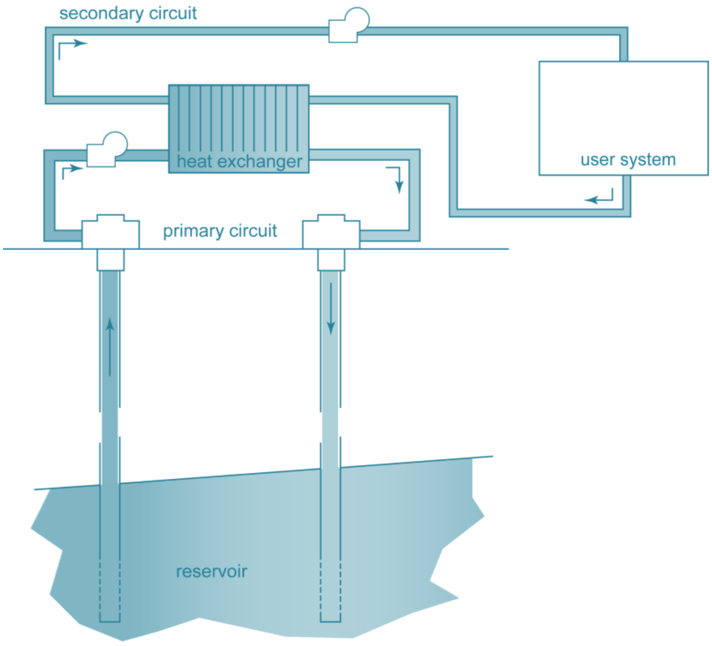

Figure 16. Indirect groundwater heat pump scheme utilized in an open loop scheme

The sizing criterion for a groundwater scheme is the groundwater flow; the scheme size is not measured in sets of length (e.g. metres of tubing for closed-loop schemes), but rather in sets of flow, measured in litres of groundwater per second. Groundwater flow is checked by the higher of the flows required for cooling design circumstances and for heating design circumstances. Determination of the flow requirements is based on the fundamental equation for thermal size:

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

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

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 circumstances, 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 displayed 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 met by the following two design methodologies, 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 methodology is defined 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 methodology requires the computation of elements that specifically belong to the heat pump scheme, it is explained later that the building supply temperature $T_{b,s}$ is close to T_{ewt}.

Approach temperature design methodologies

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

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

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

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

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

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

$$T_{g,wo} = T_{b,r} + \Delta T_a \tag{66}$$

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

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:

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

The usual 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 size.

Similarly for cooling circumstances, 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) provides the temperature of groundwater leaving the intermediate heat exchanger ($T_{g,wo}$) that is necessary to resolve Equations (61) and (62), which in turn allows to size the earth connection (e.g. the open loop scheme) by the determination of the required design well flow rate (m) for heating and cooling.

Heat Pump Scheme

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

Coefficient of performance (COP) and size ($Q_{c/h}$)

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

For cooling:

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

For heating:

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

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

The methodologies utilized to model the COP and the size 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 circumstances, 0°C for heating and 25°C for cooling), $Q_{c/h}$ is the size 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 size multiplier, calculated so that the scheme meets either the building's heating or cooling load.

Table 6. Polynomial correlation coefficients utilized 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
Size	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 utilized as the design criteria, the heat pump size is selected based only on the required heat pump size necessary to meet the cooling load. If the resulting heating size is insufficient, the model assumes that auxiliary heat will be available. The auxiliary heat will then have the same efficiency and power source as the base case Heating, Ventilation and Air Conditioning (HVAC) scheme. The resulting size multiplier λ is then expressed as:

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

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 size multiplier λ is the higher 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 size multiplier λ from Equations (74) or (75) is retained since the GSHP model assumes that the cooling requirements must, at a minimum, be met by the installed heat pumps.

Entering water temperature ($T_{w,i}$) for closed-loop ground exchanger

To evaluate the heat pump coefficient of performance (COP) and their related size ($Q_{c/h}$) for each temperature bin, a linear interpolation methodology was developed based on a process presented in IGSHPA (1988). The interpolation methodology 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} redelivers the point where the curve cuts the y-axis and all other variables were previously defined.

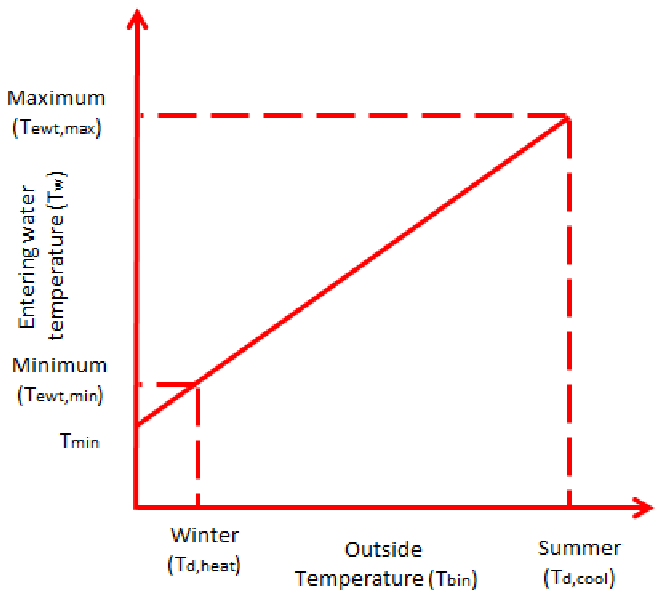

Figure 17. Determining entering water temperature as a function of outside temperature

Entering water temperature (T_{ewt}) for open-loop (groundwater) schemes

For groundwater schemes, the entering water temperature into the heat pump is linked to the groundwater temperature and building load by combining Equation (68) with the following equation for the intermediate heat exchanger size 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 size, 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 $T_{g,wi}$ provides 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:

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

A free 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 achieved as the work required raising the water over a height Δh from the pumping depth to the surface, plus a constant free 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.

Power Use Evaluation

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

Heat pump run time and power use of auxiliary pumps

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

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

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

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

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 higher the penalty due to the degradation coefficient.

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

$$HP_{e,demand} = \frac{Capacity}{COP} \quad (84)$$

The auxiliary building loop pumping power is assumed to be 17W per kW of installed cooling size. The groundwater scheme pumping power is achieved by dividing Equation (81) by a motor efficiency.

Supplemental heating or cooling requirements

The supplemental heating or cooling requirements are checked for each temperature bin simply by the difference of the building load minus the size of the heat pump. The electric power Q_e utilized by the heat pump and auxiliary pumps is:

$$Q_e = Bin(h)\left[\left(HP_{e,demand}F\right) + AUX_e\right] \tag{85}$$

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

The design auxiliary heating load is calculated by subtracting the heat pump scheme's heating size at minimum entering water circumstances from the building design load. The design supplemental heat rejector load is calculated by subtracting the GHX size at maximum entering water circumstances from the building design cooling load.

Summary

In this section the algorithms for Ground-Source Heat Pump (GSHP) development model have been displayed in detail. For data input, the model requires weather data, building data, and GSHP related data. The modified bin methodology allows the estimate of building loads. Weather data are utilized to produce temperature bins and calculate the temperature of the ground. Building data are utilized to calculate heating and cooling load vs. temperature relationships and the building's balance points. Combining weather and building data enables the computation of building loads for each temperature bin. With the GSHP related data, it then becomes possible to evaluate the actual heat pump performance and size for each temperature bin, and finally calculate the yearly performance of the GSHP scheme assessed.

References:

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